Chance encounter with a Stratospheric Kerosene Rocket Plume from Russia over California

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Abstract.
A high-altitude aircraft flight on April 18, 1997 detected an enormous aerosol cloud at 20 km altitude near California (37°N). Not visually observed, the cloud had high concentrations of soot and sulfate aerosol, and was over 180 km in horizontal extent. The cloud was probably a large hydrocarbon fueled vehicle, most likely from rocket motors burning liquid oxygen and kerosene. One of two Russian Soyuz rockets could have produced the cloud: a launch from the Baikonur Cosmodrome, Kazakhstan on April 6; or from Plesetsk, Russia on April 9. Parcel trajectories and long-lived trace gas concentrations suggest the Baikonur launch as the cloud source. Cloud trajectories do not trace the Soyuz plume from Asia to North America, illustrating serious flaws in the point-to-point trajectories. This cloud encounter is the only stratospheric measurement of a hydrocarbon fuel powered rocket.

Introduction

Rocket emissions may have a negative impact on stratospheric ozone. Assessing this impact is difficult because of limited knowledge of rocket motor and propellant emissions, emission far-field chemistry and plume wake processing, and emission dispersion to global scales. Initial concerns focused on chlorine emissions from solid rocket motors (SRMs) [*Stolarski and Cicerone,* 1974]. Recent attention has focused on heterogeneous chemical reactions on aerosols emitted from rockets, and alumina from SRMs [*Jackman et al.,* 1998]. These particles may perturb stratospheric chemistry and accelerate ozone loss [*Molina et al.,* 1997]. Calculations using a transport and chemistry model show chlorine activation reactions on alumina surfaces may decrease global annually averaged ozone by approximately 0.025% [*Jackman et al.,* 1998], although *Ross et al.* [1999] suggest a much smaller loss.

Beginning in 1996, various stratospheric aircraft have measured emissions and plume wake chemistry from SRMs. Successful measurements in Titan IV, Space Shuttle, and Delta II plumes have provided Cl_2 and submicron alumina emission indices for large SRMs. Further, these measurements show complete ozone removal in the plume during the first hour after launch. In contrast to these SRM emission measurements, there have been no direct stratospheric measurements of liquid propellant rockets.

Currently, hydrocarbon rocket emissions are not understood well enough to reliably predict their absolute stratospheric impact or in comparison with SRM emissions. Several new heavy lift hydrocarbon fueled rockets will begin operations over the next several years and it is expected that emissions from hydrocarbon rockets will approach those of SRMs within a decade. Hence, there is a need for detailed assessment of hydrocarbon motor impacts which is comparable to the assessment of SRM impacts.

On April 18, 1997 an ER-2 flight with a comprehensive instrument payload was flown near 37°N and 122°W at an altitude of about 20 km. During this flight extremely large concentrations of condensation nuclei (CN) were unexpectedly detected in several well defined regions extending over 180 km horizontally. The large scale of the aerosol cloud, together with its high CN concentration, presented a conundrum with regard to identification of its source. In this paper we show that the mysterious April 18 cloud was most probably a kerosene fueled rocket launched twelve days previously in central Asia. The cloud aerosol characteristics, the apparent origin, and air parcel trajectories are consistent with this identification. We also discuss some implications of the data for stratospheric meteorological models and the assessment of the stratospheric impact of rocket emissions.

Observations

Meteorological Data

We use meteorological analyses from the Goddard Space Flight Center's Data Assimilation Office (DAO) GEOS [*Coy and Swinbank,* 1997], with the ER-2 Meteorological Measurement System (MMS) [*Chan et al.,* 1990] in situ pressure, temperature, and winds. The GEOS temperatures are about 0.6 K cooler than MMS at potential temperatures between 460 and 520 K (approximately 50 hPa). On April 18, 1997 the winds are weak. The average MMS observed wind over the flight is 0.9 ms^{-1} and -0.15 ms^{-1} in the zonal and meridional directions, respectively. Contrasting with the GEOS wind of 0.3 and 2.1 ms^{-1} (RMS differences of 2.5 and 3.1 ms^{-1}). Such differences are reasonable, buta consistent bias in wind speed of only 1 ms^{-1} will translate into a trajectory position error of 1000 km in 10 days.

Wind field biases of a few ms^{-1} have been identified in the GEOS stratospheric meridional flow fields [*Bowman et al.,* 1998].

