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A TRAJECTORY MODELING INVESTIGATION OF THE BIOMASS BURNING - TROPICAL OZONE RELATIONSHIP

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ABSTRACT

The hypothesis that tropical total O_3 maxima seen by the TOMS satellite derive from African biomass burning has been tested using isentropic trajectory analyses with global meteorological data fields. Two case studies from the 1989 biomass burning season demonstrate that a large fraction of the air arriving at the location of TOMS O_3 maxima passed over regions of intense burning. Other trajectories initiated at a series of points over Africa and the Atlantic suggest flight strategies for field studies to be conducted in September 1992.

1. INTRODUCTION

Biomass burning in the tropics has been increasing in recent years with the demand for agricultural land. The consequences of increased burning for atmospheric chemistry and global climate are being investigated at monitoring sites and in field missions (Cros et al., 1992; DECAFE issue JGR, 97, D6, 1992). A major concern is that biomass fires are contributing to tropospheric O_3 formation because biomass fires are rich sources of NO_x, CO and hydrocarbons.

Fishman et al. (1990, 1991) inferred enhancements in tropospheric O_3 over the South Atlantic by analysis of satellite data. The tropical O_3 maximum appears in the months of August - November in both TOMS total O_3 fields and in what Fishman et al. (1990) call the "tropospheric O_3 residual." The tropospheric residual is obtained by subtracting stratospheric O_3 (derived from SAGE I and II) from the TOMS total column O_3. Fishman et al. (1990) hypothesized the maximum comes from biomass burning emissions, primarily in southern Africa. Local enhancements in ozone have been observed in ozonesonde profiles taken at Brazzaville, Congo, and at Ascension Island in the Atlantic. The ozonesondes reveal seasonally elevated peaks of O_3 in the lower troposphere, presumably resulting from low-level transport of O_3 and precursor gases when there is burning on the African continent (Fishman et al., 1991; Cros et al., 1992).

Despite evidence for the hypothesis that "biomass burning causes tropical O_3 maxima," there has not been a detailed study using trajectory analysis to prove or disprove the linkage between biomass burning regions and the appearance of the South Atlantic maximum in the O_3 residual. The objective of this study is to examine that linkage. Specifically, we have performed case studies to determine the extent to which short-term (days) tropospheric O_3 maxima observed from TOMS can be linked to regions of extensive burning in Africa, as defined by AVHRR fire count data.

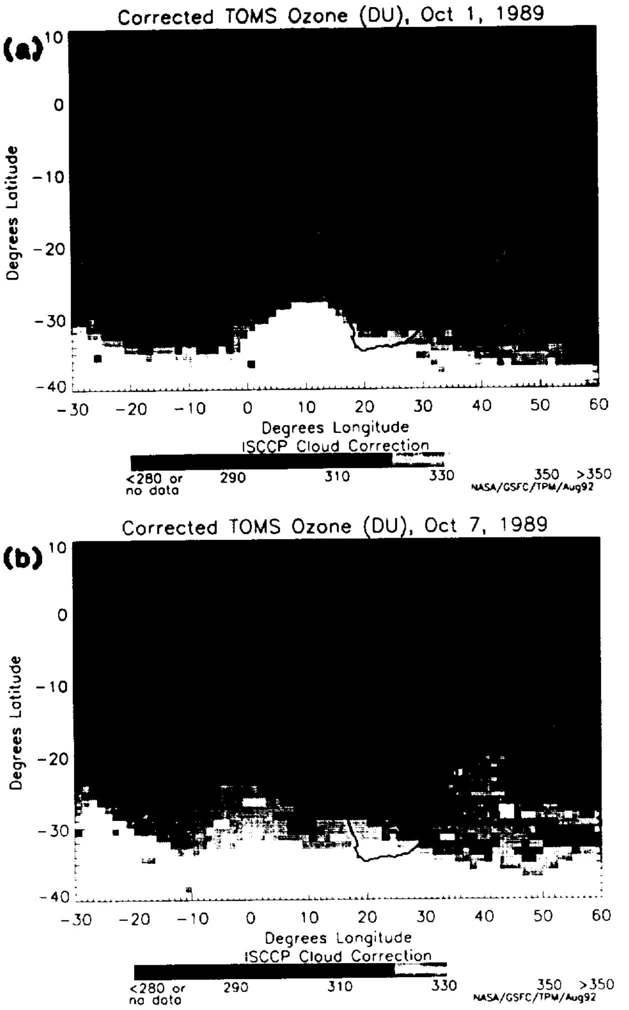
The first part of this paper is a preliminary report, focusing on links between TOMS O_3 and fires for two one-week periods in September and October 1989 for which fire counts have just become available. The second part of the paper describes results for trajectory analyses that look at flow regimes over the tropical South Atlantic on a larger scale. The aim is to anticipate conditions over South America, Africa, and the South Atlantic that are likely to be encountered during 1992 field campaigns (SAFARI = Southern Africa Fire Atmosphere Research Initiative and NASA/GTE/TRACE-A = Global Tropospheric Experiment/Transport and Atmospheric Chemistry Near the Equator - Atlantic). Methods and data sets are first described.

