Final Report

Title of Research Task:

Simulation of Tropical Biomass Burning

Grant number

NCC-2-756

Investigators and Institutions:

Dr. Patrick Hamill and Dr. Zitian Guo
Physics Department
San Jose State University
San Jose, California 95192

The work proposed was carried out as planned. It might be noted that we underwent a personnel change during this time period when Dr. Zitian Guo took over the duties carried out previously by Dr. Long Li. Fortunately, this changeover was carried out smoothly. The work described in this final report formed the basis for a follow-on research grant research grant from NASA Ames Research Center.

The research objectives that were achieved during the course of our studies include the following:

Over the last few years, a model has been developed in the Atmospheric Chemistry and Dynamics Branch at Ames Research Center in collaboration with the Physics Department at San Jose State University. It is referred to as the Global/Regional Atmospheric Chemistry Event Simulator (GRACES). Currently, the GRACES model system combines an atmospheric chemistry and transport model [Chatfield et al., 1996, Toon et al., 1988, Smolarkiewicz, 1984], and a regional mesoscale meteorological model, MM5 [Grell et al., 1995]. Therefore this system is suitable for simulating the conditions observed by the tropical observation missions, such as PEM-Tropics (the Pacific Exploratory Mission in the Tropics, SONEX (Study of Ozone and Nitrogen oxides Experiment), and other periods.

Specifically, the research carried out included the evaluation of the behavior of several components of the MM5 (Meteorological Model 5, version 2) and the GRACES combined modeling system. We initiated research on (a) the ability of the MM5 model to assimilate downward vertical velocities at least as high as the analyses (b) the ability of the Graces model to incorporate the vertical velocities from MM5, and (c) other factors related to transport patterns required to transport CO in the observed manner.

We carried out improved calculations of the transport of tracers for both NASA airborne missions, SONEX and PEM-Tropics.

We also made improved source-strength estimates for isoprene, dust, and similar emissions from the Earth's surface. This required the use of newly available databases on the Earth's surface and vegetation.

We completed atmospheric chemistry simulations of radicals and nitrogen oxide species, following work accomplished by Professor Folkins. We were fortunate to have Professor Folkins spend two periods of time (of several weeks each) working with us on this project.

We have improved the handling of cumulonimbus convection by modifying the existing Georg Grell [1993] Scheme. A newly developed deep convection scheme by Zhang and MacFarlane [1994] has been recognized among the community, and has shown promising improvements of simulating precipitation in the newly released NCAR/CCM3 [Kiehl, 1996, personal communication], which has the relatively coarse 100 km grid scale as our GRACES model.

Previous studies [e.g., Chatfield and Delany 1990, Chatfield et al., 1996] have shown that the convective boundary layers can be as high as a few kilometers during the TRACE-A experiment periods, and could play an important role on transport of the biomass burning plumes into the mid-troposphere. It is also demonstrated that the timing of the deep convective mixing within the boundary layers and the convective cloud is crucial for promoted escape to the free troposphere.

We have identified in clear detail the role of the African Intertropical Front. We will use MM5's nesting capability to refine model resolution in crucial areas, such as where low level convergence of the inflows is strong, as well as where cloud activities is the strongest. This will enhance our understanding of the impacts of various meteorological processes on affecting venting of "Great African Plumes".

In order to provide better weather presentation, we began using MRF planetary boundary layer (PBL) and CCM2 radiative schemes. The hourly averaged, instead of immediate cloud information including cloud base and top, cloud mass flux, cloud down draft heights and down draft strength are now saved for GRACES model. The precipitation efficiency was increased up to 0.9 and cloud down draft is decreased by 10and correspondence with other MM5 development scientists. We applied MM5 with these modification to NASA's PEMT-A and SONEX project. verification of wind fields and radiative cooling shows the MM5 has better performance.

We also modified the MM5 trajectory program to allow it work much better for a parcel crossing the west/east boundaries. We have used MM5 in the Mercator projection with a global wrap. Behavior at the seam is somewhat different, and we have addressed second-order effects on the models accuracy there.

We applied GRACES model to PEMT-A and SONEX projects. In the former, we aided in the modification of periodic boundary conditions. In the latter, we began work evaluating approches to lightning parameterization. The analyses of boundary values showed excessive emissions accumulating on the SONEX boundaries. Following this finding, better results were obtained by corrections to the boundary conditions and integration technique.

