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| --- | --- | --- | --- | --- | --- | --- |
| **Period** | **Cluster number** | **Direction and type** | **Relative frequency** | **Classification according to mean PM2.5 concentrations** | **Relative frequency by mean PM 2.5 concentrations (%)** | **Relative frequency by direction and type (5)** |
| November 2017 | MC1 | NW slow | 11% | High | Nearly Average:84 | NW slow 22 |
| MC2 | NW fast | 18% | Nearly average | High 17 | NW fast:73 |
| MC3 | NW fast | 14% | Nearly average |  | N slow (recirculated):6 |
| MC4 | NW fast | 9% | Nearly average |  |
| MC5 | NW slow | 11% | Nearly average |  |
| MC6 | NW fast | 16% | Nearly average |  |
| MC7 | NW fast | 15% | Nearly average |  |
| MC8 | N slow (recirculated) | 6% | High |  |
| MC9 | NW fast | 1% | Nearly average |  |
| November Climatology | MC1 | NW slow | 28% | High | High 72 | NW slow: 65 |
| MC2 | NW slow | 17% | Extreme | Extreme:17 | NW fast: 35 |
| MC3 | NW slow | 20% | High | Nearly average 11 |
| MC4 | NW fast | 13% | High |  |
| MC5 | NW fast | 11% | High |  |
| MC6 | NW fast | 8% | Nearly average |  |
| MC7 | NW fast | 3% | Nearly average |  |
| December 2017 | MC1 | NW fast | 17 | Nearly average | Nearly average: 90 | NW fast: 76 |
| MC2 | NW fast | 4 | Nearly average | High: 10 | NW slow (recirculated): 10 |
| MC3 | NW slow (recirculated) | 10 | High |  | N fast: 14 |
| MC4 | NW fast | 18 | Nearly average |  |
| MC5 | NW fast | 23 | Nearly average |  |
| MC6 | NW fast | 14 | Nearly average |  |
| MC7 | N fast | 14 | Nearly average |  |
| December climatology | MC1 | NW fast | 19% | Nearly average | Nearly average:44 | NW fast: 42 |
| MC2 | NW fast | 2% | Nearly average | Extreme:32 | Nw slow: 34 |
| MC3 | NW slow | 17% | High | High:23 | N fast: 13 |
| MC4 | NW fast | 15% | Extreme |  | NE slow: 10 |
| MC5 | NW slow | 17% | Extreme |  |
| MC6 | NW fast | 6% | High |  |
| MC7 | Nfast | 13% | Nearly average |  |
| MC8 | NE slow | 10% | Nearly average |  |

#### Air masses affecting Beijing in November and December

Fast north-westerly air masses had higher relative frequency in November 2017 (73% by MC2, 3, 4, 6, 7, 9) than in November climatology (35% by MC4, 5, 6, 7) (Table 10). Accordingly, north-westerly slow air masses In November climatology occurred more frequently (65% MC1, 2, 3) than in November 2017 (22% MC1, 5). In November 2017, an additional type of ai mass was identified (northerly slow recirculated, MC8), which had minimal relative frequency (6%) (Table 10). In December, north-westerly fast air masses were dominant in both periods, but occurred less frequently in climatology (42% MC1, 2, 4, 6) than in 2017 (76% by MC1, 2, 4, 5, 6) (Table 10) North-westerly slow were more frequent in December climatology (34% by MC3 and MC5) than in 2017 (10% MC3)(Table 10), but in the latter, it was recirculated (MC3). Northerly fast was identified in both periods of December and had similar relative frequency (MC7 in 2017, 14% and MC7 in climatology, MC7). In December climatology, a newly identified air mass type occurred (MC8, north-easterly slow) which accounted for 10% of the total air mass arriving in Beijing during that time (Table 10).

Climatology results are consistent with previous similar studies, <http://dx.doi.org/10.1016/j.jes.2016.06.03>, which found a greater occurrence of fast north-westerly air masses during winter in Beijing, with minor occurrence of slow recirculated north-westerly air masses.

