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Evidence of vertical transport of carbon monoxide from Measurements of Pollution in the Troposphere (MOPITT)

Jayanta Kar,[1] Holger Bremer,[1,2] James R. Drummond,[1] Yves J. Rochon,[3]
Dylan B. A. Jones,[1] Florian Nichitiu,[1] Jason Zou,[1] Jane Liu,[1] John C. Gille,[4]
David P. Edwards,[4] Merritt N. Deeter,[4] Gene Francis,[4] Dan Ziskin,[4] and Juying Warner[4]

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[1] Vertical profiles of carbon monoxide (CO) mixing ratio retrieved from MOPITT measurements have been analyzed. We find that variations in the vertical structure of CO can be detected in the MOPITT data. The Asian summer monsoon plume in CO is observed for the first time as a strong enhancement of CO in the upper troposphere (UT) over India and southern China indicating the effect of deep convective transport. Similarly, zonal mean height latitude cross-sections for the months of September–December, 2002 indicate deep convective transport of CO from biomass burning in the southern tropics. These findings show that MOPITT CO can provide valuable information on vertical transport phenomena in the troposphere. *INDEX TERMS:* 0368 Atmospheric Composition and Structure: Troposphere—constituent transport and chemistry; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 3362 Meteorology and Atmospheric Dynamics: Stratosphere/troposphere interactions. **Citation:** Kar, J., et al. (2004), Evidence of vertical transport of carbon monoxide from Measurements of Pollution in the Troposphere (MOPITT), *Geophys. Res. Lett.*, *31*, L23105, doi:10.1029/2004GL021128.

1. Introduction

[2] Atmospheric CO is an important trace constituent as it plays a critical role in determining the oxidizing capacity of the atmosphere through its reaction with the OH radical. It is a primary component of biomass burning products and is also emitted by various anthropological activities. CO has been measured at a network of ground stations as well as from aircraft [*Novelli et al.*, 1998; *Nedelec et al.*, 2003]. In the last few years, global measurements of CO have been carried out by the MOPITT mission [*Drummond*, 1992; *Drummond and Mand*, 1996]. These CO data have been correlated with the biomass burning fires and tropospheric ozone [*Edwards et al.*, 2003; *Bremer et al.*, 2004].

[3] With its lifetime of a few weeks to 2 months, CO is a good tracer of vertical transport. 3D chemistry transport models indicate that deep convection during the summer monsoon in the Indian subcontinent can lift boundary layer pollutions to the UT leading to a plume of enhanced CO levels in the 400–150 hPa range [*Lawrence et al.*, 2003]. The Asian plume observed in August 2001 over the Eastern Mediterranean during the MINOS campaign contained high concentrations of CO and was traced to India [*Scheeren et al.*, 2003]. However actual observations of enhanced CO over monsoon regions of India have not been reported so far.

[4] The vertical profiles retrieved by MOPITT primarily provide information about the middle troposphere and UT. Here we report the Asian summer monsoon plume in upper tropospheric CO as evidence of deep convection effects in MOPITT retrievals. Similar plumes are also seen from biomass burning in the southern hemisphere indicating large scale deep convection. These results lend confidence in the utility of CO profiles from MOPITT for studying vertical transport phenomena in the troposphere.

2. Data

[5] MOPITT is on board the Terra spacecraft and is flying in a sun synchronous polar orbit with an altitude of 705 km. Measurements of upwelling infra red radiation are performed in nadir view with a near global coverage within three days. CO vertical profiles (on 7 altitude levels) and total columns are retrieved from the radiance data with a horizontal resolution of 22×22 km^2. MOPITT retrievals employ the Maximum A Posteriori optimal estimation technique that requires an ‘a priori’ CO profile and covariance matrix [*Deeter et al.*, 2003]. These retrievals have been validated by *Emmons et al.* [2004] using in-situ correlative data from aircrafts and the results show good agreement between MOPITT and modified in-situ profiles (after applying the MOPITT averaging kernels, which describe the retrieval vertical resolution) with an average bias less than 20 ppbv at all levels.

[6] We have used CO retrievals at 850 hPa, 700 hPa, 500 hPa, 350 hPa, 250 hPa and 150 hPa levels for this study. Further, the ‘percent a priori’ diagnostic as available in the level 2 data products was used to filter the data. This diagnostic is calculated as the ratio (in percentage) of corresponding diagonal elements of the retrieved error covariance matrix and the a priori covariance matrix. As this ratio tends towards zero, the retrieval is essentially perfect, and has no weighting from a priori. As this ratio tends towards unity, however, the implication is that the retrieval has not provided useful information. Only those profiles having ‘percent a priori’ less than 50% in the retrievals at 700 hPa, 500 hPa and 350 hPa levels were

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[1] Department of Physics, University of Toronto, Toronto, Canada.

