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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Severe ozone air pollution in the Persian Gulf region" *by* J. Lelieveld et al.

Anonymous Referee #2

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General comments:

This is a scientifically well thought out study and the results have great societal implications for the Persian Gulf region. The topic fits very well within the scope of ACP. The authors carefully analyzed model results of ozone and the underlying meteorological conditions. By examining the diel and seasonal cycles of ozone and precursors, and by comparing results from this region to other subtropical regions including Los Angeles, the authors convincingly established that there is severe air pollution over the Persian Gulf region, at least in their model environment. In addition to the anthropogenic contributions including long-distance transport of pollution, the authors particularly highlighted the significant role of stratosphere-troposphere-exchange. I strongly agree with the authors' call for more ground-based measurements in the Persian Gulf region and

the Middle East in general.

Specific comments:

1. It would be useful if the authors can describe the depths of the lowest few layers in the model. One can imagine that the (dry) mixing depth is large in the region. Thus, it would be interesting to know to what extent the boundary layer height and its diel cycle modulate the diel ozone and precursors variations.

2. The authors included a tracer for stratospheric ozone, O_3s. It is necessary to explain how O_3s is treated. For example, once O_3s enters the troposphere, is it allowed to mix with hence treated like O_3 produced in the troposphere? Or is a decay time applied to the O_3s tracer in the troposphere? What happens if the O_3s tracer re-enters the stratosphere?

3. Since the importance of STE is emphasized throughout the manuscript, it would be useful if the authors can briefly discuss how well tropopause folding, as identified by the authors as the dominant STE mechanism over the Middle East, is represented in EMAC. Consider this: EMAC as used by the authors has a horizontal resolution of 2.8° or roughly 280 km (in the tropics), while tropopause folding events typically occur on the scale of 100-300 km.

4. The authors mentioned that EMAC simulations of tropospheric and stratospheric chemistry have been compared to in situ and remote sensing measurements. It is necessary to briefly summarize conclusions from those comparisons. For instance, does the model have any noticeable biases in surface, middle, and upper tropospheric ozone (and precursors)?

5. For emissions the authors refer to a couple of prior publications. It would be helpful to describe the emissions from the Persian Gulf region and the Middle East in general. How significant are these local/regional emissions, say in comparison to other regions like Los Angeles (Southern California)? Please put the emissions in perspective. How

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well (or ill) constrained are these emissions in global emissions inventories? What percentage is from oil and petrochemical industries versus other anthropogenic sources? Answers to these questions would help form air pollution control strategies for the Persian Gulf region and the Middle East. It would also be interesting if the authors could briefly mention and/or discuss IPCC projections for emissions in this region.

6. Fig. 2 and the associated text. Please consider providing latitude/longitude (range) information for the four cities Bahrain, Dubai, Kuwait, and Riyadh, as the authors did in the caption for Fig. 9, and maybe indicating their locations with symbols in Fig. 1.

7. Fig. 3 and the associated text (Page 17743, Lines 9-18). It has already been pointed out by many previous studies that it is inappropriate to compare model results directly with gridded TES ozone and for that matter any satellite data products that have associated averaging kernels. Instead, the authors need to convolute TES O_3 averaging kernels and a priori profiles with their model results sampled along TES orbital tracks for a more meaningful, direct comparison.

8. Fig. 4. In addition to O_3, CO, and PAN, it would be useful to show model simulated NO_x. With PAN, the authors seemingly emphasize the importance of long-distance transport of pollution. With NO_x, the local/regional contribution can be highlighted considering the short lifetime of NO_x.

9. Fig. 5. It is interesting to see that surface ozone concentrations over the Beijing-Tianjin (two mega-cities) corridor and its surrounding regions are considerably lower than that over the 'greater Los Angeles area' and the Persian Gulf. In fact, Fig. 5 shows that most of East and South Asia mega-cities and their surrounding regions have considerably lower ozone concentrations than Southern California, much of the Mediterranean, the Middle East and the Persian Gulf region. This is indeed surprising considering the more or less widely-held view that (ozone) air quality is so much worse in much of China than even the 'greater Los Angeles area'. There are surface ozone observations in the aforementioned regions to verify or disapprove this. It would be

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useful if the authors can comment on this subject.

10. Fig. 6. Can the author discuss in a bit more detail the seasonal variation of the high near-surface ozone levels over the Persian Gulf region and the Middle East? For example, the circulation does not change that much from September to November, yet the high ozone is essentially gone by November.