Residence time, travel path and mean PM2.5 MC concentrations

November

In climatology, MC2 (17% relative frequency) was associated with the highest mean PM2.5 concentrations. Air masses associated with MC2 travelled through some of the most industrialised areas surrounding Beijing, where PM 2.5 emissions are high (Shanxi, Shaanxi and Hebei) (Figure 11-12). The long permanence time and travel path of this cluster over these areas might justify its association with extreme mean PM2.5 concentration (Figure 11). This result is consistent with <http://dx.doi.org/10.1016/j.jes.2016.06.03>, which found clusters associated with higher mean PM 2.5 concentrations travel through the most industrialised. In 2017, MC1 and MC8 have similar travel paths than MC2 in climatology and are associated with air masses with the highest concentration observed during the period (Figure 11-12). However, the mean PM2.5 concentrations associated with MC1 and MC8 (high) are lower than those associated with MC2 (extreme). Having similar path, similar residence time but lower concentrations in 2017 than in climatology might indicate that a reduction in the emissions in local and surrounding regions in 2017 is likely. Cheng et al (doi:10.5194/acp-19-6125-2019) which conducted studies on the reduction emissions in China using model-based composition analysis, estimated that 65.4% and 22.5% of PM 2.5local emission abatements between 2013 and 2017 were due to local air pollution control policies and reduction in emissions from Beijing’s surroundings respectively). He also stated that favourable meteorological conditions were also accountable for this reduction, especially In November 2017. However, these contributed in substantially lower measure (12.1%). Therefore, it is likely that PM2.5 concentrations recorded for MC1, MC9 for 2017 were lower than MC1 due to Beijing’s effective emission reduction policy.

In climatology, MC4 (13%) and MC5 (11%) are associated with high mean PM2.5 concentrations and have similar paths (Figure 11-12 D). These originate in south-western Russia and southern Russia respectively, travelling through Mongolia (and Kazakhstan for MC4), inner Mongolia and the Hebei province before reaching Beijing. MC2 and MC3 (nearly average) in 2017 are analogous to MC4 and MC5 in climatology but are associated with approximately half mean PM2.5 concentrations than MC4 and MC5 (high) in climatology (Figure 12 A-B). (DOI: 10.3103/S1068373913020039) Dement et al, studying annual variations of PM 25 in the Eastern Gobi deser,t found that the highest monthly mean PM 2.5 concentrations are observed in spring and winter). Furthermore, (<http://dx.doi.org/10.1016/j.jes.2016.06.03>) Found that MC travelling through similar regions than the cluster analysed, were responsible for transporting PM 2.5 to Beijing. As the similar paths for cluster in 2017 and climatology, do not differ substantially, and both are recorded in winter, but with different concentrations, it is likely that a reduction in the emission in 2017 in their final section of their travel path is the cause of this difference, rather than higher proportion of PM 2.5 transported from eastern gobi desert. However, this should be confirmed by further analysis using tools to identify the relative contribution of PM 2.5 pollution sources, such as PSCF (REEF.

MC5 and MC9 in 2017 and MC6 and MC7 in climatology are associated with the lowest mean concentrations of PM2.5 (nearly average). These are associated with the Siberian airmass, which brings clean air. In both periods, they have similar contributions towards total air masses (11% and 1% for MC5 and MC9 in 2017 and 8% and 3% for MC6 and MC7 in climatology).

MC3 in climatology (20%) originated in Kazakhstan , travelling through Mongolia and inner Mongolia prior to arrival in Beijing. It had a similar travel path than MC4 in 2017 (9%), however, MC3 was associated with high mean PM2.5 concentrations, while MC4 was associated with nearly average concentrations. The difference could be explained by reduced emissions of pollution in 2017 compared to climatology in the areas travelled in the MCs final section.

MC1 in climatology and MC6 in 2017 also had similar characteristics to MC4 in 2017 (similar travel paths, similar residence time but MCs in 2017 were associated with) however, MC1 occurred more frequently in the climatology (28%) than MC4 in 2017 (9%) final stat

In climatology, MCs associated with high mean concentrations of PM2.5 had the highest relative frequency (72% given by MC1, MC3, MC4 and MC5)(Figure 12 and 12 B). Extreme mean PM2.5 concentrations were uncommon (17%, MC2), and the minority (11%) of the MCs were associated with nearly average PM2.5 concentrations (MC6 and MC7) (Figure 12 and 12 B).

Conversely, in 2017, most MCs were associated with nearly average mean PM2.5 concentrations (84% given by MC2, MC3, MC4, MC5, MC6, MC7 and MC9), while MCs with high concentrations (MC1, MC8) were uncommon (17%) (Figure 12 B, 12B). NO MC was associated with extreme PM2.5 concentrations.