[2] Now at Institute of Environmental Physics, University of Bremen, Bremen, Germany.

[3] Meteorological Service of Canada, Downsview, Canada.

[4] National Center for Atmospheric Research, Boulder, Colorado, USA.

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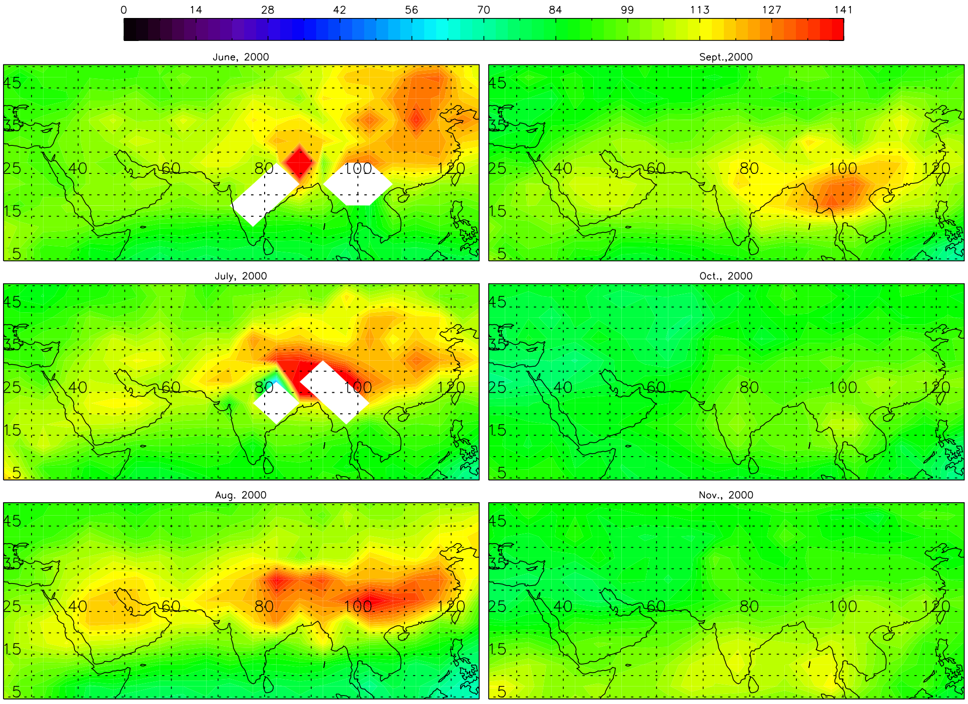

Figure 1. MOPITT CO mixing ratio (ppbv) distribution at 350 hPa for June–November, 2000. The data have been binned in 5° × 5° in latitude and longitude. Color bar saturates at 141 ppbv. White areas indicate data gaps.

included in this study to ensure that the results were minimally influenced by the assumed a priori profile.

3. Results

[7] Analysis of the averaging kernels for the MOPITT CO retrievals reveals that the retrievals can generally distinguish between the middle troposphere and UT [*Emmons et al.*, 2004; *Deeter et al.*, 2004]. *Deeter et al.* [2004] have conducted a quantitative analysis of the vertical resolution of the MOPITT CO profiles. They estimated that the degrees of freedom for signal (DFS), a quantitative measure of the independent pieces of information provided by the retrieval, varies between about 1.5 and 2 in the tropics and decreases significantly at higher latitudes. In particular over land areas, the DFS values are highest during day and fall sharply at night. MOPITT is generally sensitive to CO in the UT where the averaging kernel for the 350 hPa level, for example, usually peaks at that level or higher. Further, MOPITT retrieves a large number of profiles at any place in the absence of clouds, which should lead to statistically robust geophysical features that dominate the random errors in the retrievals and the limited vertical resolution. In particular, a single "a priori" profile was used for all retrievals and thus the variations in the retrievals are likely to reflect geophysical variations.

