

We want to thank the referee for the helpful comments and suggestions. We have revised the manuscript according to the comments and addressed the points raised by the reviewers and updated the manuscript accordingly. Please see below for specific responses to each of the points raised.

Anonymous Referee #1

This is an interesting study which investigates the high tropospheric ozone values over the Mediterranean region using satellite observations and regional air quality modelling with WRF-chem. The interpretation and discussion of the results can be improved. I suggest publication of the manuscript after taking into account the following comments.

- 1) Introduction: They authors refer to the specific summer circulation conditions by linking to the descending branch of the Hadley cell (Bolle, 2002). Then they refer to the theory of Rodwell and Hoskins (1996) in which though (and in contrast to their previous sentence) it is proved that the subsidence center in the eastern Mediterranean is governed by Asian monsoon (and not the Hadley circulation) through the interaction of eastward propagating equatorially trapped Rossby waves (induced by the Asian monsoon heating) with mid-latitude westerlies. There are also recent studies on the influence of South Asian monsoon on summer circulation over Eastern Mediterranean (see e.g. Tyrlis et al., The summer circulation in the eastern Mediterranean and the Middle East: influence of the South Asian Monsoon, *Climate Dynamics*, 2013). I would suggest more thorough discussion of the dynamical processes of the summer circulation over Mediterranean.

The discussion was updated with the dynamical process of circulation and it now reads:

[...] “The dynamical processes of the summer circulation over the Mediterranean were previously attributed to the Hadley cell considered as the driver of the major subtropical dry zones. Rodwell and Hoskins (1996) argued that during the June-August period, the zonal mean Hadley circulation has very little motion and cannot explain the dry season of North Africa and the Mediterranean. Rodwell and Hoskins (1996; 2001) suggested, through numerical simulations, that the Asian monsoon heating induces an equatorially trapped Rossby wave to its west that interacts with the mid-latitude westerlies, producing a region of adiabatic descent and triggering subsidence. Long term analysis of dP/dt (units: $\text{Pa}\cdot\text{s}^{-1}$, used to represent subsidence) shows indeed a positive enhancement over the Mediterranean region (Ziv et al., 2004) making the South Asian monsoon a fundamental driver of the summer circulation over the Eastern Mediterranean (Tyrlis et al., 2013).”

- 2) In page 12385, lines 8-9: The authors state that spring is the season known for stratosphere to troposphere exchange events. This is not absolutely true. The fact that STE maximises in late winter/early spring does not mean that is the only period that takes place (see e.g. Stohl et al., Stratosphere–troposphere exchange—A review, and what we have learned from STACCATO, *J. Geophys. Res.*, 2003; Zanis et al., An estimate

of the impact of Stratosphere-to-Troposphere Transport (STT) on the lower free tropospheric ozone over the Alps using 10Be and 7Be measurements J. Geophys. Res., 2003).

We agree. To avoid confusion, we updated this sentence and removed the confusing expression (also suggested by the second reviewer). The new sentence now reads:

“Increasing values in spring (MAM) are due to the increase of O₃ production from photochemistry, buildup of winter O₃ and its precursors, transport, and/or from O₃ of stratospheric origin integrating into the troposphere.”

- 3) In Figure 6 they WRF-chem ozone values are compared with the station data. However the comparison in Figure 6 mixes the data from the different stations into one timeseries. I would suggest a more clear presentation of the model evaluation with EMEP observations for each station separately. This does not mean to add more figures for each station but maybe a Table with the evaluation scores for each individual EMEP station.

To avoid the mixing of data in Figure 6b, we removed it and instead we added as suggested a table with the correlation coefficient of each station. The table added in the manuscript is as follows:

Table 2. Pearson correlation coefficient, bias and the corresponding mean normalized bias (MNB) of each EMEP and WRF-Chem ground station data localized in Fig. 2, for the period JJA 2010.

Station name	Corr. Coef. With WRF-Chem	Bias (ppbv)	MNB (%)
CY02	0.63	-7.78	(-14.2%)
ES06	0.41	+7.26	(+20.9%)
ES07	0.77	-7.24	(-13.4%)
ES10	0.72	+1.43	(+3.6%)
ES12	0.80	-5.96	(-12.7%)
ES14	0.78	-2.99	(-6.4%)
GR02	0.62	-7.38	(-11.3%)
MK07	0.57	-16.65	(-23.9%)

- 4) Mind that in Figure 10 the middle troposphere IASI ozone values are higher than the respective modeled values resulting in steeper ozone gradient at upper troposphere in the modeled values. Does this mean that maybe WRF underestimates the downward transport?

