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THREE DIMENSIONAL MODEL CALCULATIONS OF THE GLOBAL DISPERSION OF HIGH SPEED AIRCRAFT EXHAUST AND IMPLICATIONS FOR STRATOSPHERIC OZONE LOSS

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ABSTRACT

Two-dimensional (zonally averaged) photochemical models are commonly used for calculations of ozone changes due to various perturbations. These include calculating the ozone change expected as a result of changes in the lower stratospheric composition due to the exhaust of a fleet of supersonic aircraft flying in the lower stratosphere. However, zonal asymmetries are anticipated to be important to this sort of calculation. The aircraft are expected to be restricted from flying over land at supersonic speed due to sonic booms, thus the pollutant source will not be zonally symmetric. There is loss of pollutant through stratosphere/troposphere exchange, but these processes are spatially and temporally inhomogeneous. Asymmetry in the pollutant distribution contributes to the uncertainty in the ozone changes calculated with two dimensional models.

Pollutant distributions for integrations of at least 1 year of continuous pollutant emissions along flight corridors are calculated using a three dimensional chemistry and transport model. These distributions indicate the importance of asymmetry in the pollutant distributions to evaluation of the impact of stratospheric aircraft on ozone. The implications of such pollutant asymmetries to assessment calculations are discussed, considering both homogeneous and heterogeneous reactions.

1. INTRODUCTION

Questions concerning the environmental impact of a fleet of supersonic aircraft operating in the lower stratosphere were first considered in the early 1970's (Johnston et al., 1989; Douglass et al., 1991 and references therein). Since then, there have been advances in engineering which may make it possible to develop aircraft engines which are ten times less polluting than engines which are currently available. There have also been improvements in the ability to model stratospheric transport which make it possible to determine the likely distribution and lifetime of aircraft exhaust pollutants. Improvements in the representation of photochemical processes in the lower stratosphere, validated by comparisons with aircraft, satellite, balloon and sonde measurements, make it possible to calculate the likely impact of the pollutants on stratospheric ozone.

Currently, evaluations of the ozone changes due to aircraft exhaust are made using two dimensional (2D) models. There are uncertainties in these model evaluations due to the parameterized transport of 2D models. In particular, stratosphere/troposphere (strat/trop) exchange, which is crucial to determining the pollutant lifetime in the lower stratosphere, is poorly represented in 2D models. There are also uncertainties which arise from the three dimensional nature of the pollutant source. Aircraft are expected to fly at supersonic speeds only over the oceans as sonic booms are not permitted over land. Thus the pollutant source is restricted to oceanic corridors. During northern hemisphere winter, there are quasi-stationary features (e.g., the Aleutian anticyclone) which may lead to pollutant concentrations in the corridor which substantially exceed the perturbation to the zonal mean. The importance of these uncertainties to 2D assessments of the impact of aircraft exhaust on stratospheric ozone is considered using a three dimensional (3D) model.

2. MODEL AND EXPERIMENT DESCRIPTION

Tracer experiments are carried out using the NASA/Goddard three dimensional chemistry and transport model (3DCTM). The tracer is injected in the model continuously in specified corridors; the tracer evolution is calculated using winds from the surface to 0.4 mb taken from the STRATAN data assimilation procedure (Rood et al., 1991). In the assimilation procedure (Baker et al., 1989) data are inserted at regular intervals into a general circulation model. The data are combined with model fields using an optimal interpolation analysis; the analysis fields become the initialization for a six hour integration. At the end of six hours, the model fields are the first guess for the optimal interpolation procedure as new data are inserted into the model. Simulations for species such as ozone calculated using these wind fields may be compared with satellite, aircraft, and sonde measurements (Rood et al., 1991). Comparisons of model fields with measurements indicate that the calculated ozone fields represent the synoptic and planetary scale features evident in the satellite fields. In particular, total ozone measurements suggest that the model faithfully represents the upper tropospheric disturbances which contribute to strat/trop exchange.

At this time, the 3DCTM does not provide a quantitative estimate of strat/trop exchange. On longer time scales, the ozone experiments deviate from measurements and indicate that the residual circulation associated with the assimilated wind fields is too strong. As a result of the continual data insertion in the assimilation procedure, the expected thermodynamic balance between the horizontal eddy heat flux convergence and the vertical heat transport is never achieved (Weaver et al., 1992), leading to excessively strong upwelling in the tropics and downward motion in midlatitudes. However, the good representation of synoptic and planetary scale events indicates that these model simulations may be useful in developing a qualitative picture of strat/trop exchange, and in examining horizontal transport and mixing.