2. METHODS AND DATA SETS

TOMS Data. Gridded TOMS data (Version 6.0) are used to identify episodes of persistent high O_3 during the period August-October 1989. Tropical maxima in total O_3 that appeared unrelated to the major stratospheric horizontal gradient in the middle latitudes were identified and assumed to be tropospheric features. Fishman et al. (1990) have shown a very high correlation between total O_3 and the tropospheric O_3 residual in the tropics. Two O_3 maxima from early October 1989 were selected as likely candidates for having a biomass burning source (Figure 1).

AVHRR Fire Counts. Regions of burning each day were defined by fire count data derived from AVHRR imagery. Fires radiate at very high temperatures and their signature appears as a spike in the 3.55 to 3.93 micron channel (channel 3) of AVHRR, but has much less effect on the 10.3 to 11.3 micron channel (channel 4). The algorithm counts fires by looking for pixels with high channel 3 values and large differences between channels 3 and 4 relative to their immediate background values (Matson et al., 1987). The method performs well over uniform terrain, but is complicated by background differences (e.g., coastlines, rivers, burnscars, etc.) and very hot ground temperatures. Furthermore, deriving fire count estimates from AVHRR is complicated by smoke or fire-induced clouds that conceal fires and by uncertainty about fire size. One satellite pass over Africa per day is processed, but the orbital swath is not as wide as southern Africa. Therefore, the data are not complete enough to permit quantification of emissions. Instead, regions with large numbers of fires are identified for possible connection with high O_3.

Trajectory Model. An isentropic trajectory model developed for use in stratospheric analyses (e.g., Schoeberl et al., 1992) has been used. The model requires global gridded


Corrected TOMS Ozone (DU), Oct 1, 1989

Corrected TOMS Ozone (DU), Oct 7, 1989

Fig. 1. TOMS total column ozone on a 1°x1.25° grid for (a) October 1, 1989, and (b) October 7, 1989. Note that prior to selection of these O_3 maxima data west of Africa were corrected for anomalously high O_3 over marine stratocumulus clouds (see Thompson et al, this volume).

fields of temperatures, u and v wind components, and potential vorticity. The gridded wind fields are first interpolated to user-selected isentropic surfaces and then interpolated temporally and spatially. A time step of 0.01 days (~15 min) is used. Temperature is interpolated onto the parcel path from the gridded data and used with an assumption of potential temperature conservation along the trajectory to compute the pressure at each successive parcel position. Model output for each parcel consists of a file containing a time series of parcel positions (x,y,p), temperatures, solar zenith angles, and potential vorticity. Plots of trajectories are prepared with parcel positions indicated every 12 hours. Both backward and forward trajectories have been constructed with the model.

Two different sets of meteorological data fields have been used in the trajectory model. The National Meteorological Center (NMC) 1200 UTC global analyses of temperature and geopotential height, along with balanced winds computed from the height fields were retrieved for September and October, 1989, from the archive at NASA Goddard. The NMC data (on 18 standard pressure surfaces from 1000 to 0.4 mb) were interpolated to 2°x2.5° latitude/longitude grids. Twice-daily (0000 and 1200 UTC) analyzed fields from the European Center for Medium-range Weather Forecasting (ECMWF) were also acquired for days covering specific case study periods. These 2.5°x2.5° gridded fields are available for seven standard pressure surfaces from 1000 to 100 mb.

3. RESULTS: BACK TRAJECTORIES FROM O_3 MAXIMA

1 October 1989. The TOMS image for 1 October 1989 (Julian Day 274) showed total O_3 off the coast of Angola to have two grid cells with total O_3 at 330-340 DU and a much larger region with 320-330 DU (Figure 1a). Therefore, we have run backward trajectories from 1200 UTC on October 1 from an array of 11 air parcel arrival points ranging from 10°S to 20°S and from 0° longitude to 14°E, using the ECMWF fields.