The WRF-Chem data as shown in Figure 7 are smoothed with the averaging kernels of IASI. It shows that indeed the model underestimates IASI data below 10 km. This explains why in Figure 10 (also smoothed) this underestimation can be seen. This may imply that the WRF-Chem underestimates downward transport. The background O₃ values in the troposphere are

not only controlled by the downward transport. The fact that the underestimation is systematic tends to indicate another reason. More detailed analysis is required (that is beyond the scope of this study) to confirm it.

- 5) It should be clarified that the O₃-inflow tracer cannot distinguish between horizontal and vertical transport. Hence it is useful in the study the use of stratospheric tracers Such\ as Potential Vorticity (PV) and water vapour mixing ratio to distinguish the transport from the stratosphere. The discussion though in this part is limited lacking of interpretation of the dynamical transport processes. Why it is shown in Figure 11 only the layer between 350-250 hPa and not the 4, 6 and 8 km levels for comparability reasons with Figure 9? Also mind that theoretically the water vapour mixing ratio is a better transport tracer than relative humidity (which is used in Figure 11).

We mention in P.12383 L8-10: “Since in this version of WRF-Chem the stratospheric O₃ is controlled by the lateral boundaries, O₃ from stratospheric intrusions within the regional domain would be labeled as O_{3-INFLOW} as well.”

We agree that this should be emphasized later on too, so we add a sentence before discussing PV and the water vapor mixing ratio.

“Since stratospheric intrusions within the regional domain are included in the O_{3-INFLOW} tracer, it is useful to use other stratospheric tracers to distinguish the transport from the stratosphere. PV and Q_{vap} measurements can be used as markers of transport [...]”

As suggested, we replace RH with water vapor mixing ratio (Q_{vap}) measurements from the model and we also updated Figure 11 with the plots at 4, 6, and 8 and 10 km.

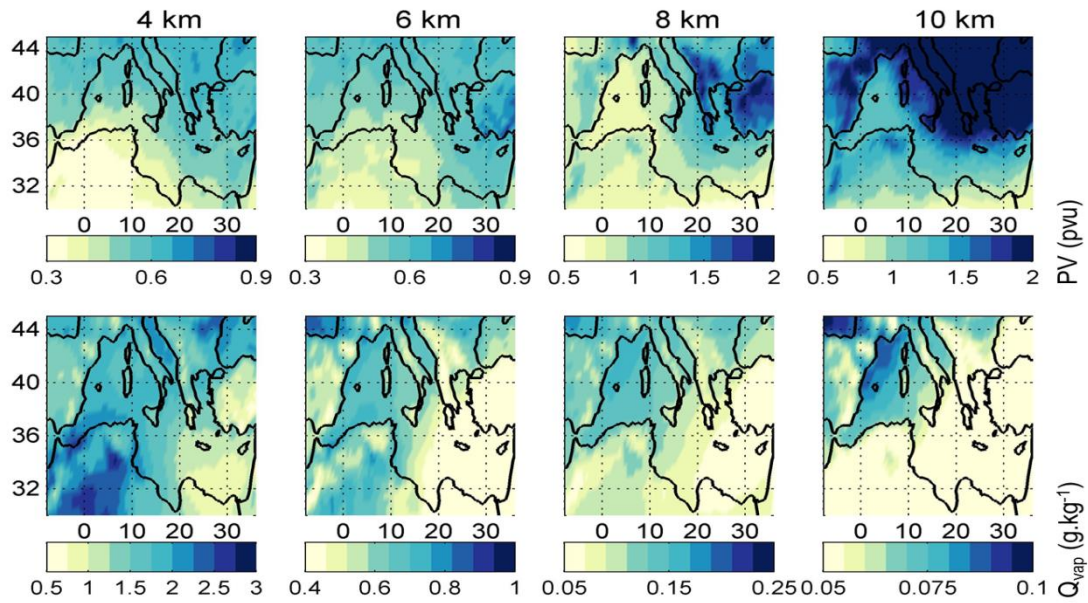


Fig. 11. WRF-Chem (a) potential vorticity (PV) at 4, 6 and 8 and 10 km over the Mediterranean region for JJA 2010. (b) Water vapor mixing ratio (Q_{vap}) for the same vertical levels and time period.

