Dear Editors and Reviewers,

Thank you very much for your careful review and helpful comments on our manuscript acp-2020-708. We appreciate very much your constructive comments and encouraging suggestions on our manuscript. We have accordingly made the careful revisions. The revised portions are highlighted in the revised manuscript. Please find our point to point responses to the reviewer's comments as follows:

Responses to the reviewer 1

[The paper describes the meteorological processes that can lead to largely increased air pollution in the Hunan and Hubei provinces in central China in winter. The authors analyse $PM_{2.5}$ observations together with ERA interim meteorological re-analysis data by means of multivariate EOF decomposition. The paper suffers from several significant shortcomings. I do not recommend its publication in ACP.

First of all the analysis deals with a very regional or local effect. The authors do not make clear why it should be of interest for an international scientific audience to get insights into the meteorological effects leading to increased pollutants concentrations in the Hunan and Hubei provinces. In particular, the authors do not put their findings in the context of similar studies or similar conditions elsewhere in the world. Also, the literature cited in the paper consists almost exclusively of Chinese authors reporting about air quality in China. Of course, this is necessary in order to put the study into the context of other similar studies. However, the authors should have taken other international studies into account.]

Response 1: Many thanks for referee's comments. In the revised manuscript, we have accordingly 1) clarified why it should be of interest for an international scientific audience to get insights into the meteorological effects leading to increased pollutants concentrations in the region of central China, 2) taken other international studies with literature cited in the paper into account, and 3) presented our finding about Meteorological mechanism of regional $PM_{2.5}$ transport in air pollution with an implication to environmental change as followings.

Regional transport of air pollutants from source to receptor regions is an important issue in atmospheric environment. The meteorological mechanism of regional transport has not been fully understood. The Twain-Hu Basin (THB), a sub-basin covering the lower plain in Hubei and Hunan provinces over the middle reaches of Yangtze River in central China, connects North China and East China. This basin lies in the downwind areas of heavy air pollution sources under the influence of East Asian winter monsoon, serving as a hub for the regional transport of air pollutants. The THB has become a regional heavy pollution center over recent decades (Shen et al., 2020). However, the meteorological influences on air pollutant transport with a receptor region for heavy air pollution in THB have not been systematically studied. Therefore, this study aimed to comprehensively investigate the meteorological mechanism of regional $PM_{2.5}$ transport during heavy pollution events over the THB based on the multi-year observation to improve our understanding on environmental change.

Regional transport of air pollutants is an important issue in atmospheric environment (Mayer, 1999; Jacobson, 2001; Kim et al., 2015; Singh et al., 2017; Crippa et al., 2018). Air pollution has become a public concern on atmospheric environment (Zhao et al., 2013; Chowdhury et al., 2018, 2019; Kanawade et al., 2019). The synoptic circulations exert an important impact on air pollutant transport (Hegarty et al., 2007; Demuzere et al., 2009; Russo et al., 2014; Pope et al., 2015; Bei et al., 2016; Yue et al., 2016). Biomass burning over the source region (i.e., northern Indochina) coincided with weak westerly system over the northern South China Sea, and the aerosols were transported to downwind regions by a cold front and low-level jet (LLJ) (Huang et al., 2020b). Exports of air pollutants from the North American boundary were the result of eastward advection over the ocean and transport in a weak warm conveyor belt airflow (Owen et al., 2006). The transport of air pollutants under the control of cold front system has a significant effect on air quality (Fuelberg et al., 2007; Xu et al., 2016b; Kang et al., 2019). Good air quality often occurs under cyclonic conditions, while poor air quality is frequently associated with anticyclonic conditions (Russo et al., 2014; Pope et al., 2015; Santurtún et al., 2015). The long-range transport of polluted air masses from the North China Plain is the main factor for the sharp increases of PM2.5 concentrations in central

China (Lu et al., 2017, 2019b; Li et al., 2019b). Fine particulates can be regionally transported over a long distance with obvious trans-boundary transport, exerting an important effect on air pollution (Kim et al., 2012; Khuzestani et al., 2017; Li et al., 2019c; Yuan et al., 2019).