The trajectories were computed for constant potential temperature surfaces ranging from 308 K to 324 K, yielding a total of 99 trajectories with arrival pressures ranging from 519 to 815 mb. Figure 2a shows that for all surfaces except 308 K the vast majority of the trajectories originate from the continent of Africa. For all surfaces combined, a total of 80 of 99 eight-day trajectories originate over the continent. While some flow off the continent may exist on the 308 and 310 K surfaces, the existence of considerable elevated terrain in Southern Africa (large regions > 1000 m elevation, corresponding to potential temperatures of 300 to 310 K) makes the surfaces 312 K and higher more likely to contain the bulk of the biomass burning emissions. Seventy of 77 trajectories on these surfaces arrive from the African continent. All 70 trajectories passed over regions with at least some burning, based on the fire data (Figure 3a) totaled over the week prior to October 1.

Several of the trajectory paths computed on the 312, 314, and 316 K surfaces (arrival pressures 649 to 763 mb) have been plotted in Figure 3a. For these three surfaces 31 of 33 trajectories originated over African burning regions, and nine trajectories passed over grid cells each containing more than 1750 pixels indicating fires. Therefore, flow characteristics in this case show that appreciable biomass burning emissions could have been transported to the region of the near-Angola 1 October TOMS total O_3 maximum.

7 October 1989. On October 6 (Julian Day 279) an O_3 maximum appeared over Zimbabwe and by October 7 (Figure 1b) had drifted to near the coast of Mozambique. The maximum column O_3 value was in the 330-340 DU range. We ran back trajectories on the 308-324K surfaces from 1200 UTC on October 7 from an array of 9 air parcel arrival points ranging from 20°S to 24°S and from 32°E to 40°E.

The arrival pressures of the 81 trajectories ranged from 467 to 840 mb. Figure 2b shows that the source regions were quite diverse in this case. No one source region dominated on any of the isentropic surfaces. Overall, 24 trajectories arrived from the Indian Ocean or Madagascar and 57 trajectories passed over the African continent. Comparison with the fire data (Figure 3b) shows that the 57 trajectories passed over regions with at least some burning. Twenty-two of the 57 trajectories were in westerly flow sufficiently strong to have passed over South America during the eight-day trajectory duration. In general, flow arrived from the east at the more northerly points in the array and from the west at points further south. Several of the trajectories on surfaces arriving near 700 mb (310 - 314 K) are also displayed in Figure 3b. On these surfaces 15 out of the 27 trajectories were from the African

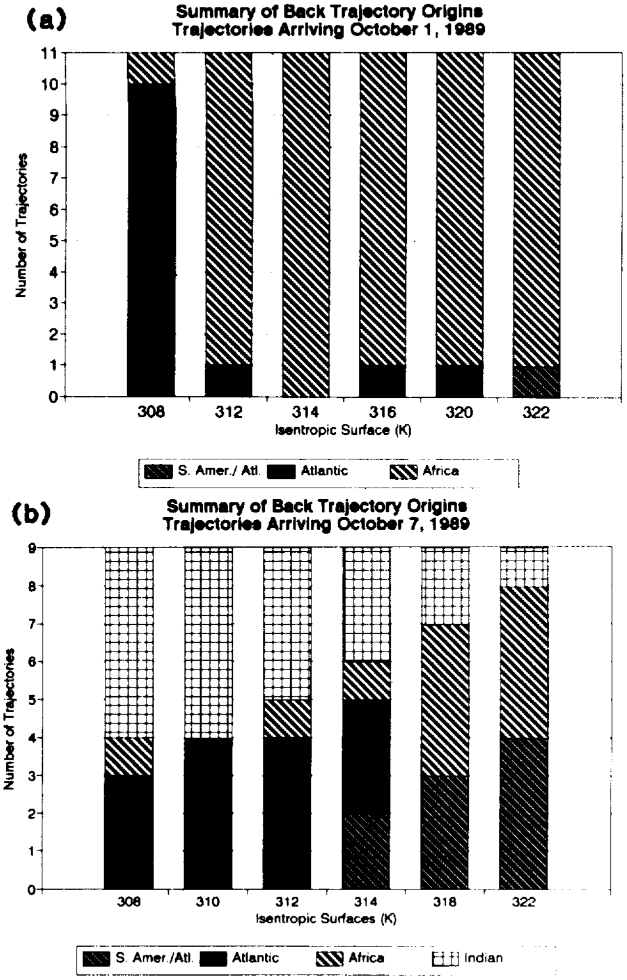


Fig. 2. Summary of back trajectory origins for six isentropic surfaces. (a) Trajectories arriving at TOMS O_3 maximum on October 1, 1989; (b) Trajectories arriving on October 7, 1989.

burning regions and eight of the remaining 12 trajectories passed over Madagascar where burning is also likely occurring (although no data for Madagascar are available at present). Particularly on the 310 and 314 K surfaces, several trajectories passed over African grid cells containing between 1000 and 1750 fire pixels. Therefore, large quantities of biomass burning emissions were likely transported to the case study region.

