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Carbon monoxide (CO) maximum over the Zagros mountains in the Middle East: Signature of mountain venting?

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[1] We report an intriguing feature observed in daytime measurements of CO over the Middle East, in spring and summer, by the Measurements of Pollution in the Troposphere (MOPITT) satellite instrument. Enhanced CO is observed over the Zagros mountains of Iran, following the local topography over this region (25–40N, 40–60E). The MOPITT averaging kernels do not seem to indicate any data artifacts in this area. We argue that this feature likely forms by the process of mountain venting by thermal winds caused by strong daytime differential heating. This is consistent with an analysis of vertical velocity in the NCEP reanalysis data in this region. The phenomenon was observed in all the years of available MOPITT measurements and may have implications for the pollution episodes in the region and the Middle East ozone maximum that has been observed earlier. **Citation:** Kar, J., J. R. Drummond, D. B. A. Jones, J. Liu, F. Nichitiu, J. Zou, J. C. Gille, D. P. Edwards, and M. N. Deeter (2006), Carbon monoxide (CO) maximum over the Zagros mountains in the Middle East: Signature of mountain venting?, *Geophys. Res. Lett.*, *33*, L15819, doi:10.1029/2006GL026231.

1. Introduction

[2] CO is an important trace gas insofar as it influences the atmospheric chemistry through its reaction with the OH radical as well as providing valuable information on the dynamical properties of the atmosphere, because of its long lifetime ($\sim$ few weeks). It is also a precursor of tropospheric ozone in high NO_x environment. Consequently, there is a strong focus on understanding the global distribution of CO in the troposphere and its variability. This has become possible in recent years because of measurements by MOPITT [*Drummond*, 1992]. The data from MOPITT now cover about 6 years and have led to significant advances in our understanding of the effects of global biomass burning, improved emission inventories, intercontinental transport of pollution and upper tropospheric processes [*Edwards et al.*, 2003; *Kar et al.*, 2004; *J. Liu et al.*, 2006]. In particular, because of the high density of the measurements as well as the ability of the retrievals to distinguish between the middle and upper troposphere, MOPITT can give new insights on atmospheric processes on local and regional scales. *J. Liu et al.* [2006] have reported strong horizontal gradients in CO distribution at synoptic scales over North America which are signatures of frontal lifting as well as local convection. Deep convective lifting of boundary layer CO has also been observed in MOPITT CO data over the monsoon regions of south east Asia [*Kar et al.*, 2004; *Li et al.*, 2005].

[3] The Middle East is an interesting area for tropospheric studies with strong topography, wide spread subsidence in the upper troposphere as well as severe dust storms and transport of pollution from Asia. However not much attention has been given to this area in the past. In a modeling analysis, *Li et al.* [2001] had reported a tropospheric ozone maximum in this area in summer which occurs as a result of ozone production over the convective regions of South East Asia with subsequent transport of this ozone by the easterly jet to the middle east. However, this is also one of the most data-poor areas on the globe and more observations of tropospheric trace species are needed. Here we present CO measurements from MOPITT over the Middle East and point out an intriguing feature that shows up persistently over the Zagros mountains of Iran during spring and summer. This is explained in terms of mountain venting, which has been previously observed in airborne lidar and in-situ measurements over the Alps and Iberian peninsula [*Millan et al.*, 1997; *Furger et al.*, 2000; *Henne et al.*, 2004].

2. Data

[4] The MOPITT instrument is onboard the Terra spacecraft, which is flying in a polar sun synchronous orbit at an altitude of 705 km. Upwelling infra red radiation near 4.7 μm is measured using gas correlation radiometry which is then used to retrieve the CO mixing ratios and total columns. The CO mixing ratio profile is reported at 7 levels (surface, 850, 700, 500, 350, 250 and 150 hPa levels) although these measurements are not independent of one another [*Deeter et al.*, 2004]. These retrievals have been validated using in-situ aircraft measurements and the results show good agreements with the average bias being less than 20 ppbv at all levels [*Emmons et al.*, 2004]. We have further used NCEP reanalyses data on vertical velocity (gridded at 2.5° $\times$ 2.5°), provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, http://www.cdc.noaa.gov/. The topography data used in this analysis were taken from the two minute gridded global relief database (ETOPO2) at the National Geophysical Data Center (NGDC), http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html.

