Three dimensional OMI observations of rapid around the world transport of an aerosol plume released from the Australian forest fires on 14 December 2006.

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ABSTRACT

We investigate rapid around-the-world transport of a smoke aerosol plume released by intense forest fires in southeastern Australia in December 2006. On 14 December 2006, a passing cold front in combination with the intense heat from the fires causing pyro-convective lofting, injected a large mass of aerosol particles into the jet stream. We track the resulting aerosol plume using Aerosol Absorbing Index (AAI) observations from the Ozone Monitoring Instrument (OMI) and find that it circumnavigated the world in 12 days. Using observations from OMI and the CALIOP (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) spaceborne lidar, we show that the plume resided in the high troposphere at different stages of its evolution. In absence of CALIOP data, we explored OMI O_2-O_2 pressures to obtain information on the aerosol plume height. The observed two-dimensional evolution of the smoke aerosol plume and the vertical distribution of the plume detected by CALIOP is matched by simulations with the TM4 chemistry transport model for an injection height of 248 hPa ($\sim$10 km). Injection heights at the surface and at 540 hPa ($\sim$5 km) resulted in simulated vertical distributions that were 2-3 km too low relative to CALIOP observations, and showed less agreement with the AAI patterns. The high injection altitude of 10 km mimics the effect of pyro-convective lofting as the additional buoyancy from the intense fires is not accounted for in the model. This is the first detailed study of around the world long-range transport of forest fire emissions in the extratropical Southern Hemisphere.

1. INTRODUCTION

In December 2006, southeastern Australia suffered from exceptionally intense forest fires. Trace gases and aerosols emitted by biomass burning and forest fires contribute significantly to atmospheric composition on regional and global scales. The sensible heat produced by the fires often leads to convective lofting of emitted species to the free troposphere (*Pickering et al.*, 1996). Once in the free troposphere the gases and aerosols can be transported over vast distances affecting the concentrations of trace substances in remote regions. So far, few studies into long range transport of pollution in the extra-tropical Southern Hemisphere have been performed, as these events are relatively rare due to few prominent sources. Fire plumes can reach a wide range of altitudes, although the majority of biomass burning plumes remains in the lower troposphere. This relates to the fact that the majority of wild fires occur in high-pressure (good-weather) conditions with corresponding thermal stability by subsidence Under favorable meteorological conditions, i.e. an unstable atmosphere, pyro-convection can quickly loft forest fire smoke to the upper troposphere or even into the lower stratosphere (*Fromm and Servranckx*, 2003). Plumes in the upper troposphere have a much longer lifetime than their lower tropospheric counterparts, because of prevailing low humidity and low temperatures that suppress scavenging, thereby augmenting the horizontal range over which they are transported. Currently, CTMs ignore the energy of fire plumes, and biomass burning emissions are released in the lower model levels. Consequently, lofting of the plume depends solely on meteorological conditions. We show that using appropriate injection heights is essential for simulation of the observed 3-D transport of the Australian aerosol plume.

2. SATELLITE OBSERVATIONS AND TRANSPORT MODEL

2.1. OMI

The Dutch-Finnish Ozone Monitoring Instrument (OMI) (*Levelt et al.*, 2006) is a UV/Vis imaging spectrometer that records the backscattered radiance from the Earths atmosphere in three spectral channels between 264-504 nm at an average spectral resolution of 0.5 nm. It combines a wide swath (2600 km) with high spatial resolution (24x13 km^2 at nadir). OMI is part of the EOS-Aura mission (launched July 2004) which is in a sun-synchronous ascending node orbit that crosses the equator at 13:40 local time. In this study we use the OMI scientific data products AAI, cloud fraction and cloud pressure, and false color RGB images.