Regional transport of air pollutants is one of the key factors affecting air quality. The meteorological mechanism of regional transport has not been fully understood. The Twain-Hu (Hubei-Hunan) Basin (THB) in Central China is located in the wintertime downwind area of major pollution sources over North and East China under the East Asian winter monsoonal winds. To understand the meteorological mechanism of regional $PM_{2.5}$ transport on air pollution, 8 typical regional transport pollution events which occurred in THB during January 2015-2019 were selected objectively by using MV-EOF (multivariable empirical orthogonal function) decomposition with multi-source observation data, and the meteorological changes driving the regional transport of $PM_{2.5}$ in heavy air pollution in the basin was studied. The results showed that the regional transport of $PM_{2.5}$ from the source area to the THB was actuated by cold air southward invasion with anomalous northerly winds in the lower troposphere, and the vertical structure of atmospheric circulation for the regional transport is characterized with the typical pattern of southward advance of cold front with the cold air confronting the warm air mass over the THB area. In the middle troposphere existed an abnormal warm air layer, referring as the tropospheric “warm lid”, suppressing the vertical diffusion of air pollutants. With such the meteorological configurations, the warm air mass and the windward side of basin terrain forming a “barrier” of regional transport could significantly accumulate $PM_{2.5}$ for heavy air pollution in the THB, where a key receptor of $PM_{2.5}$ was built in regional transport over central and eastern China. These findings (Fig. 12) could enrich the scientific understanding of the meteorological influence on air pollution with regional transport of source-receptor air pollutants.

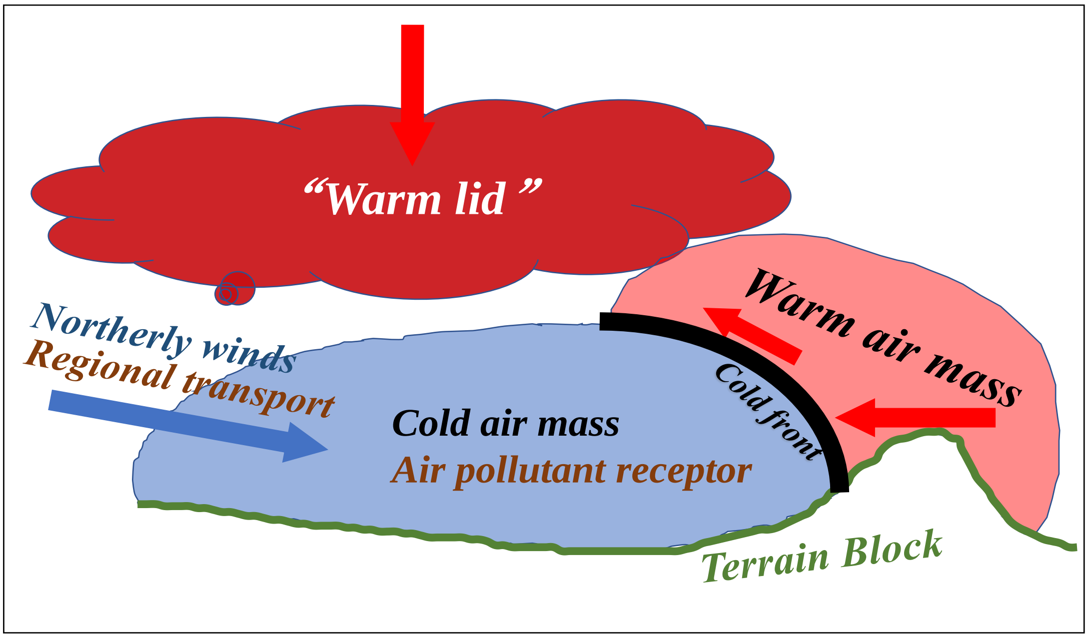

Figure 12. Diagram on meteorological mechanism of regional $PM_{2.5}$ transport with a receptor region of wintertime air pollution.