3. Results

[5] Figure 1 shows the distribution of daytime CO mixing ratios at 350 hPa between April and August, 2003 over

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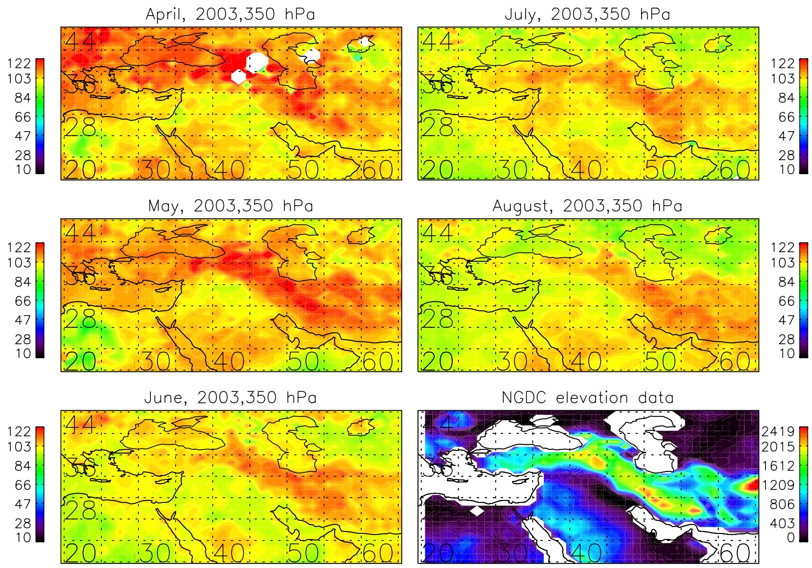

Figure 1. Distribution of CO mixing ratios (ppbv) at 350 hPa between April and August, 2003 measured by MOPITT over the Middle East and the local topography from NGDC elevation (meter) data.

the Middle East (three left panels and two upper right panels). The data have been binned in 1° × 1° in latitude and longitude. The right bottom panel shows the local topography binned in 1° × 1° in latitude and longitude. The elevated regions stretching from southeast to northwest (∼25N to 40N and 40E to 60E) correspond to the Zagros mountain range in Iran with several high peaks rising above 4 km.

[6] A clear elongated feature, aligned with the Zagros mountains with a relative maximum in 350 hPa CO mixing ratios can be seen in Figure 1 for all months between April and August, 2003. The feature lasts from about April until September. Figure 2 shows the feature for the months of June–August, 2004, once again showing the close correlation with topography and general similarity with the enhanced CO layer seen in 2003. This was observed in other years as well, with varying degrees of intensity for different years. In what follows, we shall restrict our analysis to July 2003.

[7] We have examined the possibility of the feature being a data artifact by analyzing the MOPITT averaging kernels.

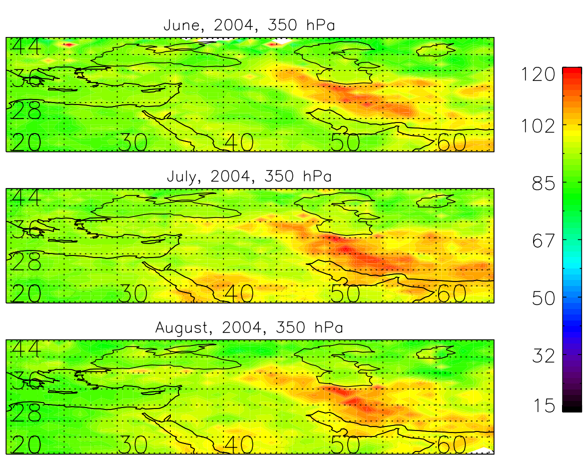

Figure 2. Similar to Figure 1 but for June–August, 2004.

These kernels describe the dependence of the retrieved state vector on the "true" state vector and are estimated from the a priori covariance and the retrieval error covariance. The averaging kernels are mostly affected by the variability of the atmospheric temperature profile, the surface pressure and temperature as well as the actual CO profile (e.g., see *Deeter et al.* [2003, 2004] for details) and may be expected to be less distinct over mountain regions. An important point in this connection is the vertical resolution of MOPITT profiles as reflected in these averaging kernels. Figure 3 shows the mean averaging kernels between 30N–40N and 40E–60E for the month of July 2003. For this plot we have only included those profiles which were retrieved directly over the Zagros topography within the above latitude-longitude box. These profiles were characterized by having the lowest retrieval level above 850 hPa. As is well known, the MOPITT averaging kernels are rather broad indicating that the CO mixing ratio at any one level is influenced by the other levels [*Deeter et al.*, 2004]. However, the averaging kernels show that the upper troposphere can be generally distinguished from the middle troposphere even over this mountain topography. Degrees of freedom for signal (DFS) values over the Zagros range, although smaller

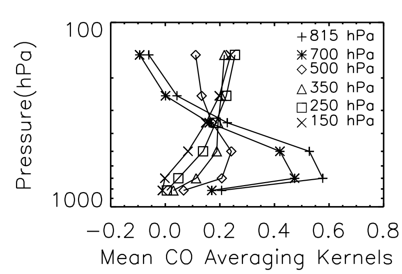

Figure 3. Monthly mean averaging kernels for MOPITT retrievals over the Zagros range for July 2003. Only retrievals with lowest retrieval level above 850 hPa (mean ∼815 hPa) over the region 30N–40N, 40E–60E are included.