[8] Figure 1 shows the monthly mean distribution of dayside CO mixing ratios at 350 hPa for June–November, 2000 over South Asia. The data were averaged in 5° × 5° bins. The dayside DFS values calculated for June-July-August, 2000 range between ∼1.5–2.0 in this region except over the Himalayan region (∼30N–40N, 75E–100E) where DFS is low (∼1). A strong plume with high CO mixing ratios can be seen developing in July over north and east of the Indian subcontinent and southern China extending to the west towards the Middle East and northern Africa. The plume reaches its maximum intensity in August and extends to eastern China. By September, the strongest parts of the plume move equator ward to Southeast Asia and subsequently dissipate. There is no significant biomass burning activity in this area during the monsoon months when deep convection and precipitation occur (June to September). Deep convection in the area during July–August 2000 is confirmed by low values of the outgoing long wave radiation (not shown). As shown by the trajectory analysis of *Traub et al.* [2003] over two major Indian cities for August 2001, deep convection can lift the boundary layer air to the UT in 2–5 days. The observed CO distribution (Figure 1) is rather similar to the model results of *Lawrence et al.* [2003] and confirms the Asian summer monsoon plume of pollutants carried aloft by deep convective activity over India and China, which can be subsequently transported to the eastern Mediterranean [*Scheeren et al.*, 2003]. However, lower data sampling on individual days due to prevailing clouds makes it difficult to observe individual plumes as a function of time using MOPITT CO data. A much weaker plume is seen over southern India in November which could be related to convective activity during the north-east monsoon. The plume seen at the lower left corner in November is due to biomass burning in Africa. Similar features were observed in the other years as well with some interannual variability.

[9] Figure 2a shows the monthly mean height latitude cross-sections of CO from daytime MOPITT retrievals for August 2000 spanning roughly the longitude range of the Indian subcontinent (65E–100E). Although the vertical profiles of MOPITT CO are reported on 7 altitude levels, the maximum DFS is about 2 and consequently the fine details of these cross-sections should be viewed with some caution. However, as mentioned above, the daytime

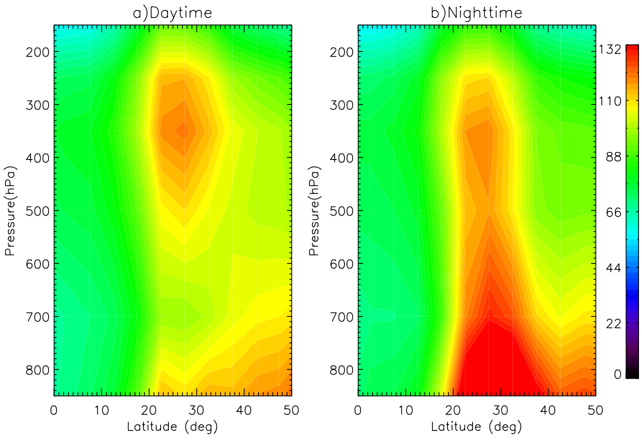

Figure 2. Pressure-latitude cross section of MOPITT CO mixing ratios (ppbv) for August 2000 between 65E to 100E for a) dayside and b) nightside data. Data binned in 5° latitudes. Color bar saturates at 132 ppbv.

MOPITT retrievals are sensitive to CO in the UT and can discriminate the latter from the middle troposphere. The Asian summer monsoon plume is seen in Figure 2a as a pronounced enhancement in CO over a deep layer in the UT. Model simulations for August 2000 performed using the GEOS-CHEM global 3D model [*Bey et al.*, 2001; B. N. Duncan et al., Mode study of the variability and trends in carbon monoxide (1988–1997): 1. Model formulation, evaluation and sensitivity, submitted to *Journal of Geophysical Research*, 2004] qualitatively reproduce enhanced CO in the UT, but suggest that the plume is restricted to a shallower layer (not shown). The deep extent of the layer of enhanced CO in the MOPITT data reflects the smoothing influence of the retrievals, which averages the CO plume over a broad range of altitudes in the UT. Analysis of the modeled fields conducted by "tagging" the CO from India and China indicates that the plume consists of CO emissions from India with a dominant contribution from China.

[10] The monthly mean height latitude cross-section of CO from the nighttime MOPITT retrievals is shown in Figure 2b, for comparison. In contrast to the daytime retrievals, the magnitude of the upper tropospheric CO maximum, relative to the CO abundance in the lower troposphere is diminished. This reflects the fact that, the nighttime retrievals have low DFS, and therefore cannot isolate the enhanced CO in the UT as much as the daytime retrievals. The CO information in the UT is distributed throughout the column.

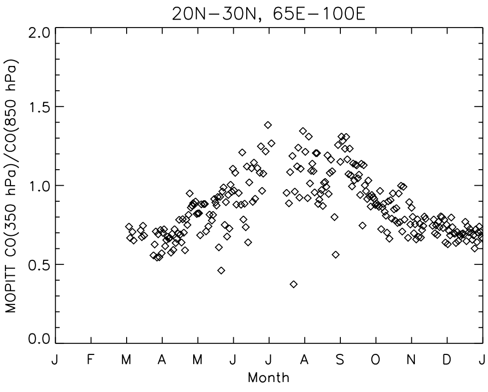

Figure 3. Daily mean CO_{350}/CO_{850} (dayside) as a function of days in 2000. The ratio was calculated over 20N–30N and 65E–100E. 2 points with values in excess of 2 have been excluded.

