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Atmospheric Chemistry and Physics Discussions

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Interactive Comment

Interactive comment on "Summertime free tropospheric ozone pool over the Eastern Mediterranean/Middle East" *by* P. Zanis et al.

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Reply to Reviewer #2

We would like to thank Reviewer #2 for the constructive and helpful comments. Reviewer's contribution is recognized in the acknowledgments of the revised manuscript. It follows our response point by point.

1) The Reviewer notes: "Especially, while the paper provides a nice "average" picture of the issue and related processes, however it do not provide much information about variability with time (even just from year to year). I would like to see more information about this (e.g. is the ozone pool position/extension/strength constant with time? and contribution from stratosphere?)." The suggestion of the reviewer for looking the in-

terannual variability of these processes is part of our on-going research. Our focus in this manuscript was to identify the processes of the Mediterranean summer circulation that control the average situation of the persistent from year to year free tropospheric ozone pool. Concerning the interannual variability we should highlight the following: The subsidence over eastern Mediterranean during summer persists from year to year with downward vertical velocities at 500 hPa ranging from 0.065 hPa/s in 2007 to 0.095 hPa/s in 2003. Furthermore the free tropospheric ozone pool is also a persistent feature from year to year over eastern Mediterranean in EMAC simulations. It should be also noted that the July-August mean observed O3 values at Finokalia station correlate positively with the July-August mean EMAC modelled O3 values at 714 hPa (=0.53) over the period 1998-2008 while showing a correlation of =0.57 with EMAC O3s and the ratio O3s/O3. These positive correlations indicate that the interannual variability of near surface ozone at Eastern Mediterranean is strongly related with the interannual variability of the free tropospheric ozone pool and the stratospheric ozone tracer. This further supports our hypothesis of the link between near surface ozone and free tropospheric ozone at Eastern Mediterranean. The following sentences were added in the manuscript: Page 11, lines 344-345: " Furthermore it should be noted that the subsidence over eastern Mediterranean during summer is a persistent feature from year to year. " Page 12, lines 365-366, "This free tropospheric ozone pool is a persistent feature from year to year over eastern Mediterranean in EMAC simulations." Page 14, lines 449-459: " As pointed earlier, the free tropospheric ozone pool is a persistent feature from year to year over EMME in EMAC simulations. Looking the year-to-year relation between the free tropospheric ozone pool and near surface ozone we found that the mean July-August observed O3 values at GR02 correlates positively with the mean July-August modelled EMAC O3 and O3s values at 714 hPa (=0.53 and =0.57, respectively) over the period 1998-2008. These positive correlations imply that the interannual variability of near surface ozone at EM is related with the interannual variability of the free tropospheric ozone pool and the stratospheric ozone tracer. Future work is need to investigate the interannual variability of the summer circulation and the

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free tropospheric ozone pool and how it is related to the interannual variability of near surface ozone at EMME. "

2) The Reviewer notes: “Moreover it should be interesting, for the STE contribution, to evaluate (if possible)how much can be related to “local” events occurring over the investigated area (i.e. the east Med) or related with events occurring far upstream and “transported” in the upper/middle free troposphere.” We agree with the reviewer that this is an interesting issue which is also part of our ongoing research. There are a number of case studies which revealed that the typical path of deep stratospheric intrusions affecting the Eastern Mediterranean (mainly in winter) is along the rather frequent pathway from the North Sea to the Mediterranean Sea (Zanis et al., 2003; Galani et al., 2003; Gerasopoulos et al., 2006; Akriditis et al., 2011). Furthermore there are a few climatological studies looking the frequency of the deep stratospheric intrusion events revealing the above mentioned pathway but also indicating the geographical distribution of all other possible source regions (close to the region of interest or far away). According to a climatological study of cross tropopause exchange for the ERA-15 time period (1979–1993), the ratio of deep STT (p>700 hPa) to total STT during the previous 4 days for the Eastern Mediterranean is below 0.08 for winter, while it is below 0.03 for the other seasons (Sprenger and Wernli 2003). Furthermore according to the study of Sprenger and Wernli (2003), the geographical distribution of the downward (STT) cross tropopause exchange mass in summer shows maxima occurring northern from the EMME region, over the continental mid-latitudes of Europe and Asia. In the study of James et al. (2003) it is also clear that apart from the deep STT events affecting the lower 3 km of the Eastern Mediterranean, medium and swallow STT events affect the whole tropospheric column over the area during summer. Furthermore (as it is already pointed in the discussion) Traub and Lelieveld (2003) investigated the cross-tropopause transport over the Eastern Mediterranean by analyzing trajectories for the MINOS campaign (August 2001) and found from analysis of the residence times in stratosphere and troposphere after crossing the tropopause (set at 3.5 PVU), that the transport is vertically shallow and that this mixing of tropospheric and stratospheric air

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is largely confined to the tropopause region during summer.