[Second, the paper repeats its findings several times, partly even by using exactly the same expressions. The explanations given in section 4.2 are more or less repeated in 4.3 (lines 488-501), 5.1 (lines 547-560) and 5.2 (617-622). This makes the reading of the paper very tedious.]

Response 2: In the revised manuscript, we have made the substantial revisions especially in English language following the referee's suggestions with modifying the repeated explanations in Sect. 4 and removing the Sect. 5.

[Third, the English used in the paper needs significant improvements and corrections. Sometimes, it is very difficult to understand what the authors really want to say. For example, the expression "the effect mechanism of (...) meteorological conditions" or the "effect mechanism of pollutant transport" is central to the paper and appears five times. However, it isn't clear what the authors mean with the "effect mechanism".]

Response 3: With the English language editing service, the language usages have been improved with correcting the errors of grammar, confusing wording and inappropriate expression in the revised manuscript. The title of manuscript, has been changed to "Meteorological mechanism of regional $PM_{2.5}$ transport in wintertime heavy pollution over the Twain-Hu Basin, Central China".

[Other major comments:

In the abstract and at several other places in the document, the authors mention the pollution transport pathways through "Nanxiang Basin-Yunmeng Plain pathway and the Dabie Mountain's Hilly Area-Yunmeng Plain pathway". If you are not from China, it is quite hard to understand these descriptions unless you provide a map.]

Response 4: That section 5.1"Nanxiang Basin-Yunmeng Plain pathway and the Dabie Mountain's Hilly Area-Yunmeng Plain pathway" has been deleted in the revised manuscript.

[Lines 126 – 129: The authors argue that their findings are of practical value by broadening the scientific understanding of heavy pollution formation mechanisms. However, the findings may be of scientific interest but I cannot see the practical value. The differences to other regions of China (and perhaps to other regions with similar topography) are not much discussed in the paper. In addition, because the authors themselves demonstrate in section 5.2 that chemistry transport models like WRF-CHEM are able to reproduce the pollution transport towards the Hunan and Hubei provinces, the question arises which additional insights this study gives.]

Response 5: We thank the referee for the kind suggestions. In the revised manuscript, we have made the according revisions with removing "practical value" and addressing the scientific interest of our study.

Under the stagnant meteorological conditions with weak winds, strong and thick temperature inversion layers, sinking motion and low mixing layer heights are unfavourable for the diffusion of air pollutants for the formation of heavy air pollution. Differently from air pollution in most parts of China, the pollutant transport and the meteorological mechanism in heavy pollution in the receptor region have not been systematically studied.

Furthermore, the section 5.2 about WRF-CHEM simulation has been deleted in the revised manuscript.

[Section 2.2: The methods are not well described, the explanations are too brief and too general. The authors should have made an attempt to better explain their approach to the reader. They could also give references for those who are not deeply involved in MV-EOF and EEOF or give more details in an appendix.]

Response 6: Following the referee's suggestion, we have added the brief description of MV-EOF in the revised manuscript as follows:

2.2 Decomposition of multivariable empirical orthogonal function (MV-EOF)

The empirical orthogonal function (EOF) analysis is a method used to identify patterns of simultaneous variation (Schepanski et al., 2016). The EOF can concentrate the information of original field into several main modes to describe the changes of the complex element field through the dimensionality reduction. The principle is to decompose the spatio-temporal matrix of observation data into a linear combination of the spatial eigenvector matrix and the corresponding time coefficient matrix.