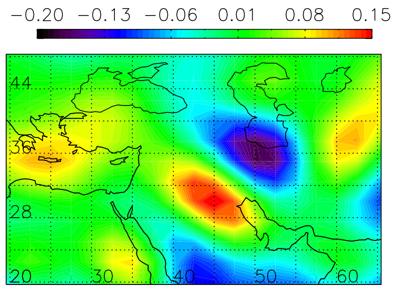

Figure 4. Vertical velocity over the Middle East (omega, in pascal/sec) from NCEP reanalyses at 700 hPa for July 2003 around 1030 am local time.

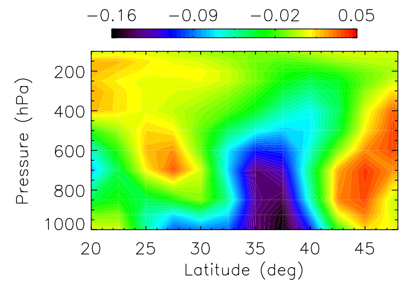

Figure 6. Height-latitude cross section of the vertical velocity between 50E–55E (omega, in pascal/sec) for July 2003 around 1030 am local time.

than the surrounding desert areas, are still ~1.5–1.6, implying significant vertical information over the range. In order to further examine if the observations can be solely explained by differences in averaging kernels, we used the mean MOPITT averaging kernels (within 30N–40N, 40–60E) for July 2003 both over and away from Zagros and the MOPITT a priori profile in the retrieval equation [see, e.g., *Emmons et al.*, 2004]. A monthly mean CO profile for July 2003 over the same area as obtained from the GEOS-CHEM chemical transport model [*Bey et al.*, 2001] was used as the "true" profile. The resulting CO mixing ratios retrieved at 350 hPa over Zagros and away from it differed by ~1 ppbv, much less than the observed difference (~20 ppbv). Using various "true" profiles does not change this result. This implies that the observations are not likely to be significantly influenced by retrieval artifacts, although analysis of averaging kernels alone may not guarantee that.

[8] Given the close correspondence with the topography, it is likely that local meteorology is partly responsible for the CO feature in the upper troposphere. Figure 4 shows the vertical velocity at 700 hPa level (omega, dp/dt, in pascal/sec) in this region for July 2003, as obtained from the NCEP reanalyses interpolated to 10:30 am local time (~7:30Z), which is the MOPITT overpass time. As can be seen in Figure 4, upward motion generally prevails along the Zagros range at this time. Further, the 6 hourly vertical velocity data from the NCEP reanalyses show significant diurnal variation along this range with maximum alignment of the upward motion with the range at 12Z or about 3 pm local time and replaced by mostly downward motion at 0Z or about 3 am local time (Figure 5). This suggests that the upward winds are probably thermally induced winds that develop due to the strong temperature differential between the valley and mountain range during sunlit hours in summer [*Whiteman*, 2000]. This feature (i.e., upward motion aligned with Zagros) stands out strongly in the NCEP reanalyses in this region for summer months (May–September) in all years. Indeed the prevailing conditions over Zagros in spring and summer are generally similar to those associated with mountain venting over the Alps as discussed by *Henne et al.* [2004]. These authors found slope winds to be the dominant mechanism for vertical export of boundary layer air to free troposphere under fair weather conditions on spring and summer days with strong irradiation. Strong temperature differentials in the Middle East and the high mountains are likely to make mountain venting stronger than over Alps. Over the Zagros range the upward motion at 700 hPa is most intense within the longitude band of about 50E–55E (Figure 4), which also includes some of the highest peaks. Figure 6 shows the height latitude cross sections of the NCEP reanalyses' vertical velocity for the longitude range 50E–55E at 10:30 am local time. Strong upward motion between about 30N–40N extends to the middle troposphere and above.