Bad inputs provided to MM5 often resulted in crashes of the GRACES's model. A program has been generated to check all the input meteorological variables from MM5 in order to run GRACES more smoothly.

The project involved using various programs and languages such as VIS5D, GRADS and IDL. A moderate amount of work was required to show model results well on a Lambert map projection with the GRADS program. This helped us in understanding our model's behavior.

A simple model has been generated to calculate NOx due to the lightning from MM5 hourly data. In this model, the scheme based on height of cloud top or based on cloud mass flux is used.

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Publications and Presentations

A number of presentations at scientific conferences and at seminars have helped to make our work known to the scientific community.

"Meteorology of the Southern Global Plume: African and South American Fires Pollute the South Pacific" Z. Guo and R.B. Chatfield. Atmospheric Sciences and Applications to Air Quality 6th International conference. Nov. 3-5, 1998 Beijing, CHINA.

"Mechanism of the Southern Global Plume: How tropical burning plumes affect the remote Pacific, R.B. Mechanism of the Southern Global Plume: How tropical burning plumes affect the remote Pacific," Z. Guo, G.W. Sachse, N. Blake, and E. Browell, submitted to J. Geophysical Res., 1998.

APPENDIX

Meteorology of the Southern Global Plume: African and South American Fires Pollute the South Pacific

by
Zitian Guo
and
Robert B. Chatfield

METEOROLOGY OF THE SOUTHERN GLOBAL PLUME: AFRICAN AND SOUTH AMERICAN FIRES POLLUTE THE SOUTH PACIFIC

Z. GUO+*, R. B. CHATFIELD*
+San Jose State University, San Jose CA
*NASA Ames Research Center, Moffett Field CA

Abstract — An immense global plume of CO meanders widely around the world in the Southern Hemisphere. It arises over Southern America and Africa and flows eastward. The first emissions are in tropical Brazil, and the plume circulates around the world to South America again. The plume was largely unexpected until there were aircraft studies made in NASA's Pacific Exploratory Mission - Tropics (Part A). This paper describes the meteorology of the Global Plume, as our simulation, with a synoptic model adapted to global transport, reveals it with a tracer-CO simulation. The observations and their simulation require a particular set of conditions of pollutant accumulation, cumulonimbus venting with required strengths at a narrow range of altitude. Additionally, a particular subtropical conduction region, over the Indian Ocean, Australia, and the westernmost South Pacific, relatively free of storms, appears to be a key part of the mechanism. These conclusions are the results of a synoptic reconstruction of the PEMT-A period, September-October, 1996.

INTRODUCTION

When the Pacific Exploratory Mission Tropics (Part A) - PEMT-A - was planned, it mainly appeared an opportunity to sample the clean atmosphere. Although pollution was known to occur in the Southern Hemisphere, it was presumed to be concentrated mainly in the South Tropical Atlantic and its adjoining continents. There was considerable surprise when the DC-8 aircraft repeatedly discovered plumes of pollution, evidently mostly from biomass burning. For the plumes sampled in the South Pacific, questions immediately arose (i) How typical was the sampling along the chosen DC-8 flight paths? (ii) To what extent were the plumes a feature of just one exotic month during the year, or to what extent did they describe a broader seasonal pattern? Most importantly, of course, came the question: (iii) if these were signals of biomass burning pollution, where did they come from and how did they get to the mid-Pacific? To the extent that the plumes did modify a significant amount of the Pacific large-scale chemistry, there is a fourth question: (iv) what algorithms, parameterizations, and what numerical parameter settings are necessary to represent this global pollution chemistry?

METHODS

MM5 Simulations

The fifth-generation PSU/NCAR mesoscale model (MM5) was used to provide hourly weather conditions for this study. MM5 is a three-dimensional, primitive-equation model with terrain-following sigma coordinates (Grell et al., 1995). The model simulation domain has 37x160 grid points and 23 sigma levels. The nominal grid size is 249 KM and the top layer is 70 hPa. The initial and lateral boundary conditions were interpolated from 2.5 x 2.5 global objective analyses supplied by European Centre for Medium-Range Weather Forecasts (ECMWF). These analyzed fields are also used for four-dimensional data assimilation (FDDA). An analysis-nudging FDDA approach is applied continuously to force the model simulated wind components (u,v), temperature (T) and water vapor mixing ratio (qv) toward grided analyses based on the observations.