[11] Further evidence of the development of convective activity over the sub continent as reflected in MOPITT CO profiles can be seen in Figure 3, where we have plotted the daily mean ratio of CO mixing ratio at 350 and 850 hPa levels for latitudes between 20N–30N and longitudes between 65E–100E. The ratio clearly shows a strong rise during the monsoon months. As shown by *Deeter et al.* [2004] this ratio has some correlation with convection. The ratio values greater than 1 likely indicate contribution by advection from China as was discussed above. Further, the actual surface CO values over this region can be much higher than at 850 hPa level (which can be lifted quickly by deep convection) but may not be captured by MOPITT because of low sensitivity in the lower altitudes.

[12] The characteristic CO altitude distribution with high CO mixing ratios in the UT (Figure 2a) is consistent with the model simulations of mesoscale convective systems [*Pickering et al.*, 1996]. In particular, rapid convective updrafts (over few hours) associated with thunderstorms leading to high CO mixing ratios in the UT has been observed by *Dickerson et al.* [1987] from aircraft measurements. It may be mentioned that the Indian regions north of 20N and eastward of 79E, experience intense thunderstorm activity during the monsoon, aided by local topography [*Manohar et al.*, 1999; *Manohar and Kesarkar*, 2003]. Thus deep convection associated with this strong thunderstorm activity is likely to contribute to the high CO mixing ratios in the UT during the monsoon months over the north eastern parts of the sub continent.

[13] Evidence of large scale convective transport in MOPITT CO data can be seen in Figure 4 where we have plotted the global zonal mean height latitude cross sections of CO for the months of September–December, 2002, using only the daytime data. The MOPITT retrievals capture the evolution of the upper tropospheric CO in the southern

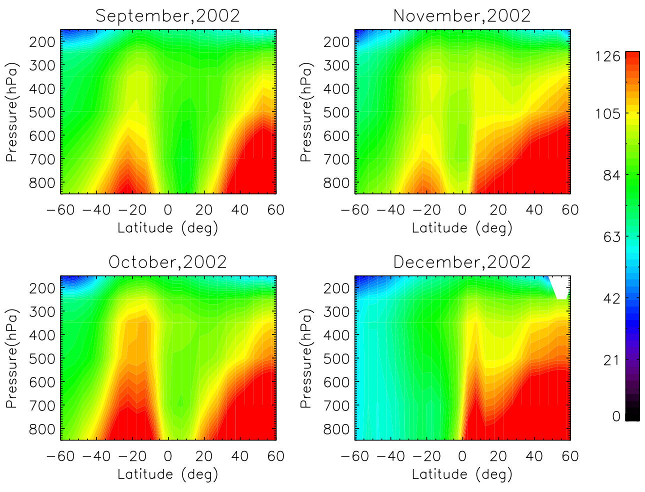

Figure 4. Zonal mean pressure-latitude cross sections of CO retrievals (dayside) for September–December, 2002. Color bar saturates at 126 ppbv. Data binned in 5° latitudes.

tropics and subtropics from September to November, which is indicative of deep convection that is known to carry the biomass burning products to the UT in these areas [*Pickering et al.*, 1996; *Thompson et al.*, 1996]. *Pickering et al.* [1996] had earlier observed upper tropospheric CO plumes resulting from a series of mesoscale deep convective systems over Brazil during TRACE A. By November while biomass burning declines in the south, it starts increasing in the Sahel region of Northern Africa. The latter intensifies in December and upward transport of CO can be clearly seen in the northern tropics at this time. Similar effects were seen in MOPITT CO data for all the years available, albeit with some interannual variations.

4. Conclusions

[14] We have shown that the daytime retrievals of CO from MOPITT contain sufficient information to capture the increased CO mixing ratios in the UT in the Asian monsoon region associated with the deep convective activity, confirming for the first time the Asian summer monsoon plume which was predicted recently on the basis of model calculations. Further, the monthly averaged global distributions of CO indicate signatures of deep convection in the southern tropics. These results indicate that MOPITT CO profiles can provide significant information on vertical transport phenomena in the troposphere.

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H. Bremer, Institute of Environmental Physics, University of Bremen, Otto-Hahn-Allee 1, D-28359 Bremen, Germany.

M. N. Deeter, D. P. Edwards, G. Francis, J. C. Gille, J. Warner, and, D. Ziskin, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307, USA.

J. R. Drummond, D. B. A. Jones, J. Kar, J. Liu, F. Nichitiu, and J. Zou, Department of Physics, University of Toronto, 60 St. George Street, Toronto, Ontario, Canada M5S 1A7. (jkar@atmosp.physics.utoronto.ca)

Y. J. Rochon, Meteorological Service of Canada, 4905 Dufferin Street, Toronto, ON M3H 5T4, Canada.