The experiments here consider a passive tracer inserted continuously on great circle paths for three proposed aircraft routes: North Atlantic (Boston-London (BLO)); North Pacific (Los Angeles - Tokyo (TLA)), and Tropical (Los Angeles - Sydney (LAS)). Simulations were considered using STRATAN for Jan - Mar, 1989. STRATAN winds are not available for a full year, but assimilation wind fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) analyses were available up to 10 mb. Since the ECMWF wind fields do not have the vertical range necessary to repeat the ozone experiments, the LAS calculation was repeated using ECMWF winds for transport to compare the two analyses. These two simulations showed remarkable agreement. Year long integrations were completed using ECMWF fields for each of the three corridors beginning October 1986.

3. RESULTS

a. Stratosphere/Troposphere Exchange

A qualitative picture of strat/trop exchange is produced by noting the correlation between areas of high tracer concentration at levels below the injection level and areas of low geopotential height on the 500 mb surface. An example of the tracer concentration at 250 mb for TLA is given in Figure 1(a); the 500 mb geopotential height is given in Figure 1(b). The high values of tracer are correlated with low values of 500 mb geopotential height. Comparison with Total Ozone Mapping Spectrometer (TOMS) data for the same period indicate that these highs in tracer are also correlated with highs in total ozone. This behavior is found for all tracer experiments, indicating that transport to the troposphere is associated with upper tropospheric synoptic scale features, and occurs primarily at middle latitudes (30°-60°).

The importance of this result is made clear by examining the time series of the fraction of the total pollutant mass which is found between the surface and the 250 mb pressure level for each of the three corridors (Figure 2). Transport to the troposphere is nearly equivalent for the two mid-latitude corridors and for the tropical corridor. For the tropical corridor, this transport is mainly associated with synoptic scale events poleward of the subtropical jets; the tropical troposphere remains largely tracer free.

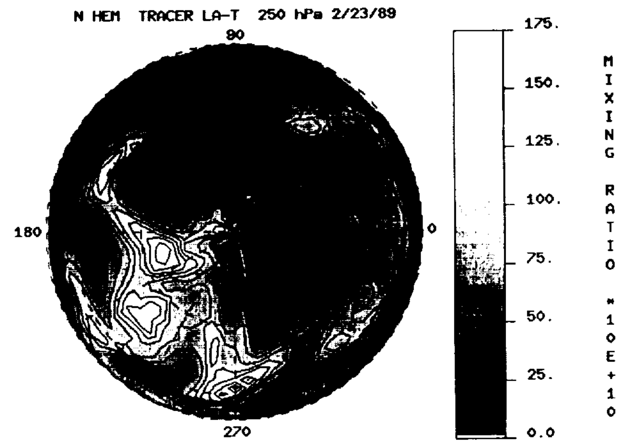

Fig. 1(a): The tracer mixing ratio at 250 mb (LA-T corridor) shows high values between 150°E and 180°E and near 270°E.

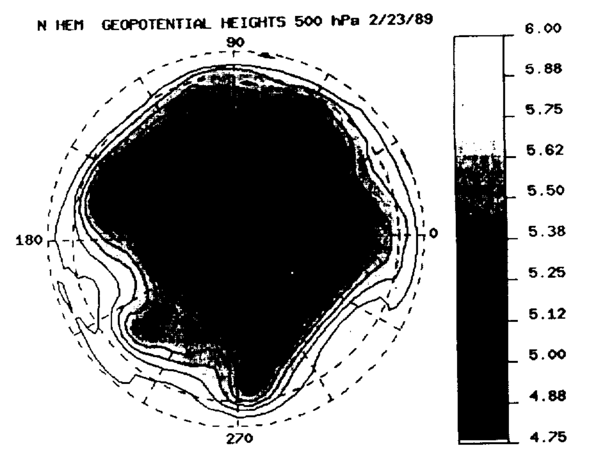

Fig. 1(b): The 500 mb geopotential height show troughs associated with the high tracer values at 250 mb in Fig. 1(a).