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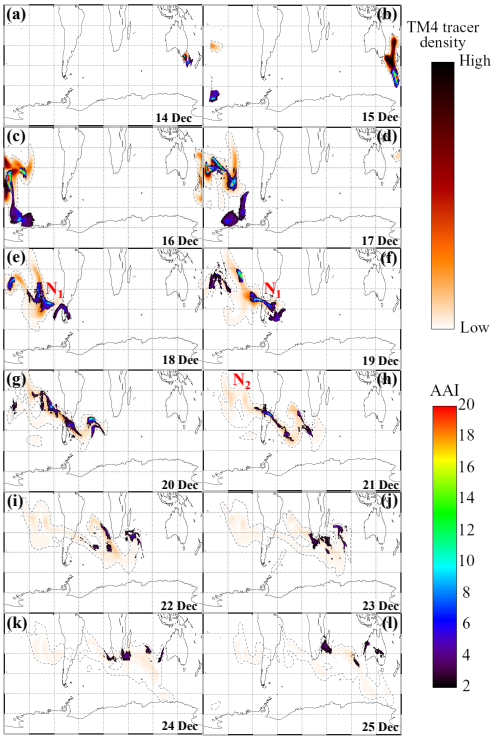

Figure 1. Time series of TM4 simulation of a water soluble passive tracer released on 14 December at 248 hPa. Panels show the integrated tracer column density between 540 and 130 hPa at 24 hour intervals. The dashed contour represents the 1% level. Simultaneous OMI AAI observations with AAI > 2 are co-plotted with the colorscale indicating the AAI value between 2 and 20.

2.2. OMI AAI

The Absorbing Aerosol Index (AAI) is a measure of the spectral slope of the atmospheric backscattered radiance in the UV as compared to the spectral slope of a pure molecular atmosphere described by Rayleigh scattering (*Herman et al.*, 1997). The AAI is the positive part of the residue which is defined as

$$r_{\lambda_1,\lambda_2} = -100 \cdot \left\{ {}^{10}\log\left(\frac{R^{\text{meas}}_{\lambda_2}}{R^{\text{meas}}_{\lambda_1}}\right) - {}^{10}\log\left(\frac{R^{\text{Ray}}_{\lambda_2}}{R^{\text{Ray}}_{\lambda_1}}\right) \right\} \quad (1)$$

Positive values of the residue denote the presence of UV absorbing particles. The AAI can detect aerosols over a wide variety of scenes, including bright surfaces and clouds, which makes it a powerful method for tracking aerosol plumes in satellite measurements.

2.3. OMI O2-O2

The OMI cloud retrieval algorithm uses the O_2-O_2 absorption feature at 477 nm (*Acarreta et al.*, 2004). The continuum reflectance of the scene is used to determine the effective cloud fraction c_{eff}. A DOAS (Differential Optical Absorption Spectroscopy) fit of the OMI reflectance spectrum between 460 and 490 nm is used to determine the slant column amount of O_2-O_2. Over cloudy scenes, the effective scattering height is situated in the middle of the cloud.

2.4. CALIOP/CALIPSO

The CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) satellite carries a two-wavelength (532 and 1064 nm) lidar, named CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization), and uses backscattered lidar pulse to measure the vertical distribution of aerosols and clouds, with a horizontal resolution of 333 m along track and a vertical resolution of 30-60 m. Being part of the A-train, CALIPSO observes the same scene 5-10 minutes prior to OMI, albeit with a much narrower swath.

2.5. TM4

The Tracer Model version 4 (TM4) is a 3-D CTM with a spatial resolution of 3°x2° and 34 sigma-pressure levels up to 0.1 hPa in the vertical direction. The model is driven by 6-hour (3-hour in the boundary layer) meteorological fields from 90-layer ECMWF operational analysis data.