The convective parameterization suggested by Grell (Grell, 1993, Grell et al, 1995) is used for the non-resolved convective motion. The information on hourly averaged cloud tops, cloud bases, heights of downdraft levels, strength of downdraft and mass fluxes of clouds is output to a history file.

The GRACES Model

We employed our GRACES (Global Regional Atmospheric Chemistry Event Simulator) model much as described previously in Chatfield et al. (1996) and Chatfield et al. (1998). The record of winds, temperatures, surface pressures, boundary-layer mixing heights, and Grell-scheme parameters from the MM5 history was used to drive the model. GRACES runs on essentially the same grid as MM5; Arakawa B-grid winds from MM5 are simply averaged for use on GRACES Arakawa C-Grid (Arakawa and Lamb, 1977). Cloud fluxes of carbon monoxide are extremely important in explaining CO distributions (Pratt and Falconer, 1979 , Dickerson et al., 1987, Chatfield and Delany, 1990) and correct mass-transport paramaterizations are essential to estimates of the CO budget (Chatfield et al., 1998). Subgrid vertical transport of CO in cumulonimbus clouds is parameterized by using a single upward pipe and a single downward pipe; that is, entrainment of air in core updrafts and downdrafts is ignored (Grell et al., 1995). Our previous experience with the TRACE-A data suggested that this disregard of entrainment, or other causes, may have underestimated vertical transport, although locations of convection appeared to be acceptably forecast. Following Chatfield et al. (1998), then, we multiply the vertical transports in the pipes by a factor of 2.5, and set other (environmental-air) transports to conserve mass. Additionally, we spread the detrainment of material at cloud top over the top three layers, with one half at the cloud-top the Grell scheme provides, one-third in the layer below, and the rest in the next layer down.

Carbon monoxide is treated as a passive tracer without chemical loss or production in the atmosphere. CO is produced by methane in the free atmosphere to a compensation level of somewhere below 40 ppb, and even more is produced within a biomass burning plume with increased levels of methane and other organics. The behavior of our CO tracer in this simulation is therefore of an accumulating tracer whose concentrations are kept bounded by the 50-ppb northern and southern boundary conditions; the boundary conditions and the length of simulation tend to set a reasonable level of non-plume CO

RESULTS AND DISCUSSION

Statistical Comparisons of Observations and Simulation

Figure 1 shows comparisons of the CO observed during the DC-8 flights made in the South Pacific and our simulation of the biomass-burning CO tracer. Histograms present the number of incidences of CO in each of four different layers of the atmosphere. The left column shows the histogram of observed CO along the aircraft flight tracks, as measured by the Sachse NASA Langley group. The right column shows samples from the model along the same flight tracks and the same times, figuratively "flying the plane through the model
results."

Table 1 gives the median, mean and standard deviation of Observed and simulated CO.

Table 1. Mean and Standard Deviation for Observed and model CO

	OBS	MODEL	
median	55.9300	61.8800	
mean	58.7150	62.4520	--> 200-400 hPa
Sdev	11.1260	4.19691	
median	60.3100	62.1500	
mean	69.5730	62.4452	--> 400-600 hPa
Sdev	25.6856	4.00454	
median	60.6700	59.3000	
mean	63.2366	58.8764	--> 600-800 hPa
Sdev	11.1307	5.51434	
median	53.5000	57.8500	
mean	56.4003	57.8709	--> 800-1000 hPa
Sdev	7.27314	4.97084	

It may be seen from the graphic and the table that the DC-8 may have made a reasonably representative sampling of the Equatorial and South Pacific. The mean status of CO are simulated very well. On average, the model CO is a little bit larger than observed CO on upper and lower atmosphere. The larger standard deviation shows the observations having of some relatively smaller scale feature. The model obviously underestimates CO extremes.

Study of a Mid-Tropospheric Plume: Sept. 14, 1996

Trajectory analysis of the origins of the plume. Figure 2(g) shows a map view of the plume obtained from our GRACES run. A wispy trace of the plume can be seen around the 180 line, especially just to the west of the line. The origins of the plume at our kilometers can be traced back by the MM5 trajectory and tracer analyses. That is, In a air-composition-origin techniques, concentration maxima, indicating plumes, may be traced in the CO-tracer field itself.