The observation data of a certain variable field is given in the form of X_{mn} matrix:

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & & \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \quad (1)$$

where m is the space point (it can be the number of stations or grid points), n is the length of time series. Through EOF expansion, Formula (1) is decomposed into the product of the space function V and the time function T, and the matrix form is

$$X = VT \quad (2)$$

where:

$$V = \begin{bmatrix} v_{11} \cdots v_{1m} \\ \vdots \\ v_{m1} \cdots v_{mm} \end{bmatrix}, \qquad T = \begin{bmatrix} t_{11} \cdots t_{1n} \\ \vdots \\ t_{m1} \cdots t_{mn} \end{bmatrix} \tag{3}$$

V is called the spatial function matrix (space mode), which represents a typical field that does not change with time; T is called the time coefficient matrix, representing the weight coefficient of the spatial mode.

We process X_{mn} as an anomaly, get the eigenroot λ_m and eigenvector v_m of the real symmetric matrix, and then calculate the variance contribution rate ρ_i of the i-th eigenvector and the cumulative variance contribution rate P_i of the first p eigenvectors：

$$\rho_i = \lambda_i \Big/ \sum_{i=1}^{m} \lambda_i \tag{4}$$

$$P_i = \sum_{i=1}^{p} \lambda_i \Big/ \sum_{i=1}^{m} \lambda_i \tag{5}$$

The eigenvector represents the variation structure of a variable field, and its spatial distribution form represents the main distribution structure of variable field. The corresponding time coefficient is positive, indicating that the variable at that time has the same variation trend as this type of distribution. On the contrary, a negative coefficient denotes that the changing trend of variable at the corresponding time is opposite to this kind of distribution, and larger value means a more significant corresponding spatial distribution.

Multivariate empirical orthogonal function (MV-EOF) decomposition is an extended variant of EOF (Wang et al., 1992; 2008). In this method, two or more variables with the same time length and space points are standardized, and a new variable field is constructed, and then EOF decomposition is performed on the new variables. MV-EOF has advantages in simultaneously representing the spatial distributions of multiple elements and the spatial connections among various elements, and can be used to explore the coupling process of interactions in complex systems (Sparnocchia et al., 2003).

To obtain the synergistic variation of $PM_{2.5}$ concentration and meteorological elements in atmospheric circulations of heavy pollution events in the THB, we choose the daily average $PM_{2.5}$ concentrations, 10-m wind speed (including meridional and zonal components) and SLP from 31 urban observation sites in the THB in January of 2015-2019 for MV-EOF decomposition. Since the magnitude of different elements varies greatly, all elements have been standardized before the MV-EOF decomposition.

The data matrix X_{mn} constructed by using the four elements is as follows:

$$X_{mn} = \left[X_{m_1 n}, X_{m_2 n}, X_{m_3 n}, X_{m_4 n}\right] \quad (6)$$

where $X_{m_1 n}$, $X_{m_2 n}$, $X_{m_3 n}$ and $X_{m_4 n}$ represent $PM_{2.5}$, SLP, 10-m meridional wind and zonal wind, respectively; $m_1 = m_2 = m_3 = m_4$ =31 is the number of urban observation sites in the THB, n =155 is the length of the daily time series in January of 2015-2019; X_{mn} is the extended new variable fields. Then, the new variable matrix is introduced into Formula (2) to do the EOF decomposition.

[Line 183: It is not clear what "synthetic analysis" exactly means in this context.]

Response 7: In the revised manuscript, we have changed "synthetic analysis" to "average" .

[Line 221: What is meant with the "most obvious spatial characteristics"?]

Response 8: In the revised manuscript, we have removed the "most obvious spatial characteristics" for focusing this study at the regional $PM_{2.5}$ transport.

[Figure 2: What re the units of the color scale? If this is $PM_{2.5}$ is this in $\mu g/m^3$ or perhaps mg/m^3 ? What is the unit of the arrow? The number 0.15 below the arrow doesn't have units, either.]

Response: In the revised manuscript, Figure 2 show the first three modes decomposed by MV-EOF with $PM_{2.5}$ loads, the SLP loads and 10-m wind loads, rather than the elements themselves. Since the magnitude of different elements varies greatly, all elements have been standardized before the MV-EOF decomposition. Therefore the elements loads are dimensionless.