FREQUENCY AT THE END

#### December less cluster travel in poll areas so rel contr is less, they are also carrying less conc

In climatology, MC5 and MC4 are associated with the highest mean PM2.5 concentrations (extreme). This might be justified by their travel paths over the industrial areas on the west and south west of Beijing (Shaanxi, Hebei and Shanxi). MC5 and MC4 are common in climatology (32% of total air masses, 15 for MC4 and 17% for MC5). In November, no MC had similar paths to MC4 and MC5 climatology. The MC associated with highest PM2.5 mean levels is MC3 (high). This cluster originated in southern Russia and recirculated over the polluted regions south of Beijing (Hebei and Shandong). However, MC3 in 2017 had lower mean PM2.5 concentrations than MC4 and MC5 in climatology, with lower frequency 2017. MC3 and MC6 in climatology were associated with high mean PM2.5 concentrations. These clusters had similar travel paths, however MC6 was faster than MC3. The lower residence time of MC6 in the polluted regions of western Beijing were reflected in the lower concentrations when compared to the longer residing MC3. MC3 and MC6 in climatology had a relative frequency of 23% (17% for MC3 and 6% for MC6). MC1 and MC5 in 2017 had analogous travel paths to MC3 and MC6 in climatology. However, these clusters were associated with a mean PM 2.5 concentration substantially lower than MC3 and MC6 in climatology. This is likely due to a reduction of emissions along the final stages of their travel paths. Furthermore, they occur with higher frequency in 2017 than in the climatology (40% total, 17% for MC1 and 23% for MC5). The remainder of the MCs were associated with a nearly average meanPM2.5 concentrations in both 2017 (MC2, MC4, MC6 and MC7) and the climatology (MC1, MC2, MC7, MC8). The relative frequency of these clusters was higher in 2017 (51%), than in climatology (44%).

Overall, it appears as clusters in 2017 were associated with lower mean PM2.5 concentrations than in the climatology. Furthermore, a higher frequency of air masses associated with lower concentrations was recorded in 2017 than in the climatology.

In climatology, most MCs (44%) were associated with nearly average PM2.5 mean concentrations (MC1, MC2, MC7 and MC8). 32% MCs were associated with extreme concentrations (MC4, MC5), and the minority was associated with high (23% MC3 and MC6). In December 2017, most clusters were associated with nearly average PM2.5 concentrations (90% from MC1, MC2, MC4, MC5, MC6 and MC7). MCs with high concentrations occurred rarely (10% MC2).

In JF1 2018, all MCs (100%) were associated with nearly average mean NO2 concentrations, while in JF1 climatology, MCs associated with above average concentrations (58%) occurred more frequently than MCs with nearly average concentrations (41%)(Figure 6 and Table 5). In JF2 2018, most MCs had NO2 mean concentrations nearly average (77%) and the remainder were associated with above average concentrations (23%) (Table 5). IN JF2 climatology, MCs with nearly average concentrations (47%) and above average concentrations (46%) occurred with similar frequency, but MCs with above average concentration occurred more frequently than in 2017 (Table 5). Furthermore, a cluster with high concentrations of mean NO2 concentration was observed (MC7), with a frequency of 7% (Table 5).

In climatology, MC5 and MC4 are associated with the highest mean PM2.5 concentrations (extreme). This might be justified by their travel paths over the industrial areas on the west and south west of Beijing (Shaanxi, Hebei and Shanxi). The MC associated with highest PM2.5 mean levels in 2017 is MC3 (high). This MC originated in southern Russia and recirculated over the polluted regions south of Beijing (Hebei and Shandong). However, MC3 in 2017 had lower mean PM2.5 concentrations than MC4 and MC5 in climatology, despite having similar path and residence time. This is likely due to a reduction in local emissions in Beijing, which contributed to the lowest mean PM 2.5 concentrations associated with the MC3 in 2017. This is also true for MC8 in climatology and MC7 in 2017, MC7 climatology and MC6 in 2017, MC2 in both climatology and 2017.

In climatology, most MCs (44%) were associated with nearly average PM2.5 mean concentrations (MC1, MC2, MC7 and MC8). 32% MCs were associated with extreme concentrations (MC4, MC5), and the minority was associated with high (23% MC3 and MC6). In December 2017, most clusters were associated with nearly average PM2.5 concentrations (90% from MC1, MC2, MC4, MC5, MC6 and MC7). MCs with high concentrations occurred rarely (10% MC2).

It is likely that the lower PM 2.5 levels recorded in Beijing during December 2017 than during previous years are due to the higher proportion of MCs associated with nearly average mean PM2.5 concentrations in 2017 (90%) than in climatology (44%), similarly to November. It was found that a reduction in local emissions in Beijing in 2017, caused air masses that period to transport lower PM2.5 concentrations than in climatology due to the reasons explained above.