Using our own MM5- reconstruction trajectory information (3) to find an approximate plume starting point, we will follow our tracer simulation forward in time. Figure 2 shows a set of maps of simulated tracer CO for the 4 km and 7.5 km altitude regions. (These trace the history of material from the South Atlantic - Southern Africa source region to the observational point near the dateline. The top figure, Figure 2a, shows the situation of 12 September, 12 days before the DC-8 intercepted the plume near the 180 line. The 7.5 km map (and a 4 km map, not shown) show a large region of polluted air, in excess of 120 ppb, is sweeping out from the South African Coast, south of Madagascar at 30 E, 35 S. The MM5 back-trajectories over Africa become complex. The maps of 46igure A2a, and similar analyses of previous days sow accumulation of pollutants in the Central African region and a round-the-coast transport process.

Modeling papers (Chatfield and Delany, 1990, Garstang et al. 1996, Chatfield et al., 1996, Jenkins et al., 1997, Chatfield et al., 1998) have described these accumulation patterns: in Africa, the continental accumulation over bring accumulating pollutants fromsouthern, eastern equatorial, and eastern Central Africa into a convergence- divergence region near the western equatorial coast. Continental accumulation and convergence-divergence are points (a) and (b) of our suggested general pattern. This process feeds a Great African Plume, which may in many cases feed CO and pollutants into a large accumulation region south of the Equator in the Atlantic Ocean.

Alternatively, approaching South Atlantic storm patterns may divert pollutants around the Cape of Good Hope toward the Indian Ocean. Two related circulation patterns, one acting both below 5 km (due to boundary layer or non-precipitating convection) and one above 5 km (typically due to venting by tropical convective clouds) seem to be operating in the complex weather leading up to the large plume shown in A2a.. In two of the trajectories shown in Figure 3, air has also passed over tropical South America. The intricacy (and, hence, uncertainty!) of the trajectories suggests that the effect of South America is part of a complex intercontinental accumulation pattern. This illustrates our observation, based on the entire two-months simulation of these general patterns: (c) a tendency toward intercontinental accumulation in the South Atlantic and (d) often, a final injection of highly polluted material as air crossed Southern Africa, with output between 9 and 15 km.

Following our air mass from Figure 2a, to 2b two days later, the 14th , the CO-rich airmass has moved rapidly out to the Central Indian Ocean to about 60 E, much as the trajectories show. Figure 2b shows a large plume migrating rapidly and directly across the Indian Ocean in a westerly jet. Figure 2c, two days later on the 16th, shows a distinct plume maximum crossing west Central Australia, its progress slowed somewhat. By the 18th, Figure 2d, the plume has reached nearly the observation longitude, approximately 170 W, just north of the north tip of New Zealand's main islands. The rapid, direct motion up to this point illustrates our general observations listed in the introduction (e) rapid and undilute, undulating transport and (f) subsidence of the plumes. The subsidence is quite episodic in this example. According to the trajectories shown, the plume then encounters a weather pattern which slows it and redirects it considerably from direct westward progress. Moving northward to 20 S and across the 180 longitude line, isentropic motion takes it downward as seen in Figure 2e (actually below the 4 km level shown). The isentropy of the analysis suggests that the plume was not affected by strong cloud or radiation effects in this looping motion, thus perhaps preserving the concentration of the plume eventually sampled. Note that at this point, CO levels above 80 ppb are still simulated. The cyclonic motion continues, and the plume rises up isentropically to the 170 E region by the 22nd (Figure 2f); finally the plume begins to be cross the dateline again to the position shown in Figure 3. The maps suggest that the simulated plume becomes largely attenuated and broadened in these final four days of complex motion. Apparently the observed plume did not disperse nearly as much. Nevertheless, the motion of the pollutant maximum plumes illustrates the general features of increasing undulation and dispersion within the Pacific Ocean atmosphere.

As we have seen, this study of progress of the pollutant plume from the South Atlantic / Southern Africa pollution source to the observation point illustrates many common features of such southern plumes. There are many variations on the plume behavior which we cannot detail, but our generalizations (a)-(g) seem to characterize many of them. Applying the similar analysis techniques to Sept.6 1997 case, we have found three more pattern: (e) a pattern of undulating but rapid undilute transport across the South Indian Ocean and Australia (f) subsidence of the plumes by both isentropic and diabatic, radiative processes (g) increasing undulation, splintering, and likelihood of dispersion as the plume moves into the Pacific Ocean, affected first by the Southern Pacific Convergence Zone and then by the Andes. Wisps of plumes probably continue to circulate around the globe.