The following paragraph in pages 15-16, lines 492-517m was modified accordingly: " Furthermore the EMAC simulations indicate the large contribution of stratospheric ozone to the pool of high ozone values over EMME in the middle and lower free troposphere. Traub and Lelieveld (2003) investigated the cross-tropopause transport over the EM by analyzing trajectories for the MINOS campaign (August 2001) and found from analysis of the residence times in the stratosphere and troposphere after crossing the tropopause (set at 3.5 PVU), that the transport is vertically shallow and that this mixing of tropospheric and stratospheric air is largely confined at the upper troposphere during summer. According to the study of Sprenger and Wernli (2003), the geographical distribution of the downward (STT) cross tropopause exchange mass in summer shows maxima occurring to the north of the EMME region, over the continental mid-latitudes of Europe and Asia. Sprenger et al. (2007) showed that the most of the STT events are rather shallow on short timescales, with most of the stratospheric tracer mass remaining in the upper troposphere over periods up to a few days. The more deeply intruded air the larger the age of the stratospheric air, which is subsequently, embedded into the large-scale general circulation. The contribution of the rare deep STT events (lower than 3 km) should not be disregarded since the EM is a favourable destination region of deep STT events as has been shown in both case studies (Zanis et al., 2003; Galani et al., 2003; Papayannis et al., 2005; Gerasopoulos et al., 2006a; Akritidis et al., 2010) and climatological studies (Sprenger and Wernli, 2003; James et al., 2003). In the study of James et al. (2003) it is shown that the EM (e.g. see their Figure 4) is a favourable destination region not only of deep STT events but also of medium and swallow STT events affecting the whole tropospheric column over the area during summer. Recently, Tyrlis et al. (2013b) indicated a global ‘hot spot’ of summertime troppopause fold activity over a sector between the eastern Mediterranean and Afghanistan, in the vicinity of the subtropical jet, with the rare deeper folds penetrating towards the Levantine region. "

3) The Reviewer notes: “Fig. 3: A notable difference in the location of the area with O3 maximum is evident comparing ERA-interim and TES measurements. Maybe the differences are not statistically significant, but some comments should be provided. Is this a “systematic” feature or it is related to a different depiction of specific events/periods? ” Even though we are satisfied that both datasets capture the general picture in Figure 3, we agree with the reviewer that there is a slight geographical shift of the ozone anomalies between ERA-Interim and TES data. This might related to the much coarser grid resolution of TES data (4o x 2o) compared to ERA-interim (0.75o x 0.75o). The following sentence was added in the revised manuscript at page 9, lines 267-271. "A geographical shift of the maximum ozone anomalies between ERA-Interim and TES data could be attributed to the coarser grid resolution of TES data (4o x 2o) compared to ERA-interim (0.75o x 0.75o) and limitations of the simplified ozone chemistry scheme in the ECMWF model, which misses part of the photochemical ozone buildup over the EM. " We also added more technical details about the TES data in page 7, lines 200-212. See below: " At Level 2 (L2) processing step, TES calibrated spectral radiances derived from the observed interferograms at Level 1B (L1B) are used to retrieve vertical profiles 0–32 km of atmospheric temperature and chemical species such as carbon monoxide, ozone, methane, and water vapor on a global scale every other day. These L2 data at the observation geolocations and times are used as the inputs to produce the TES Level 3 (L3) data that fill with horizontal interpolation the spatial gaps in global scale of the L2 orbital data (http://tes.jpl.nasa.gov/uploadedfiles/Level3_UserGuide_v1.0.pdf). The TES L3 ozone data provides information for mapping the global distribution of tropospheric ozone with special focus on understanding the factors that control ozone concentrations (Osterman et al., 2008; Voulgarakis et al., 2011). The TES data used in the current analysis include daily L3 ozone values for the period 2005-2009 with grid spacing 4o x 2o in longitude and latitude."

4) The Reviewer notes: “Comparing Fig 3e and 3k it is nice to see that the region with highest subsidence is located to the West of the region with high PV. This seems to be

in agreement with Sprenger et al. (2007) showing that STT (stratosphere-troposphere transport) usually occur upstream of stratospheric PV streamers" Taking into account the suggestion of the reviewer we added the following paragraph in page 10, lines 290-297: "It is interesting to note in Figures 4e and 4k (at 500hPa) as well as in Figures 4f and 4l (at 250 hPa) that the region with the highest subsidence is located to the western flank of the higher PV streamers extending southwards as would be expected from a dynamical perspective with anomalous subsidence upstream a positive PV anomaly (Hoskins et al., 1985). Taking into account the study of Sprenger et al. (2007) that identified a STT maximum on the western flank of the stratospheric PV streamers it is implied a coincidence of the region with the strongest subsidence and that of maximum STT."