4. SUMMARY OF SEPTEMBER 1989 TRAJECTORIES

Trajectories based on the NMC analyses with balanced winds for September and early October 1989 were run to examine the larger-scale flow patterns. Forward trajectories were initiated every third day between September 11 and September 28, 1989, from an array of 15 points located from the equator to 30°S over the African continent. Trajectories that intersect the elevated terrain were not used. Backward trajectories were initiated every third day between September 19 and October 6, 1989, from an array of 19 points located from the equator to 25°S over the South Atlantic.

Eight-day forward trajectories from points on the African continent from the equator to 20°S show flow toward the South Atlantic at the low levels (theta < ~315K, ie., below ~700 mb). At points further south flow is toward the Indian Ocean. At higher altitudes (theta > 320K; ie., pressures <~500 mb) trajectories go toward the Indian Ocean from points as far north as 15°S. In mid September extreme variation in the flow patterns was observed over a period of just a few days. Trajectory characteristics varied widely. In one case all the flow on the 316K surface from points at or south of 15°S headed for the Indian Ocean; three days later on the same surface almost all the flow was toward the South Atlantic.

Table 1 summarizes all the forward trajectories initiated in September from two specific points where controlled burns will be carried out in September 1992. These are Etosha National Park in Namibia (20°S, 15°E) and Kruger National Park in South Africa (25°S, 30°E). In both cases, flows are predominantly to the Indian Ocean, with a greater fraction of

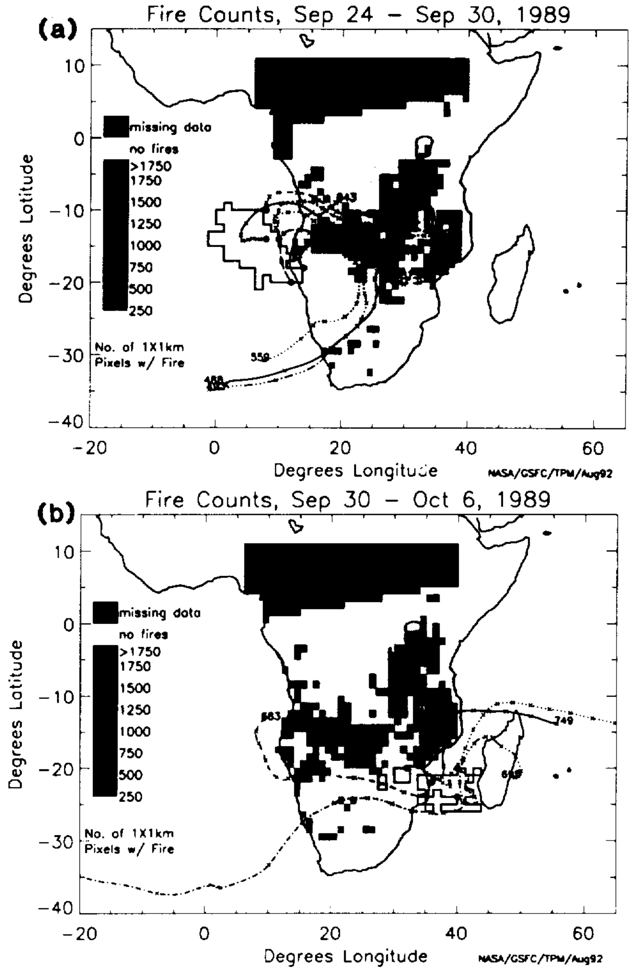


Fig. 3. Total biomass fire counts (derived from AVHRR imagery) for (a) September 24 - September 30, 1989; and (b) September 30 - October 6, 1989. The data displayed are counts of the number of 1.1 x 1.1 km pixels that have fires for each 1° latitude by 1° longitude grid cell. Superimposed are selected back trajectories and the TOMS maxima. In (a) trajectories are on the 312, 314, and 316 K surfaces and in (b) on the 310, 312, and 314 K surfaces. Numbers at the trajectory origins are pressures in millibars.