4. CONCLUSIONS

We have illustrated a mechanism that conducts air pollution to the South Pacific from sources predominantly in Central Africa and South America. This we have called the Southern Global Plume. A frequently occurring sequence of events elaborated in the introduction has been illustrated with two case studies. We are unable to discuss our entire simulation or each plume sampled in the PEM Tropics A experiment. Our general impression is similar to the case studies, with some variation noted below. We find (a) a pattern of continental accumulation, (b) characteristic convergence and divergence associated with each continent associated with cumulonimbus convection, (c) a tendency toward intercontinental and plume merging near the source region, with (d) often a final pollutant injection by cloud convection over Southern Africa. Quite frequently, there is (e) a pattern of undulating but rapid undilute transport across the South Indian Ocean and Australia, (f) subsidence of the plumes by both isentropic and diabatic, radiative processes, especially below 9 km. Finally, there is (g) increasing undulation, splintering, and likelihood of dispersion in the Pacific. We found in our simulation also isolated incidences of two other pollution patterns. Some low-lying plumes below 4 km seemed to trace back to nearby Australia. Additionally, there were instances in which plumes from Southeast Asia would drift westward across the Indian Ocean, perhaps reaching Africa. They would then recurve and join the general pollutant flow. Broad et al. (1998) describe this source region more fully, and find instances of trajectories recurving as far east as the region south of the Bay of Bengal. Though the illustrated trajectories do not show this, our trajectories tend to have more daily alteration in course than do the Broad et al. trajectories, since they are based on assimilated hourly wind data.

We can make some tentative suggestions about the simulation of the Southern Global Plume. We suspect that the weak variation of CO-tracer in our model was due to several causes that may be improved in more complex models. First, we expect that the grid resolution over the source regions of Africa and South America was too coarse. Vented pollution never made as concentrated plumes as should occur naturally. This would explain some differences of these results and those of Chatfield et al. (1998). Convective parameterizations more appropriate to the large grid resolution may also help. We expect all such parameterizations will need careful checking with tracer simulations; CO seems to provide a very good test.

Two other effects are more complex, and are connected. The conduction mechanism and the degree of subsidence experienced by the plumes seem to be governed by two major variables: the primary venting altitudes of cumulonimbus- borne material (8-10 km appears optimal) and the degree of radiative cooling that is simulated by the dynamical model. It is conceivable that the CCM-2 radiation as we employed it within MM5 did not provide sufficient radiative cooling. This could be due to our lack of feedback of the plume composition to MM5, or it could be a more general feature of the radiative cooling algorithm as we employed it. If this is the case, we venture that proper treatment of the whole vertical profile of radiative cooling as well as the profile of cumulonimbus detrainment must be carefully simulated to obtain good tracer distributions in remote regions. This imposes a high standard of accuracy on large regional and global atmospheric chemistry transport models!

Acknowledgments--This model development and analysis was supported by Jack Kaye under NASA Research Program 579-24-13-10, and a cooperative agreement between SJSU and NASA Ames, NCC-2-756. We appreciate the programming support of Robert Esswein, Long Li and Yvonne Chen, and the use of the National Aerodynamic Simulator and National Center for Atmospheric Research computers for portions of this work. Donald Blake and Nicola Blake of the University of California, Irvine provided hydrocarbon sample analysis for PEM-Tropics A, and the Edward Browell's DIAL Lidar group of NASA Langley contributed their ozone analyses.