[9] Figure 7 shows the height latitude cross sections for daytime CO mixing ratios from MOPITT retrievals for July 2003 over the longitude range 50E–55E. Details of these cross sections should be viewed with some caution because of limited vertical resolution of MOPITT retrievals. However, a distinct plume of CO can be clearly seen in the upper troposphere corresponding to location of the strongest upward winds between 30N–37N. This suggests that mountain winds are carrying the polluted daytime boundary layer air and venting it above the mountain crests, and thus

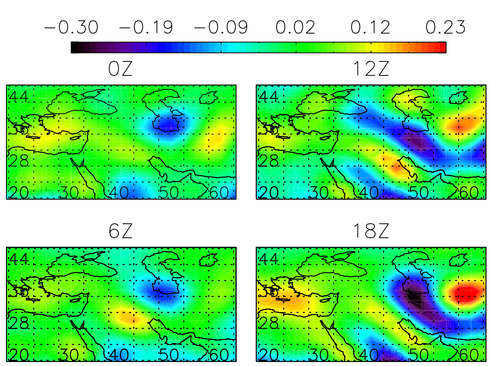

Figure 5. Diurnal variation of vertical velocity (omega, pascal/sec) for July 2003 over the Middle East from NCEP reanalyses.

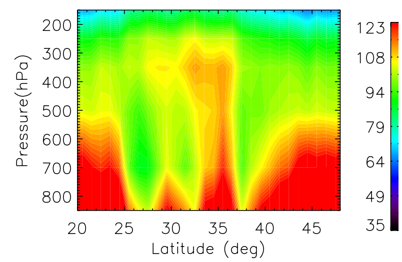

Figure 7. Height-latitude cross section of MOPITT CO daytime mixing ratios (ppbv) between 50E–55E in July 2003.

causing the enhanced CO feature over this region as seen in Figure 1. The overall CO distribution over this region in spring and summer will be determined by both the local vertical transport of CO and the horizontal transport of CO into the region, such as the CO lifted over south east Asia by deep convection [*Kar et al.*, 2004; *Li et al.*, 2005] and transported by the easterly jet of the Tibetan anticyclone to the Middle East. The local vertical flux of CO will, in turn, depend on the strength of the vertical velocities and the CO loading in the boundary layer, which will reflect local CO emissions as well as CO transported from other parts of the Middle East into the region in the boundary layer.

4. Discussion

[10] Mountain venting is still largely uncharacterized in various locations of the globe. We believe that this is the first time the phenomenon has been detected from satellite observations. However, an examination of the EOS MLS measurements of CO in the upper troposphere (147 hPa) in summer of 2005 does not reveal any CO enhancement over the Zagros range. The reason is not entirely clear at this time, but it will be interesting to see if this feature shows up when improved retrievals from MLS become available near 350 hPa (EOS-MLS data quality document: http://mls.jpl.nasa.gov/data/v1-5-report-29jul05b.pdf). It should be mentioned that MOPITT daytime measurements are near a fixed local time (10:30 am equator crossing time) and it is not possible to examine the time evolution of the feature using these data.

[11] This persistent layer of enhanced CO in summer over the Zagros area should have interesting consequences for atmospheric chemistry in the region. The vented pollution may recirculate locally, subside and eventually get mixed with new pollution, thus having significant impact upon the pollution scenario in the regional level as has been observed over the western Mediterranean [*Millan et al.*, 1997]. This is consistent with generally anticylonic circulation over the area in summer and subsidence flanking the region of upward motion in Figure 6. Further, *Li et al.* [2001] had pointed out the existence of a tropospheric ozone maximum in their model around this same time (May–September) over this area and a similar ozone maximum in the middle troposphere (6–8 km) was seen from the tropospheric ozone measurements from SAGE II [*Kar et al.*, 2002]. Therefore it is possible that this CO layer would contribute to the ozone maximum in the Middle East by in-situ production of ozone. NO2 columns retrieved by GOME and SCIAMACHY show generally enhanced values over the Middle East (not shown). However recent tropospheric ozone column retrievals from GOME data do not seem to show this enhancement in ozone over Middle East [*X. Liu et al.*, 2006].

5. Conclusions

[12] We have presented evidence of a characteristic daytime upper tropospheric CO maximum along the Zagros mountain range in the Middle East. This occurs primarily during the spring and summer months and was seen in all years with available MOPITT data. It is argued that the feature is caused by thermal mountain winds venting the boundary layer air over the Zagros topography. This CO layer may have implications for local pollution episodes in summer and may contribute to the ozone maximum in the upper troposphere. More observations and modeling are required to understand this phenomenon over the Middle East.

[13] **Acknowledgments.** MOPITT mission and data analysis are supported financially by the Canadian Space Agency, the Meteorological Service of Canada, the Natural Sciences and Engineering Research Council and the National Aeronautics and Space Administration. The referees are thanked for insightful comments that helped improve the manuscript.

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