3. TRANSPORT AND ALTITUDE OF THE PLUME

Figure 1 presents, together with TM4 simulation results, the OMI AAI observations of the time evolution and transport of the Australian biomass burning event from 14 to 25 December 2006. A large amount of absorbing aerosol was released into the atmosphere on 14 December 2006 from southeastern Australia, and the resulting plume was subsequently transported over the Pacific Ocean. The plume travelled from Tasmania to Chile within a period of five days, corresponding to an average (Eastward) plume velocity of more than 100 km/h. The frontal part of the plume completed its journey around the world and reached the point where it was emitted after 12 days. OMI RGB images reveal that the aerosol plume was often situated over cloudy areas, and persisted for more than a week, suggesting that the aerosol plume resided in the dry air well above the clouds. This is considerably longer than the typical average lifetime of 3.8 days for aerosols in biomass burning outflow plumes.

Because CALIPSO was switched off between 6 and 18 December 2006 due to space weather conditions, we use effective cloud/aerosol pressures from the OMI O_2-O_2 algorithm (*Acarreta et al.*, 2004) to evaluate the vertical distribution of the aerosol plume. Figure 2 shows that clouds adjacent to the plume on average reside between 800 and 400 hPa, corresponding to altitudes of

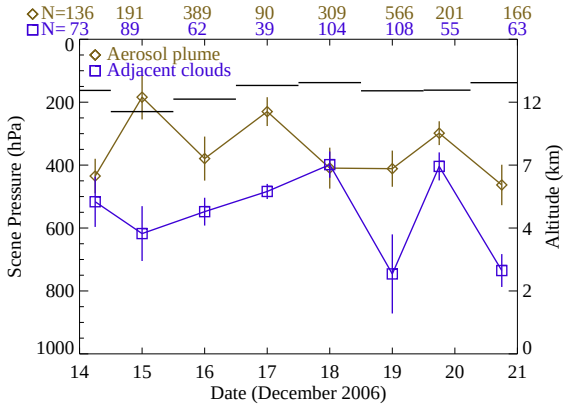

Figure 2. Temporal evolution of (O_2-O_2) effective scene pressure for clouds adjacent to the aerosol plume (blue squares), and the aerosol plume (brown diamonds) originating from Australian forest fires in December 2006, as observed by OMI. The error bars represent the standard deviation of the distribution; the number of pixels used for each datapoint are given in the upper x-axis. The right y-axis represents approximate altitudes for the pressures on the left y-axis. The black line represents the ECMWF tropopause height (WMO 1985 criterion).

up to 6 km. These O_2-O_2 cloud levels provide a lower limit for the height of the aerosol plume. Using the O_2-O_2 pressures retrieved for the OMI pixels with enhanced AAI, we find significantly lower pressures (brown diamonds in Figure 2) than for the adjacent cloud scenes, which confirms that the absorbing aerosol plume is situated in the upper troposphere above the clouds.

On 14 December the pressures indicate that the plume is at approximately 450 hPa right after the biomass burning event. This is due to pyro-convection and rapid uplifting by a frontal system that reached southeastern Australia on 14 December. On 15-17 December, right after the biomass burning event on 14 December, the plume appears to be particularly high, with O_2-O_2 pressures of approximately 300 hPa. At these altitudes, the aerosol plume is rapidly transported in easterly direction by the subtropical jet stream, in line with the observations shown in Figure 1. Between 18 and 23 December, the plume O_2-O_2 pressures gradually decrease to values around 500 hPa.