The common time for strat/trop exchange for these corridors stands in sharp contrast to the 2D transport to the troposphere using the NASA/Goddard 2D model (Douglass et al., 1989) for a tropical source (30°S-30°N) compared to the 2D transport for a midlatitude source (40°N-50°N). The difference is emphasized by comparing the time series of the ratio of the fraction of pollutant in the troposphere for a midlatitude source to the fraction in the troposphere for a tropical source (Figure 3). The transport is much more rapid for the midlatitude source. In the 2D model, diffusive transport to the troposphere is independent of latitude, and advective transport takes place at mid to high latitudes (poleward of 40°). The tropical tracer must undergo significant horizontal transport before it can reach the troposphere. The maximum pollutant level for a tropical tracer is substantially higher for a 2D calculation than for a 3D calculation. The transport to the troposphere for a flight path in midlatitudes where most of the synoptic scale events associated with strat/trop exchange occur may also be underestimated by a 2D calculation.

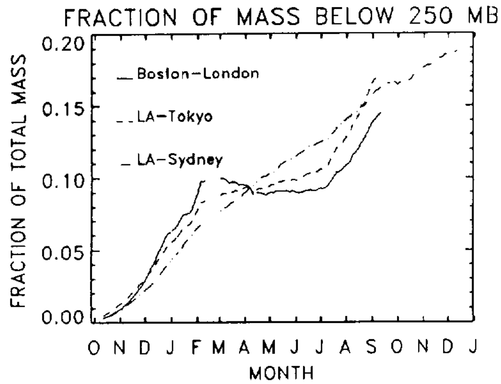

Fig. 2: The time series of the fraction of the total mass below 250 mb for tracer calculations for the 3 corridors shows no difference in the mass transported to the troposphere for a midlatitude or tropical route.

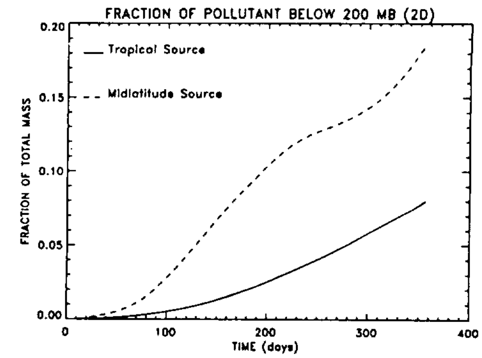

Fig. 3: The time series of the fraction of the total mass below 250 mb for tracer calculations using the NASA/GSFC 2D model shows transport to the troposphere is more rapid for a midlatitude injection than for a tropical injection.

b. The corridor effect

Time series are given in Figure 4(a,b,c); the tracer maximum and minimum are indicated by solid lines; the zonal mean bounded by the standard deviation is indicated by the shaded areas for each of the 3 corridors. Generally, the maximum value for the midlatitude corridors exceeds the zonal mean by a factor of 2-4 in winter and a factor of 5-7 in summer. In the tropics, the zonal asymmetry is pronounced during the westerly phase of the quasi-biennial oscillation (QBO), and drops dramatically during the easterly phase. Studies with SAGE aerosols (Trepte and Hitchman, 1991) show that transport from the tropics to middle latitude occurs more during the westerly phase of the QBO than the easterly phase.

For all 3 corridors, because the tracer maximum is so much larger than the zonal mean, and the lower stratospheric turnover time is on the order of a few years at most, the zonal mean pollutant value will never be as large as the maxima. There will always be significant asymmetries and clearly defined corridors in experiments such as these. However, it should be noted that the tracer distribution for a combination of flight paths, such as Boston-London and LA-Tokyo, is more symmetric than that calculated for a single corridor. This indicates the importance of a good estimate of the probable city pairs and flight frequency to the assessment calculations.

4. DISCUSSION

The placement of strat/trop exchange in middle latitudes (30°-60°) by the 3D model through synoptic scale events contrasts with the mid to high latitude poleward of 40°) placement of strat/trop exchange by the 2D model through latitude independent diffusion and mid to high latitude advection. This model result suggests that two dimensional models may underestimate the rate of return to the troposphere for tropical and midlatitude pollutant sources, leading to higher estimated pollutant values than would be realized. Conversely, they may overestimate the rate of return for a high latitude source. This result must be reconciled with results of 2D calculations of the behavior of measured tracers such as excess ^{14}C produced by atmospheric tests of nuclear weapons during the 1950's and 1960's; these calculations suggest that the return to the troposphere in 2D models is too rapid (Jackman et al., 1991). It is possible that the 2D models overestimate the rate of transport of ^{14}C to the troposphere because the most of the nuclear explosions which produced excess ^{14}C took place poleward of 60°N.