11. The authors emphasized the significant contribution from STE to the near-surface ozone maximum in the Persian Gulf region. It would be very interesting to investigate the relative contributions from local and/or regional emissions followed by ozone production versus long-distance transport versus STE. More specifically, how large is the contribution from pollution transported from Europe? How large is the South Asian contribution? What is the relative contribution from lightning from upwind regions? Is it possible to define a background ozone level for this region? What is the implication for achieving air quality standards (are there any by countries in this region) in this region?

12. I would like to see the authors discuss how pollution from long-distance transport from Europe, the Middle East, and South Asia is mixed down to the surface in the Persian Gulf region in their model. Or are they mostly transported in the boundary layer in the case of European air pollution? By the same token, how is STE O3s mixed down all the way to the surface, general a very rare occurrence, considering especially that the surface over the Persian Gulf region is under the influence of thermal lows?

13. Fig. 9 and the associated text. The authors missed an opportunity to talk about the 'background ozone', i.e., the green line (excluding anthropogenic sources) and the implications for air pollution control in the Persian Gulf versus other regions. For instance, the 'background ozone' at Bahrain reaches above 30 ppbv throughout much of the summer, leaving little room for regional air pollution control strategy if the EU ozone air quality standards are applied. In contrast, the 'background ozone' in Los Angeles mostly is around 20-25 ppbv, which means there is a lot room to work with for local/regional air pollution control (emission reductions).

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14. Are there any inter-annual variability and/or trend in this near-surface ozone maximum over the Persian Gulf region? Their Fig. 2 shows quite some differences between 2000 and 2004.The authors mentioned that they have done model simulations for 1996-2006. It would be interesting to examine the inter-annual variation and/or trend if any, particularly any connection with large-scale circulations such as the Asian Summer Monsoon and the North Atlantic Oscillation.

Technical corrections:

Proposed deletions are underlined and proposed additions and/or changes are in italic.

1. (Optional) Abstract.

- Line 6: 'where *European Union* air quality standards are violated'.

Be specific. For example, the U.S. sets ozone air quality standard as 75 ppbv, 8-hour average (2008 standard), much higher than the 55 ppbv set by EU which has tighter standards than both the U.S. and China.

- Line 7: 'Long-distance transports of air pollution from Europe, *and* the Middle East'.

- Line 10: 'which are likely to get worse in *the* future.'.

2. (Optional) The authors used both 'ozone' and 'O_3' throughout the manuscript including Figure captions. Please consider use either rather than both as much as possible. Exceptions: starting a sentence always with 'Ozone' instead of 'O_3'.

3. **Section 4. Regional ozone hot spot.**

- Page 17745, Lines 11-12: '... the *relative* contribution by STE is largest ($\sim$30%)'.

The original statement can be misleading because the largest STE contribution is in Feb.-Apr.

- Page, 17747, Line 5: '... (near the Mt. Everest) ...'.

4. **Section 5. Comparison with other locations.**

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- Page 17747, Line 18: '... per surface area is *the* lowest of the 20 largest cities.'

- (Optional) Page 17748, Line 1: '... downwind of China *East Asia*.'

- Page 17748, Lines 1-2: '... O_3 decreases from the top down *in the said order*.'

The original statement can be confusing.

5. **Acknowledgements.**

'... and TES *(Tropospheric Emission Spectrometer on NASA's Aura satellite)* teams (Tropospheric Emission Spectrometer on NASA's Aura satellite) ...'.

6. **References.**

'Osterman, G. B. et al., ... 2008.'.

Figure captions.

7. Fig. 1. 'Moderate resolution Imaging Spectrometer *Spectroradiometer (MODIS)*'.

8. (Optional) Fig. 2. '... modeled O_3 mixing ratios ...'. Just to be consistent within the same Figure caption.

9. Fig. 3. '... 25-30°N *latitude* and 45-55°E latitude *longitude* ...'.

10. (Optional) Fig. 4. 'Model calculated ozone O_3, ... contribution by ozone O_3 transported ...'. Again, just to be consistent with the labels (O_3, O_3s) in the Figure. I would suggest that the authors use either 'O_3' or 'ozone' rather than a mixture of both, in all Figure captions to be consistent.

11. (Optional) Fig. 5. Please consider adding a short title to the Figure (e.g., 'EMAC surface O_3, July-August 2006') or the color bar (e.g. 'O_3'), as the authors did for Figures 7 and 8, for example.

12. (Optional) Fig. 6. Please consider adding a title to the color bar, e.g. 'O_3'.

13. Fig. 7. '... vertical distributions ...'.

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14. (Optional) Fig. 9. 'surface mixing ratios of ozone O_3 and O_3s'.

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