Final Responses to Anonymous Referees on "Meteorological modes of variability for fine particulate matter ($PM_{2.5}$) air quality in the United States: implications for $PM_{2.5}$ sensitivity to climate change" by A. P. K. Tai et al.

We thank the reviewers for their thoughtful and supportive comments. Our responses are provided below. The reviewers' comments are italicized, and new text is highlighted in bold.

<u>Review #1:</u>

Pg 31043, lines 20-: This is one example of a place where additional figures, and some more discussion, would be very useful. An additional figure showing the synoptic maps of the phases of dominant mode (as in fig 6) for each region would help the reader see the differences / similarities between the different regions. It would also provide more support for statements made in the abstract and conclusions (e.g., pg 31047, line 20).

Pg 31044, lines 9-: Again, figures showing the different behavior in the Southeast would be very helpful to a reader.

> We have extended Sect. 4.2 and added a few more figures similar to Fig. 6 for the other regions to the paper and supplementary materials. The relevant paragraphs are quoted below.
>
> "**Figure 7 shows as another example the dominant meteorological mode of $PM_{2.5}$ variability in California, demonstrating again a strong anticorrelation between the time series of this mode and $PM_{2.5}$ concentrations (r = -0.80). This mode has similar meteorological composition to that in Fig. 6 except for wind direction. Positive phases of this mode represent ventilation by cold maritime inflow associated with synoptic disturbances, whereas negative phases represent warm, stagnant condition associated with a high-pressure system. The bottom panel shows, for instance, that between 6 and 8 January 2005, a precipitating maritime inflow reduced $PM_{2.5}$ by 16 μg m^{-3}.**
>
> The analysis above was conducted for all regions of Fig. 1. **Figures similar to Fig. 6 and 7 for other regions are included in the Supplementary Materials.** Table 2 summarizes the characteristics of the dominant PC controlling $PM_{2.5}$ variability for five selected regions. In the eastern US (Northeast, Midwest and Southeast), the observed dominant modes resemble that for the Midwest described above (Fig. 6). In the Northeast, another mode representing southwesterlies associated with high pressure over the western North Atlantic is equally important. **In the Pacific Northwest, the dominant mode resembles that for California (Fig. 7).** In general, the PCR results illustrate the importance of synoptic-scale transport in controlling the observed

daily variability of $PM_{2.5}$. As shown in Table 2, this control appears to be well represented in GEOS-Chem, supporting the ability of the model to describe the variability in $PM_{2.5}$ associated with this transport."

Pg 31045, lines 15-19: How different are the statistics for your diagnostic of cyclones and that used by Leibensperger et al.? I imagine it would be relatively easy to apply your method to same region / period as in Leibensperger et al., and to show directly the (in)sensitivity to diagnostic used.

We will now mention in the text:

"**Cyclone frequencies found by Leibensperger et al. (2008) are generally lower, possibly because their storm-tracking algorithm may neglect weaker cyclones and fronts.**"

It should also be noted that the southern storm track region (70°-90°W, 40°-50°N) used by Leibensperger et al. (2008) to track cyclones is too large to define spatially coherent meteorological modes with our PCA-spectral-autoregressive method.

Pg 31046: The result from the climate runs is one of the papers major conclusions, but there is only 2 paragraphs discussing this analysis. Again I would prefer to see more results. In fact, I think this analysis could be expanded and form its own paper.

The discussion on results from a single GCM in this paper serves as an introductory illustration on how the PCA-spectral-autoregressive method can be applied to diagnose future changes of synoptic frequencies. We are currently using the same approach to conduct a multi-model comparison of 15 GCMs from IPCC AR4 similar to what is done here. It will become the focus of another paper, as is now mentioned in the conclusion:

"**The climate trend analysis in this study, using the Midwest as an illustration, is preliminary. A comprehensive analysis using outputs from various GCMs will be the topic of a future paper.**"

Minor comments: Pg 31037, line 17: Why are the EPA data interpolated onto the model grid? Wouldn't it be better to interpolate met fields onto the location of the EPA data and perform the analysis on these locations?

We now mention in Sect. 2.1 that: "**These sites measure every one, three or six days.**" Many sites do not have daily measurements, so it would be difficult to do day-to-day correlation analysis for these individual sites. Interpolation ensures that each grid box, as long as it covers enough sites that measure daily, would have a nearly complete $PM_{2.5}$ time series with few missing data.

Review #2:

The authors attempted to establish connections between meteorological modes and PM2.5 air quality. To do that, they first identified the modes for various regions in the US. I would like to know, for example, how much each of the identified modes explains the total variability in meteorology over that region. The authors showed in Section 4.1 "The PCs are ranked by their variance, usually with the leading two or three PCs capturing most of the meteorological variability". Can the authors show how much their "mode of cold front" explains the meteorological variability in their NE, MW and SE US regions? As the model is driven by reanalysis or GCM, it should show the same modes with similar meteorological variability explained, is that right?