Cloud Data

April 18, 1997 ER-2 measurements included CN concentration, aerosol sizing, aerosol collection and analysis, CO_2 and N_2O concentrations. Figures 1a and 1b shows CN concentration as a function of time and potential temperature, respectively, from the University of Denver CN Counter (CNC) [*Wilson et al.,* 1983]. CNC measures particle concentrations with diameters from about 0.008 to 2.0 microns. The CNC contains two, parallel particle counting channels, one having a heated inlet that has been demonstrated to effectively volatilize small particles composed of sulfuric acid [*Brock et al.,* 1995]. Both channels have a 1 Hz sampling rate and a total accuracy of about 15% when particle concentrations exceed 100 cm^{-3}. The cloud CN increased from a typical lower stratospheric value of about 5 cm^{-3} to 1000 cm^{-3}. The cloud contained both a volatile and a nonvolatile component in a ratio of about 2:1. Figure 1b shows that the cloud was confined in a narrow layer (¡600 m) centered on the 518 K isentropic level. The bottom side of the cloud sharply cuts-off at 500 K; the plume topside was not penetrated by the ER-2. Weakly elevated CN concentrations were also detected northward of the main cloud. The ER-2 also encountered a similar, though less dense, cloud on another southbound April 22 flight.

Figures 1

Figure 1c shows the ER-2 track and elevated CN concentration. The elevated CN (denoted by the thicker dots) cover a larger area than San Francisco Bay. On the initial outbound leg, the CNC instrument detected moderately elevated levels of CN northeast of the Bay and to the WNW of the Bay. On the return leg, the highest CN levels were measured about 100 km west of the Bay. Prior to landing, the ER-2 exited the cloud while flying north. The cloud's structured nature makes it difficult to accurately gauge the cloud size. We estimate that the horizontal dimension of the cloud to exceed 180 km. The greatest continuous region where the CN count exceeded 500 cm^{-3} was about 50 km in extent, an area of 2500 km^2. Using the main region of the cloud with CN greater than 7 cm^{-3} we estimate a cloud size of 11,000 km^2. Models of aerosol coagulation, in conjunction with the observed CN concentration, suggest that the cloud was less than 21 days old.

Aerosol particles in the cloud were gathered by the Multi-sample Aerosol Collection System (MACS), a thin-plate inertial impactor that collects particles larger than about 0.02 microns for electron microscopy and individual particle elemental analysis. The elemental analysis revealed that the ratio of the volatile and nonvolatile components was about 3:1, similar to the ratio measured in the CN data. Further, the nonvolatile fraction of the aerosol was composed of almost entirely of carbon-rich material with the morphology of soot, a rare component of undisturbed lower stratospheric air [*Sheridan et al.,* 1994]. The volatile fraction of the cloud aerosol was composed of sulfate droplets. The MACS cloud samples did not show alumina particulate emitted by SRMs.

Nitrous oxide (N_2O) concentrations in the cloud (when CN exceeded 500 cm^{-3}) were found to be about 210 -230 ppbv, consistent with N_2O midlatitude values. N_2O measurements from polar campaigns have demonstrated that very low values of N_2O are associated with polar vortex air [*Schoeberl et al.,* 1992; *Loewenstein et al.,* 1990]. N_2O at the polar vortex edge on April 26, 1997 was less than 100 ppbv, while N_2O in the cloud was greater than 200 ppbv. Thus, the cloud had a northern midlatitude stratospheric origin. This also excludes both a tropospheric and upper stratospheric source.

The soot and sulfate composition identifies the cloud source as a high altitude aircraft or hydrocarbon combustion rocket. *Fahey et al.* [1995] report CN concentration of about 2000 cm^{-3} in a Concorde plume of about 1 km in horizontal extent. CN concentration in the cloud was only a factor of 2 less less than CN in the Concorde plume, yet the 180 km longitudinal extent of the cloud was much greater than the 1 km width of the Concorde plume. The cloud was too large and morphologically different from a stratospheric aircraft.

By elimination, the cloud source was most likely a large kerosene fueled rocket. A comprehensive search of launch records shows two candidates: (1) a Cosmos satellite from Plesetsk, Russia (65°N, 35°E) on April 9 (0859 UT) and (2) a Progress M-34 from the Baikonur Cosmodrome, Tyuratam, Kazakhstan (48°N, 30°) on April 6 (1604 UT). The rockets in both cases were Soyuz boosters.

Plume Transport Analysis

Since the cloud was produced by one of two rocket launches, we apply meteorological analysis techniques to determine which launch was the most likely source. Emission of the cloud by the April 6 or the April 9 launch does not greatly affect subsequent analysis with regard to stratospheric impacts since the rockets were the same and the plume age at the time of the ER-2 encounter was similar. Air mass tracing using potential vorticity and trajectory calculations illustrates the cloud transport from central Asia to the North American coast. Neither technique provides unambiguous information on the dynamical history of the airmass sampled over California on April 18.

Trajectories using the GEOS analyses were run forward from the launch sites and backward from the ER-2 encounter site. The trajectories consist of constructing 600 km diameter rings of parcels around the launch and encounter sites and transporting them with the winds from the meteorological analyses. Three trajectory cases are calculated: 1) parcels surrounding Baikonur on April 6 are carried forward for 13 days, 2) parcels surrounding Plesetsk on April 9 are carried forward for 10 days, and 3) parcels around the April 18 plume encounter are carried backward for 13 days. Using reasonable estimates of trajectory position errors, altitude registration, and release times, we find that the forward launch site and backward encounter site air parcels do not overlap. The first calculation shows that the Baikonur launch is the more probable source.