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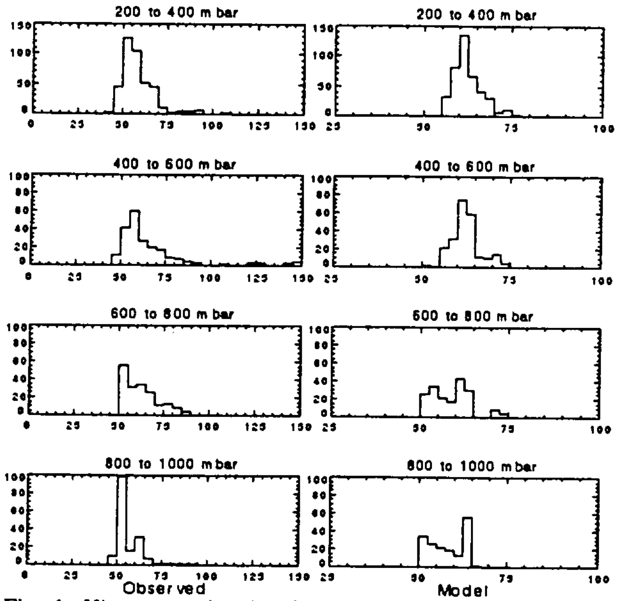

Fig. 1. Histograms showing the relative frequency of occurrence of carbon monoxide in the South Pacific. Histograms are shown for four altitude layers, each essentially representing one quarter of the tropospheric mass below 12 km. The sampling area is indicated, from 155 E near New Zealand to 100 W, including Easter Island. (a) CO, ppb, sampled along the DC-8 flight tracks made in the area, as measured by the Sachse DACOM (Differential Absorption of Carbon Monoxide) instrument on board. (b) CO tracer from our model, as sampled along the same DC-8 flight track. Note different scale.

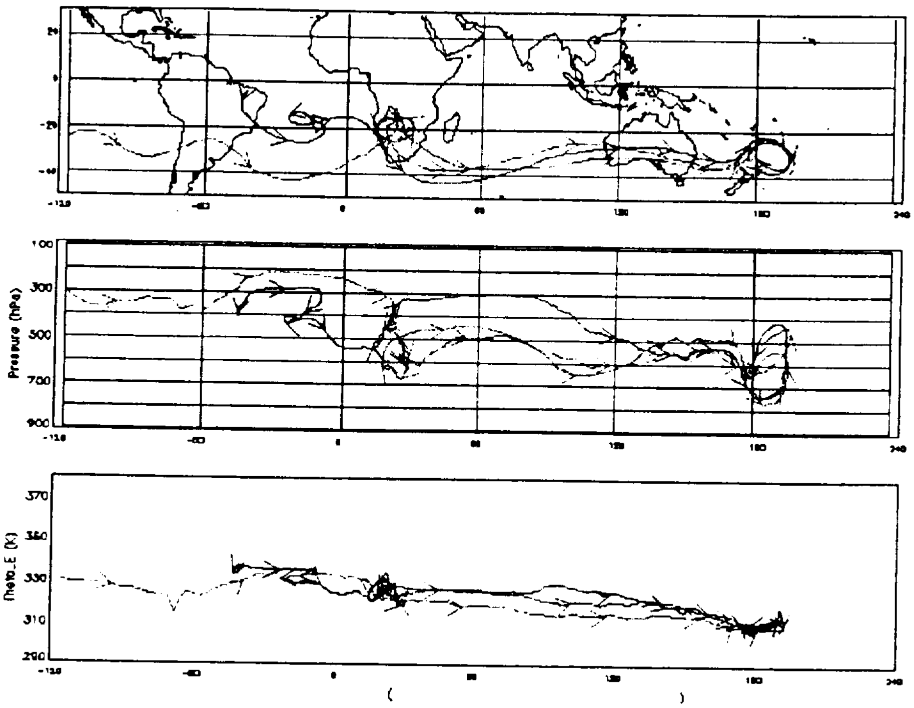

Fig. 3. Back trajectories from several points along and near the region of DC-8 decent of September 23-24, 1996. Top panel maps trace back to source regions over southern Central Africa and Brazil. Middle panel shows altitude in pressure units (hPa). Arrows are plotted showing instantaneous direction every 2 days backward from the final sampling point, e.g, at Sept. 6, Sept. 4, Sept 2., etc. In (a) and (b), regions of trajectory looping and hesitation are those most typical of a larger selection of trajectories not shown: the South Atlantic, over Central Africa, and then again in the Pacific east of New Zealand (c) Pattern of change of θ_e, equivalent potential temperature, in K. Near-conservation of θ_e, suggests that the trajectory is believable, not crossing into other air masses