- 6) The fact that the northeastern corner of the modelled domain in panels 9d-f show anthropogenic contribution between 20 and 40% needs more elaboration and justification.

We agree that the contribution of anthropogenic tracer is not negligible, and we attempt to discuss it as follows:

“The northeastern corner of the modeled domain in panels (d-f) show anthropogenic contribution between 20 and 40%. This might be due to important vertical transport and mixing in the free troposphere. These values can be correlated with the O_3 residuals plotted in panels (j-l). These panels show an O_3 signature in the north eastern corner of the domain. This signature is probably related to the emitted O_3 precursors from fires sources in the model domain (Fig. 2) and lifted to the upper troposphere due to convective movements during the Russian fires of summer 2010. We can also suppose that certain anthropogenic O_3 precursors, like NO_x , near the fire sources were also transported with the same convective movements to the same part of the domain and contributed eventually to the production of anthropogenic O_3 in that region .”

- 7) The section with the conclusions should be elaborated more with discussion in association with previous published studies. There are a number of published studies that have looked the high mid-tropospheric ozone values over Eastern Mediterranean.

We updated the manuscript with a new elaborated conclusion with a discussion of previous works:

“[...] Focusing on summer 2010, we use IASI and the regional chemical transport model WRF-Chem to interpret these maxima. A tagging scheme is used to keep track of O₃ from anthropogenic sources in the domain (O_{3-ANTHRO}) and O₃ from inflow at the domain boundaries and stratosphere (O_{3-INFLOW}). Our results show that transport plays an essential role in the O₃ budget over the Mediterranean troposphere and that summer O₃ maxima over the region are recorded especially in the eastern part of the basin. Even though high local anthropogenic emissions are responsible to 60-100% of O₃ in the boundary layer (surface-2 km), as demonstrated by the anthropogenic O₃ tracer of the WRF-Chem model, above 2 km, O₃ is mainly transported. Kalabokas et al. (2007, 2013) showed that the highest ozone concentrations in the low troposphere are associated with large-scale subsidence of ozone-rich air masses from the upper troposphere. However, Zanis et al., (2013) using model simulations reported, that at the low troposphere, long distance transport and local photochemical processes dominate. In the free troposphere, WRF-Chem shows that vertical and lateral transport of O₃ take place represented by the O_{3-INFLOW} tracer which is responsible for 70-100% of O₃ at 4, 6 and 8 km. In the Eastern Mediterranean, Roelofs et al. (2003) showed important contributions to elevated O₃ in the middle troposphere by transport from the stratosphere. More recently, Hess and Zbinden (2013) showed that stratospheric inter-annual O₃ variability drives significantly the O₃ variability in the middle troposphere, between 30° and 90°N but not the overall trend which is largely affected by transport processes. The increase in O₃ seen by the model and the IASI instrument in the eastern part of the Mediterranean basin suggests that stratosphere to troposphere exchange (STE) events contribute to elevated ozone in the upper free troposphere. This is further shown in the WRF-Chem simulations that predict elevated potential vorticity (PV) and water vapor mixing ratio (Q_{vap}) over the same region. This result is in agreement with many previous studies e.g. Butkovic et al. (1990); Varotsos and Cracknell (1993); Kalabokas and Bartzis (1998); Kalabokas et al. (2000, 2007); Kouvarakis et al.(2000); Lelieveld et al.(2002); Sprenger and Wernli (2003); Papayannis et al. (2005); Gerasopoulos et al. (2006a); Akritidis et al. (2010); Zanis et al. (2013); Doche et al. (2014) that have shown the occurrence of STE events in the eastern Mediterranean region in summer. Since O₃ maxima have the potential to strongly impact regional air quality and climate (e.g. Hauglustaine and Brasseur, 2001), the present study further demonstrate the importance of quantifying and analyzing O₃ and its sources at different altitudes in the atmosphere. Quantifying long term trends and a distinction between the different sources is crucial. This should be possible with observations and model runs over longer time scales with additional tracers to identify all O₃ sources.”

- 8) The authors may consider that there is another similar study about summer ozone over Mediterranean from IASI under discussion in ACPD (Atmos. Chem. Phys. Discuss., 14, 13021–13058, 2014).

This reference was added in the section discussion and conclusions of the manuscript.

“A complementary study by Doche et al. (2014) using IASI data at 3 km height, also showed 6 years recurrent O₃ summer maxima in July to the east of the basin.”