Table 1. Number of Forward Trajectory Destinations
September 11-28, 1989

Destination	Isentropic Surface (K) 308	310	312	314	316	318	320
	Starting point 20°S, 15°E						
Atlantic Ocean	0	0	1	1	2	1	1
Africa	0	0	1	1	2	3	4
Indian Ocean	0	0	0	2	5	4	4
	Starting point 25°S, 30°E						
Atlantic Ocean	0	0	0	0	1	0	0
Africa	0	0	1	1	1	3	3
Indian Ocean	4	4	3	5	5	4	4

Table 2. Number of Backward Trajectory Origins
(Direction of Origin Relative to Arrival Point)
September 19 - October 6, 1989

Direction	Isentropic Surface (K) 308	310	315	320	325
	Arrival point 10°S, 0° long..				
East	7	7	7	7	6
West	0	0	0	0	0
	Arrival point 20°S, 0° long.				
East	0	1	2	1	1
West	5	6	5	5	5

the total number of trajectories from the Kruger area (38/39) than from the Etosha area (26/32) reaching that ocean. Virtually none of the trajectories from the Kruger region in 1989 went over the Atlantic.

Back trajectories from points in the South Atlantic show flow from the African continent arriving at the more northerly and easterly points in the array and flow from the South American continent arriving at the more southerly and westerly points. Trajectories on the 308K surface show the most air arriving from Africa and the least from South America. With increasing potential temperature more of the air arrives from South America. At 325K, for example, air arrives from South America as far north as 10°-15°S.

Table 2 summarizes the backward trajectory origins for two specific points over the South Atlantic (10°S, 0° and 20°S, 0°). The results are strikingly different for these two points. At the more northerly point all of the trajectories arrive from the easterly sectors (ie., likely African origin), whereas at 20S the majority of the trajectories arrive from westerly sectors (ie., likely South American origin).

5. DISCUSSION

The controlled burns of September 1992 in Etosha and Kruger National Parks will be the focus of intensive measurements during the TRACE-A and SAFARI experiments. During TRACE-A the NASA DC-8 aircraft will be flown to measure O_3, CO, hydrocarbons, NO_x, and meteorological data. Flight tracks will be directed along African coastlines to characterize outflow from the continent to the oceans.

If the results of 1989 are any indication of typical flow patterns for this region and time of year (they agree in general with longer-term climatologies), our trajectory results stongly suggest that most of the burning emissions from southern Africa (south of 20°) will be transported off the eastern coast. Flights tracks should be included over the Indian Ocean.

In terms of identifying sources of high O_3 episodes over the tropical Atlantic, the back trajectories underscore the need for flights planned to measure outflow from South America as well as Africa.

6. CONCLUSIONS

We have performed trajectory analyses to explore linkages between biomass burning emissions in Africa and tropical O_3 maxima seen by the TOMS satellite instrument.

(1) Back trajectory analyses in two case studies show that a significant fraction of the air arriving at locations of TOMS total O_3 maxima near the coasts of Africa passed over regions of intense burning during the prior eight days. Therefore, ozone generated from the precursor emissions could have contributed to the total O_3 maxima measured by the satellite.

(2) Examination of 1989 trajectories throughout the month of September shows that points of intense burning in southern Africa will tend to export fire emissions to both the Atlantic and Indian Ocean regions. Backward trajectories computed for an array of points over the Atlantic have suggested significant influences by burning occurring on the African and South American continents.

(3) These results suggest that research flights off southern Africa to capture outflow from burning regions include sampling along both eastern (Indian Ocean) and western (Atlantic) coasts. Characterization of tropical O_3 maxima west of Africa also requires flights along South America.

(4) There are several caveats regarding the analyses performed to date. The fire data do not cover all of southern Africa on any given day. In addition, the representativeness of the 1989 fire data will not be known until more years are processed. Even after performing a correction of regions of marine stratocumulus clouds, there remains considerable uncertainty in interpreting the TOMS measurements in cloudy and partly cloudy regions. The meteorological fields are uncertain because of the scarcity of observations over Africa and the tropical Atlantic. There is also uncertainty in using the isentropic trajectory technique over tropical Africa where the temperature profile frequently approaches adiabatic and where clouds may produce important diabatic effects. However, the consistency of the transport characteristics over a deep isentropic layer suggests robustness in the results.

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