5) The Reviewer notes: "Pag 22034, line 17: I would speak about "higher" PV and "lower SH". Indeed the PV values showed for the 500hPa and the 700 hPa are far from typical values observed during stratospheric transport into troposphere (typically above 1.6-1.8 pvu). This, obviously, is also an effect of the averaging process and/or of the mixing of stratospheric air into the troposphere: : :Can you provide and information about the fraction of time by which PV exceeded these threshold values over the investigated area for the 500hPa and the 700 hPa surfaces?" We agree with the reviewer that the PV values at 500hPa and the 700 hPa are far below the typical stratospheric values due to averaging in monthly time scales and the mixing processes. Even in cases of deep STT events, mixing processes with tropospheric air may reduce PV to values lower than 1.5 pvu in a synoptic timescale. Our approach, being Eulerian, cannot provide information on the age of stratospheric air into the troposphere. However, there are a number of Lagrangian studies on this issue based on dispersion modeling and back trajectories (e.g. Sprenger and Wernli, 2003; Traub and Lelieveld, 2003; James et al., 2003; Sprenger et al., 2007). For example, according to Sprenger et al. (2007) the most of the STT events are rather shallow on short timescales, with most of the stratospheric tracer mass remaining in the upper troposphere over periods up to a few days. The more deeply intruded air the larger the age of the stratospheric air,

which is subsequently, embedded into the large-scale general circulation. Taking into account the comment of the reviewer we used "higher" PV and "lower " SH instead of high and low Also the Following paragraph were added in: page 9-10, lines 288-290: "The PV values at 500hPa and the 700 hPa are below the typical stratospheric values (>2 pvu) due to averaging in monthly time scales and mixing processes." page 15, lines 502-506: "Sprenger et al. (2007) showed that the most of the STT events are rather shallow on short timescales, with most of the stratospheric tracer mass remaining in the upper troposphere over periods up to a few days. The more deeply intruded air the larger the age of the stratospheric air, which is subsequently, embedded into the large-scale general circulation."

6) The Reviewer notes: “Fig. 3: please make the divergence labels readable. ” The divergence was removed from Figure 5g and 5h but was included in Figures 4j, 4k, 4l. The discussion of the Figures 4 and 5 was adjusted accordingly.

7) The Reviewer notes: “Fig 3 and Pag 22035, line 14: I assume that the downward transport should be traced by the vertical velocity. However, looking at Fig 3 the maximum of O3 is shifted easterly in respect than the maximum of subsidence (for the 700hPa map). This is evident also from the cross section at the 32.25N latitude where the highest subsidence is located at 20E but the O3 tongue is centered more than 10 degree eastwards: : :Please can you provide an explanation? ” We agree with the reviewer. There is a shift towards south-east for ozone and specific humidity which can be explained by the combination of subsidence in the vertical and the north – northwesterly flow at the horizontal level related to the nearly isentropic sloping and downgliding of the air masses towards the Levantine region. In order to make this more clear in Figures 4 and 5 we included the horizontal wind vectors together with the vertical velocities. The divergence was removed from Figure 5g and 5h but was included in Figures 4j, 4k, 4l. The discussion of the Figures 4 and 5 was adjusted accordingly. The following paragraph was added in page 10, lines 297-311: "It is also interesting to note that there is a shift towards the south-east (at 500 hPa and 700 hPa)

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or towards the east (at 250 hPa) of the maximum of ozone and the minimum of specific humidity structures with respect to the maximum of subsidence. This horizontal shift can be attributed to the persistent north-westerly flow at 500 hPa and 700 hPa (Figures 4j and 4k) or the westerly flow at 250 hPa (Figure 4l). Hence the maxima of ozone or the minima of specific humidity lie a bit downstream to the areas of strongest subsidence. Most importantly, the location of the ozone maximum is observed further downstream towards the south-eastern Mediterranean at lower tropospheric levels. For example, the maximum of ozone and the minimum of specific humidity at 700 hPa are located over the Sinai Peninsula whereas in the mid-troposphere the ozone pool and drier air masses are encountered further to the north-west. This is related to the nearly isentropic sloping and downgliding of the air masses towards the Levantine region that also results in the formation of rare deeper folds over the Levantine region (Tyrlis et al., 2013b)."

8) The Reviewer notes: “Pag 22037, line 9: I think that this confirm just the existence of the increasing O3 towards East, more than the enhanced subsidence: : :” See the reply for point 7.

9) The Reviewer notes: “Fig. 8 (714 hPa analysis): I would see the same plots from TES measurements and a comparison the model against the satellite” The lower troposphere TES measurements have larger uncertainties and this is the reason not included.

10) The Reviewer notes: “Pag 22038, line 15-25. I’m wondering if this discussion about the shape of the annual cycle (especially about the different identification of the summer maximum between model and surface observations) is really sounding: e.g. are the differences between July and August average O3 mixing ratios statistically significant at Cyprus?” Yes, the differences between July and August average O3 mixing ratios are statistically significant at Cyprus even at 98% confidence level (two tailed t-test with a t-value of 2.89).

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