> The model is driven by GEOS5 assimilated meteorological fields, which are also used to correlate with observed $PM_{2.5}$ concentrations, so it shows the same modes with similar meteorological variability explained. Also, the following text is added to Sect. 4.1.
>
> "… The PCs are ranked by their variances, usually with the leading three or four PCs capturing most of the meteorological variability. **For instance, in the eastern US, a single mode representing cyclone and cold frontal passages (discussed further in Sect. 4.2) typically accounts for ~20% of total meteorological variability.**"

Then, the authors showed dominant meteorological modes of PM2.5 variability. Over MW US, they identified the mode as "eastward propagating mid-latitude cyclone with precipitating cold front at the southwest tail end". It is not very clear to me how they can determine this mode. They showed in Figure 6 that the mode occurs with "low temperature, high precipitation, low and rising pressure, and strong northwesterly winds". Are these criteria enough to define "eastward propagating mid-latitude cyclone with precipitating cold front at the southwest tail end"? They also showed two weather maps as examples of "stagnation" and "frontal passage". Are these also used as a way to define this mode as "eastward propagating mid-latitude cyclone with precipitating cold front at the southwest tail end"? Did the authors also check the weather maps on many other days?

> The following text was added to Sect. 4.1 to clarify how the nature of the meteorological mode is determined.
>
> "… Each PC represents a distinct meteorological regime **or mode. We identified the nature of meteorological mode by examining the values of α_{kj} in Eq. 3. PCs with high $|\alpha_{kj}|$ values (e.g., greater than 0.3 and topping the other $|\alpha_{kj}|$ values) for geopotential height, pressure tendency, and wind direction are presumably associated with synoptic-scale weather systems, and can be referred to as synoptic transport modes. We then followed $U_j(t)$ day by day and visually examined the corresponding weather maps for multiple**

months during 2004-2008. From this we assigned a generalized meteorological feature for a given PC when the same feature could be associated with the majority of peaks and troughs of $U_j(t)$."

The authors show the case on Jan 28 and Jan 30, both are nice examples. I am also curious about some disagreements from the top of Figure 6, i.e. Jan 13, Jan 15? What happened on those days?

As explained in the text and in Tai et al. (2010), meteorological variables or modes can explain up to 50% of total $PM_{2.5}$ variability. The other 50% can arise from non-meteorological factors, e.g. weekend effects, and random noises. Jan 15, 2006, was the Sunday before the MLK holiday, which might partly explain the dip in total $PM_{2.5}$ despite the existence of a high-pressure system.

In addition, I wonder if the authors have done this analysis: let's focus on the mid-west US, the author already have a time series of daily PM2.5 (detrend and deseasonalized). If they do a correlation/regression study of this MW PM2.5 time series (Yt, t represent each date) with their meteorological field (i.e., SLPi,j,t or HGHTi.j,t) on each U.S. model grid (i,j), and map the correlation coefficient (Ri,j) over each grid. If PM2.5 is strongly associated with low pressure system and cyclone passages, would we see a center of strong correlation somewhere on the map of Ri,j?

This analysis has been done and the results are discussed in details by Tai et al. (2010), who observed strong positive correlation between $PM_{2.5}$ and geopotential height. We cited Tai et al. (2010) whenever relevant.

Pg 31044, line 5-9: I agree with Anonymous referee #1, more figures and detailed explanations are needed here. Can the authors explain how they define high |alpha kj| values?

See response above.

And how they obtain 70% of the observed PM2.5 components with temperature? Also, Line 9-11, how do they obtain 60% for the SE US?

As explained in Sect. 4.1, we used Eq. (6) to calculate these fractions. We now clarify it in the text:

"**Using Eq. (6), we** find overall that the synoptic transport modes account for more than 70% of the observed correlations of $PM_{2.5}$ components with temperature in the Northeast and Midwest. …"

Pg 31043, line 12-14, "From synoptic weather maps, we can verify that high positive values of this PC represent the center of an eastward propagating mid-latitude cyclone with a precipitating cold front at the southwest tail end. ". I would like to see more *explanation here. How many weather maps are examined? How exactly do the authors verify this mode? By any quantitative methods or just visually chosen?*

See response above.

Pg 31044, Pg 31045: so far, section 5 focuses solely on the cyclone frequency change under climate change. However, climate change may have effects on weather at different temporal scales: climate shifts (a general increase in humidity and temperature), interannual scales (NAO, ENSO), seasonal scales and so on. Discussion on climate change effect on PM2.5 should be much complicated than just considering cyclone frequency.

More discussion of how other climatic factors may affect $PM_{2.5}$ is now included in *Sect. 5*, quoted below:

"**Other climatic factors than cyclone and frontal frequency may also affect future $PM_{2.5}$ air quality in the US. Mean temperature increases may be particularly important for the Southeast as discussed previously. Changes in precipitation and PBL depth are obviously important. As scavenging within a precipitating column is highly efficient (Balkanski et al., 1993), precipitation frequency, often modulated by synoptic weather, may be more relevant as a predictor than climatological mean precipitation.**"

Minor comments: Pg 31033, line 6-8: a potential reference to cite here: Rasmussen, D J., Arlene M Fiore, V Naik, Larry W Horowitz, S J McGinnis, and M G Schultz, February 2012: Surface ozone-temperature relationships in the eastern US: A monthly climatology for evaluating chemistry-climate models. Atmospheric Environment, 47, doi:10.1016/j.atmosenv.2011.11.021

It is now cited.