4. PLUME ALTITUDE MEASURED BY CALIOP

Figure 3 shows a comparison between the vertical distribution of the aerosol plume observed by CALIOP and by OMI for four cases on 19 and 21 December 2006. We selected OMI pixels with AAI$>$2 collocated with the CALIOP track. For all four cases, the altitude associated with the OMI O_2-O_2 pressures is significantly lower than the vertical distribution of the plume observed by CALIOP. For OMI orbit 12923, shown in Figure 3(a), CALIOP observed the aerosol plume at approximately 10 km above a low-lying cloud layer at approximately 1 km altitude (illustrated by gray colors indicating high backscatter signals). For this situation, OMI O_2-O_2 pressures agree well with the altitude of the low-lying cloud layer (solid red line). For OMI orbit 12924, when the aerosol plume crossed South America, CALIOP indicates the aerosol plume at 12 km altitude above a 8 km high cloud layer (Figure 3(b)). Again, the OMI O_2-O_2 pressures correspond with the CALIOP cloud levels, indicating that OMI O_2-O_2 pressure retrievals are mainly sensitive to bright clouds in such situations, and not to aerosol plumes residing above. Figure 3(c) shows the comparison for a situation with a high aerosol plume (10-14 km) over high, intermittent clouds (OMI orbit 12925, western Atlantic). Here, O_2-O_2 pressures indicate altitudes as high as 8 km, notably between 33°S and 36°S, a region where CALIOP did not observe clouds. This finding suggests that the OMI O_2-O_2 retrieval is sensitive enough to detect the presence of a high aerosol plume over cloud-free scenes, but also that the O_2-O_2 pressures are an overestimate of the actual aerosol plume pressure. This is confirmed by Figure 3(d) showing the comparison for orbit 12953, observed on 21 December 2006 over South America. On this clear-sky day, CALIOP measured the plume between 12 and 14 km, but the OMI O_2-O_2 pressures correspond to altitudes up to 5 km.

Figures 3(c)-(d) suggest that the discrepancies between CALIOP and OMI plume heights over cloud-free scenes decrease with increasing backscattered signal from the plume. This is most evident in orbit 12925 where OMI observes highest altitudes for backscatter values up to 0.006 $km^{-1}sr^{-1}$.

5. TM4 RESULTS AND INJECTION HEIGHT

To evaluate the injection height and subsequent transport of the biomass burning plume, we released a passive, but water soluble, tracer in TM4 on this date in the grid cells with fires between 30-40°S, and 140-154°E. We conducted simulations with tracer emissions at the surface level (1013 hPa), and at 540 hPa. Figure 4 shows that emissions at the surface and at 540 hPa, lead to remarkably similar tracer vertical distributions, with highest tracer concentrations between 300 and 400 hPa.

Figure 4(b) and 4(d) clearly show that after 5-7 days the simulated tracer plumes are too low by 2-3 km relative to CALIOP observations. These results suggest that TM4 has some skill in simulating the lofting of the plume by the cold front, but also that the model fails to push the plume towards altitudes where it is picked up by the jet stream and where it has actually been observed. This deficiency of the model is likely a result of TM4 not accounting for the enhanced buoyancy of the plume provided by the heat of the extensive fires. To circumvent this shortcoming, and to mimic the effects of pyro-convection, we conducted a simulation where we released the tracer at 248 hPa. Figure 4 shows that injection at 248 hPa results in tracer plumes that are higher by 2-5 km, and closer to the observed CALIOP

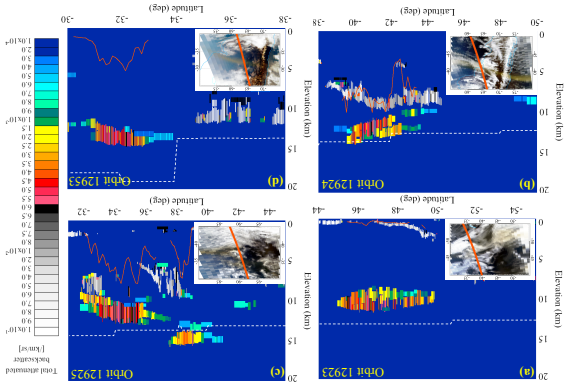

Figure 3. CALIOP observation of the aerosol plume on 19 and 21 December 2006. The color coding represents the total attenuated backscatter (1/km/sr) from the CALIOP aerosol and cloud layer product. The OMI O_2-O_2 derived plume height is co-plotted in red. The insets show the OMI RGB image of the plume together with the CALIOP footprint in orange. The dashed white line represents the ECMWF tropopause level. The corresponding OMI orbit numbers are given in the upper right corner of each panel.