The corridor experiments indicate that pollutant levels in flight corridors may exceed the zonal mean perturbation by factors of 3-5 or more. For gas phase photochemistry, the loss of ozone is nearly a linear function of odd nitrogen, and zonal asymmetry in the perturbation would not impact the zonal average of the impact on ozone. However, the heterogeneous reaction of N_2O_5 with H_2O on background sulfate aerosols to produce HNO_3 has recently been found to be important to the lower stratosphere. This reaction would convert the odd nitrogen in the aircraft exhaust to the reservoir HNO_3, and drastically reduce the impact of aircraft exhaust on the ozone layer (Weisenstein et al., 1991). However, in the corridor, this could lead to a very large increase in HNO_3 and H_2O, and a significant increase in the formation temperature for nitric acid trihydrate clouds (NAT). Heterogeneous reactions on the surfaces of these cloud particles involving chlorine reservoirs have been shown to be responsible for large scale ozone depletion in the Antarctic winter. The possibility of cloud formation within flight corridors and the importance of concurrent heterogeneous reactions involving chlorine species to assessment calculations is under consideration (Considine et al., 1992). Preliminary results indicate that there would be a substantial increase in the probability of NAT formation, particularly near the edge of the north polar vortex.

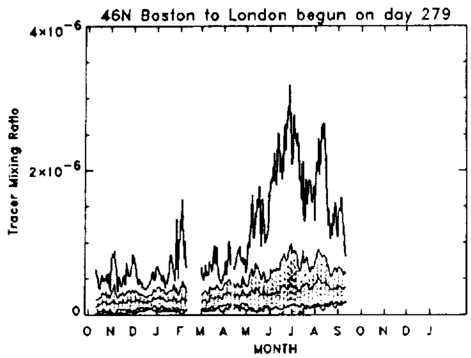

Fig. 4 (a): The maximum tracer value for the Boston-London corridor (bold line) is substantially larger than the zonal mean ± sigma (shaded area).

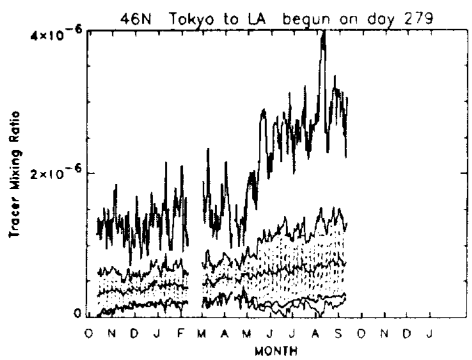

Fig. 4 (b): Same as (a) but for Los Angeles - Tokyo corridor

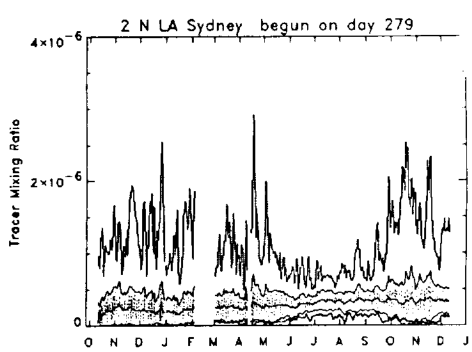

Fig. 4 (c): Same as (a) but for Los Angeles - Sydney. The period of near zonal symmetry during the summer and fall corresponds to the easterly phase of the QBO.

5. SUMMARY

The transport in 2D models may affect assessments of the impact of aircraft exhaust on stratospheric ozone. The 3D calculations indicate the importance of mid-latitude synoptic scale events to strat/trop exchange. The rate for return of tracer to the troposphere is comparable for a tropical and midlatitude corridor. In contrast, 2D model results indicate a longer perturbation lifetime for a tropical tracer source compared to a midlatitude source.

The results for three flight corridors show that substantial buildup of tracer compared to the zonal mean is possible. Such a buildup is important if non-linear chemical processes are important. In particular, it is possible that NAT clouds could form sporadically in the corridors, which could produce substantial ozone loss for current levels of inorganic chlorine and bromine.

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