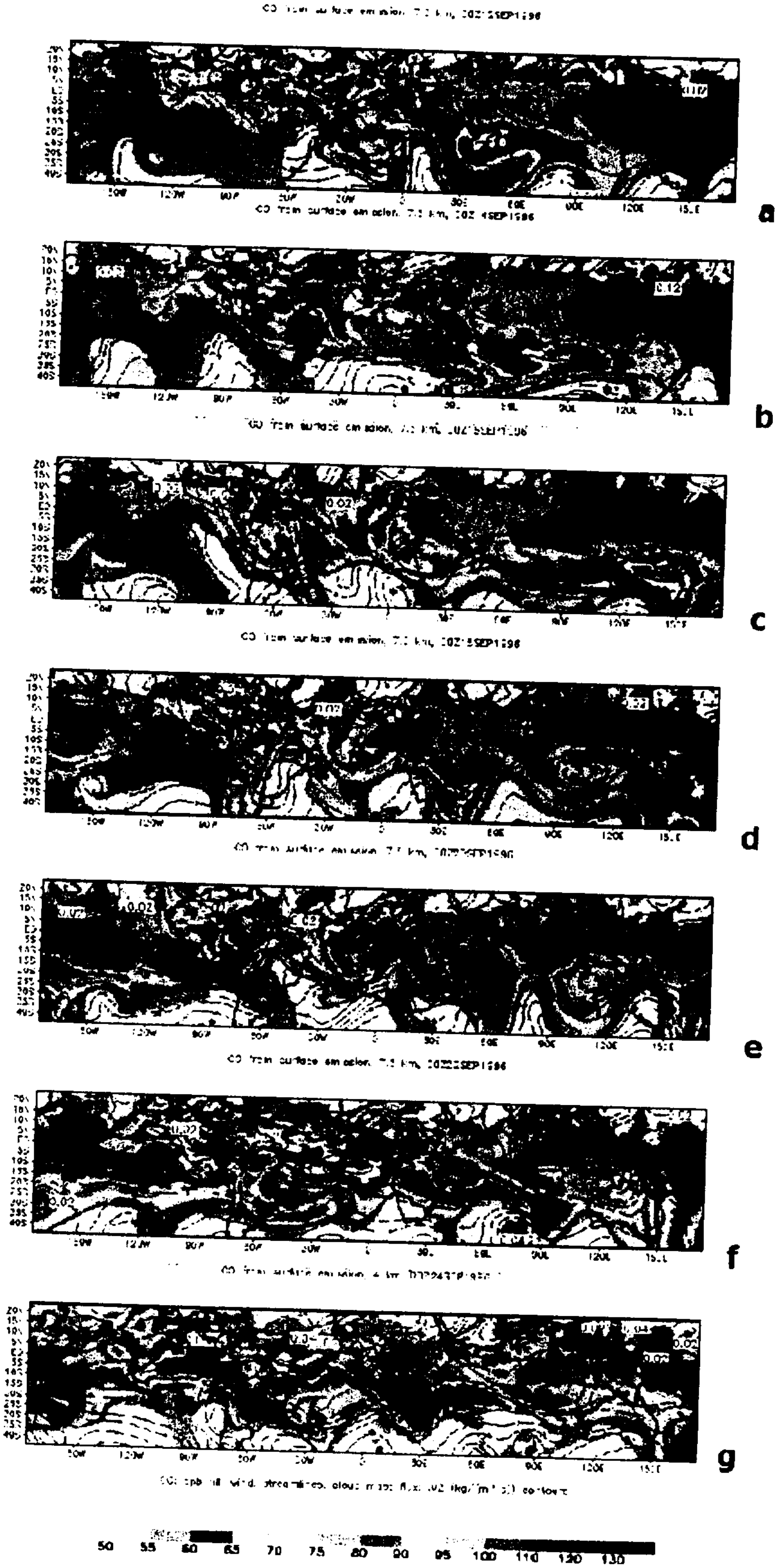

Fig. 2. Sequence of maps showing the development and propagation of the Southern Global Plume (a) Sept. 12, 00 UT, 7.5 km. (b) Sept. 14, 00 UT, 7.5 km (c) Sept. 16, 00 UT, 7.5 km, (d) Sept. 18, 00 UT, 7.5 km (e) Sept. 20, 00 UT, 4 km, , (f) Sept 22, 00 UT, 4 km. (g) The final position sampled by the DC-8 aircraft on September 24 near the 180 meridian. See text and Figure 2 to follow progress of main contributors to the plume.