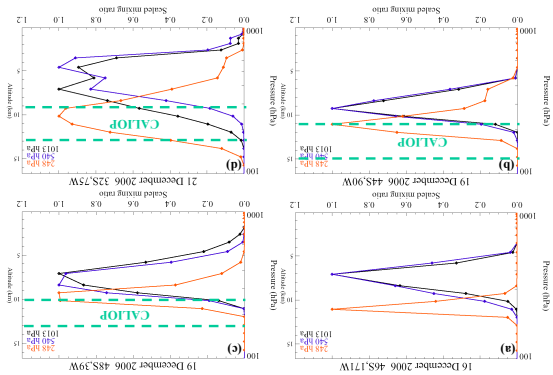

Figure 4. Mixing ratio profiles of a passive tracer emitted in TM4 on 14 December 2006. Different injection heights result in different profiles (colors). The profiles have been scaled to unity peak intensity. Each panel shows the profiles for a specific day and location; see Figure 1 for the 2-D shape of the tracer field on these dates. In panels (b)-(d) the plume altitude observed by CALIOP is indicated in green.

plume altitudes. That injection at 248 hPa closely approximates the true emission height is confirmed by Figure 1 that compares the evolution of the passive tracer with the OMI AAI observations. The tracer fields represent simulated vertical tracer columns between 540 and 130 hPa (5-15 km), sampled at 13:30 hrs, close to the OMI overpass time. A primitive kernel, accounting for the increasing AAI-sensitivity with height, has been applied to the simulated fields for consistency. We see a good correspondence between the simulated tracer columns and the observed AAI fields between 14 and 19 December. The elongated structure simulated over the southern Pacific on 16 December (Figure 1 (c)) coincides with the observed split-up in the AAI field.

The locations of the AAI plumes are captured very well on 18 and 19 December although the modeled feature west of South America has dispersed more and is spatially more extended than the AAI plume marked N_1. On 20 and 21 December the remaining AAI plumes are all captured by the model, especially the narrow band-like structure over South America on 21 December is reproduced well. We also see that the modeled tracer features appear more extended than the AAI plumes, and that tracer features persist over the east Pacific Ocean which are not seen in the AAI observations, such as the feature marked N_2 on 21 December. However, the AAI observations coincide remarkably well with the maximum values of the tracer simulations for 18-21 December. For 22 and 23 December the discrepancy between model and observations appears larger, but the scattered remains of the AAI plume still coincide with the front moving part of the modeled tracer. On 25 December, when the aerosol plume completes its circumterrestrial tour, AAI and the simulations do not correspond anymore.

REFERENCES

Acarreta, J. R., J. F. de Haan, and P. Stammes (2004), Cloud pressure retrieval using the O_2-O_2 absorption band at 477 nm, J. Geophys. Res., 109, D05204, doi:10.1029/2003JD003915.

Fromm, M. D., and R. Servranckx (2003), Transport of forest fire smoke above the tropopause by supercell convection, Geophys. Res. Lett., 30, doi: 10.1029/2002GL016820.

Herman, J. R., P. K. Bhartia, O. Torres, C. Hsu, C. Seftor, and E. Celarier (1997), Global distribution of UV-absorbing aerosols from Nimbus 7/TOMS data, J. Geophys. Res., 102, pp. 16,911-16,922.

Levelt, P., E. Hilsenrath, G. Leppelmeier, G. van den Oord, P. Bhartia, J. Tamminen, J. de Haan, and J. Veefkind (2006), Science Objectives of the Ozone Monitoring Instrument, IEEE Trans. Geosci. Remote Sens., 44 (5), pp. 1199-1208, doi: 10.1109/TGRS.2006.872336.

Pickering, K. E., A. M. Thompson, Y. Wang, W.-K. Tao, D. P. McNamara, V. W. J. H. Kirchhoff, B. G. Heikes, G. W. Sachse, J. D. Bradshaw, G. L. Gregory, and D. R. Blake (1996), Convective transport of biomass burning emissions over Brazil during TRACE A, J. Geophys. Res., 101, pp. 23,993-24,012.