[Table 1: You list 8 typical regional pollutant transport events. No 2 & 3 as well as 6 & 7 have just one day difference. How can you consider them as another event? In the rightmost column it is stated that they belong to the same transport event.]

Response 9: In the revised manuscript, we have changed to 8 typical air pollution days with regional pollutant transport.

[Figure 3: The arrows in (c) and (d) have different standard length (6 in (c) and 3 in (d)) which is misleading.]

Response 10: In the revised manuscript, the Figure S2 (Figure 3 of the previous version) has been corrected to the same arrow lengths.

[Line 308 – 310: It is not clear what you want to say with the temperature differences. A change by 3 ◦ or only 1 ◦ in 24h does not seem to be much.]

Response 11: In the revised manuscript, it has been corrected with "Affected by the cold air southward invasion, the 24-h temperature changes in the most northern areas of China drop by -2~ -5℃, and decline by -2~ -3℃ in the THB."

[Line 330: What is Figure 2d?]

Response 12: In the revised manuscript, we have corrected this print error.

[Figure 5: If boundary layer height is given in color scale, what are the units and what does this figure say?]

Response 13: In the revised manuscript, Figure 5 show spatial distribution of correlations of daily changes of the third-mode time coefficients respectively with the SLP, atmospheric boundary layer height and 10-m wind vectors in January of 2015-2019. The corresponding discussion has been modified to "In the third mode, the heavy pollution in the THB is controlled by the bottom of the high pressure over CEC, and near-surface anomalous northerly winds as well as the upraised boundary layer (Fig. 5), which was a typical pattern of synoptic circulation for regional transport of $PM_{2.5}$ over north to central China (Yu et al. 2020). This circulation condition could drive air pollutants from the source areas of North China to the downwind THB."

[Figure 6: You should not use different standard lengths for arrows when graphs are combined in one figure.]

Response 14: In the revised manuscript, Figure 9 (Figure 6 of the previous version) has been corrected to the same lengths for arrows.

[Line 374: What would you call a "pollution-free day"? This might be very subjective.]

Response 15: In the revised manuscript, we have removed the unnecessary descriptions of "pollution-free day".

[Line 407: How was the synthesis of the 8 pollutant transport events done?]

Response 16: In the revised manuscript, it has been corrected with "By comparing the 8-case averages with the January averages during 2015-2019, the anomalies of air pollutants and meteorology in $PM_{2.5}$ heavy pollution in the THB with regional transport of air pollutants (or transport-type $PM_{2.5}$ heavy pollution) were assessed."

[Figure 9 and Figure 10: How were the soundings "synthesized"? Is this an average of the vertical soundings? If yes, this could be misleading.]

Response 17: In the revised manuscript, we have changed "synthetic analysis" to "average". It has been corrected with "All the profiles are averaged for 8 days of transport-type $PM_{2.5}$ heavy pollution (Table 1) with the anomalies relative to the monthly mean in January of 2015-2019.

[Line 493: What is meant with "cold air degenerates"?]

Response 18: we have deleted the "cold air degenerates" in the revised manuscript.

[Lines 579 – 585: It is quite hard to understand what is meant in this sentence.]

Response 19: In the revised manuscript, we have removed all the descriptions and discussions about the WRF-Chem simulation.

[Lines 586 – 597: Even if the WRF setup that was used is described somewhere else, it needs a better and more detailed explanation here, e.g. what was the spatial resolution and the number of vertical layers?]

Response 20: In the revised manuscript, we have removed all the descriptions and discussions about the WRF-Chem simulation.

[Line 726 - 731: I could imagine that there are AQ forecast systems running in China and such a “predictive warning sign” is not much needed.]

Response 21: In the revised manuscript, we have removed the unnecessary descriptions of “predictive warning sign”.