The 600 km diameter rings of parcels around Baikonur is stretched into two major streamers extending eastward from the launch site by 18 April Figure 2 (red). The Baikonur trajectories are started on April 6 at 0800 UT as indicated by the 600 km radius black filled circle at 46°N and 63°W. By April 18 that collection of parcels has been stretched and distorted into a mass of air that has drifted eastward towards Japan and a second streamer of air that has come full circle around the globe. Part of this second streamer comes to within about 900 km of the ER-2 intercept site, a large error given the 12-day trajectory. Plesetsk and the April 18 ER-2 flight region are also shown with 600 km circles centered on the stars.

Figure 2

Figure 2 also shows the Plesetsk second case, trajectories run forward starting from April 9 at 0900 UT (blue). Here, the Plesetsk region trajectories remain confined to the polar vortex and do not spread southward to the plume encounter region, consistent with the N_2O observations in the cloud. This indicates that the Plesetsk lower stratospheric exhaust was trapped in the polar vortex.

The third case, back trajectories from the ER-2 plume encounter (not shown), do not carry back into central Asia following a 10 to 14 day transport, within the 12 day window required for the April 6 launch. These back trajectories indicate that that some fraction of the encounter airmass was from a region about 1500 km east-northeast of Baikonur, an error that again must be considered large given the 12 day trajectory.

The trapping of Plesetsk emissions in the polar vortex are consistent with the April 9 meteorological analysis. Reverse domain filling techniques (RDF) have been used to locate the Plesetsk launch at the vortex edge (see [*Newman et al.* 1996] for a discussion of such air mass tracing using RDF calculations), in agreement with the forward trajectories (Figure 2). These analyses, consistent with the midlatitude N_2O data, eliminates the Plesetsk launch as the source of the April 18 plume.

Since the trajectories do not successfully relate the Soyuz plume to Baikonur, we have tested trajectory sensitivity to release time and the initial isentropic level. The trajectories show great sensitivity to the initial starting time near Baikonur because of the evolving synoptic situation near Baikonur at the release time. The trajectories also depend on the initial isentropic surface. A high density cross section of back trajectories from the ER-2 intercept shows large vertical variation with respect to exact air parcel origin. Trajectories at 435 K came directly from Baikonur according to the trajectory calculation, whereas material 5 K above and below this narrow layer came from no closer than 1000 km to Baikonur on April 6.

Summary and Discussion

The NASA ER-2 intercepted a large, dense aerosol plume on April 18, 1997. CN concentrations demonstrate the anomalous character of this plume while the soot and sulfate composition show that the plume source was a kerosene propulsion system. Comparison of the plume size and structure eliminates known aircraft as sources. Analysis of the long-lived constituents in the plume show that it originated at mid-latitudes and not from within the polar vortex. Aerosol coagulation arguments indicate that the plume had been deposited within 21 days of the April 18 encounter. Trajectories suggest the plume source was a Soyuz rocket launched from Baikonur Cosmodrome on April 6, 1997 to resupply the MIR space station. This means that the plume was advected more than 10,000 km over a 12 day period while remaining fairly intact and well defined horizontally and vertically.

Trajectories poorly trace the rocket plume both forward from the April 6 Baikonur launch or backward from the ER-2 plume encounter on April 18. Insofar as the plume source was the Soyuz rocket, this illustrates the problem of trajectory error amplification for extended calculations. The plume also serves as a case study in the limitations of trajectory accuracy under some circumstances. Depending on the isentropic level chosen, material can in fact be directly traced backward to the Baikonur launch site, viz 435 K. Unfortunately, this cannot be done within 10 K of the principal isentropic level where the material was sampled, 516 K. The back trajectories from the ER-2 intercept are insensitive to release time, while the forward trajectories from Baikonur are very sensitive to wind analysis resolution and release timing.

A more detailed analysis of the plume aerosol data, in conjunction with the NO_y data obtained in the plume, can be expected to lead to increased understanding of the stratospheric chemistry of kerosene fueled rocket motors, especially with regard to environmental impacts.

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Figure 2. Air mass positions on April 18 (1200 UT) that were released from the Baikonur region on April 6 (red), and the Plesetsk region on April 9 (blue). The air masses are initialized over a 600 km radius circle around each site on the 516 K potential temperature surface (filled black circles).

Figure 2. Air mass positions on April 18 (1200 UT) that were released from the Baikonur region on April 6 (red), and the Plesetsk region on April 9 (blue). The air masses are initialized over a 600 km radius circle around each site on the 516 K potential temperature surface (filled black circles).

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