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Mechanisms of ozone enhancement during stratospheric intrusion coupled with convection over upper troposphere equatorial Africa

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HIGHLIGHTS

- ► Ozone enhancement over upper troposphere equatorial Africa is investigated.
- ► Planetary waves are responsible for ozone enhancements over equatorial Africa.
- ► The MTM–SVD method reveals how planetary waves modulate stratospheric PV intrusion.
- ► Coupling of PV intrusion and deep convection during ozone enhancement is confirmed.
- ► PV and wind anomalies during a particular cycle of the wave govern ozone variation.

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ABSTRACT

The possible cause and sources of enhanced ozone at upper tropospheric equatorial Africa, observed by cruise Measurements of OZone by Airbus In Service Aircraft (MOZAIC) during the Northern Hemisphere winter in 1996 and 1997 on flight routes from Johannesburg to Vienna, are investigated. Two enhanced ozone events over upper tropospheric equatorial Africa are identified from MOZAIC observations on April 6, 1996 and March 27, 1997. High resolution ECMWF reanalysis GOME ozone has exhibited enhancement as well during these periods suggesting that the two events are not isolated small scale events but part of a larger scale process. As a result, the source and mechanisms of ozone increase over the region are further analysed using reanalysis data from ECMWF, outgoing long wave radiation (OLR) from NOAA and Meteosat images from NASA, International Satellite Cloud Climatology Project. Equivalent latitude computed from potential vorticity has shown that massive mid- and high-latitude stratospheric ozone rich airmass is funnelled into lower latitude troposphere through troughs extending from large amplitude planetary waves towards equator. The Space-time Fourier decomposition of meridionally averaged zonal wind has revealed that these planetary wave activities are linked to waves with zonal wavenumber 1–2, which prevail during Northern Hemisphere winter. Additional analysis to understand the mechanisms of ozone enhancement was made using Multitaper Method–Singular Value Decomposition (MTM–SVD) spectral approach. The analysis confirms that ozone enhancement over the region is dependent on the relative position of positive PV and direction of wind anomalies. The high relative humidity measured simultaneously with ozone onboard MOZAIC, Meteosat imageries and circulation during the events have shown presence of deep convection. The coherent variation of OLR and ozone found over 8-day temporal cycle determined from MTM–SVD has indicated existence of OLR negative forcing in the upper troposphere and positive forcing in the lower stratosphere. These results show coupling of PV intrusion and deep convection over continental equatorial Africa in the same manner as the climatologically preferred intrusion over mid-ocean in eastern pacific. Moreover, the results enrich previous understanding with purely observational high resolution MOZAIC and ERA-Interim datasets, and statistical method.

1. Introduction

Various studies have shown that there are different mechanisms for ozone enhancements. Winterrath et al. (1999) have concluded from simultaneous measurement of O_3 and NO_2 in clouds and model studies that three mechanisms are likely to account for O_3

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and NO_2 enhancements: convective transport from the boundary layer, stratospheric intrusion, and discharge induced production. Regener (1957), Junge (1962) and Winterrath et al. (1999) considered the stratosphere to be the main source from which ozone enters the troposphere via tropopause exchange processes. Ozone is usually transported from the lower stratosphere into the upper troposphere through tropopause folding (Danielsen, 1968; Danielsen et al., 1987) and is exchanged with the troposphere via diabatic processes and turbulent diffusion (Lamarque and Hess, 1994), as well as mixing processes and convective erosion during the breakup of stratospheric filaments (Appenzeller et al., 1996; Gouget et al., 2000). Though stratosphere–troposphere exchange is limited by the large potential vorticity jump (>1 PVU; 1 PVU = 10^{-6} K kg^{-1} m^2 s^{-1}) associated with the subtropical jet, synoptic scale instabilities in the upper troposphere can induce transport across the tropopause (Chen, 1995). Experimental evidence already exists of a two-way exchange, using e.g. the water vapor distribution in the lowermost stratosphere (Dessler et al., 1995) or ozone mixing ratios from aircraft observations (Folkins and Appenzeller, 1996).

The details of how tropospheric air enters the stratosphere in the tropics and the scales involved are still the focus of several observational and model studies (e.g. Folkins and Martin, 2005). The extreme dryness of the stratosphere and the fact that the most convective cells extend only to the level of maximum outflow of the Hadley cell at about 200 hPa or at most below 140 hPa in the case of cumulonimbus cloud tops, which are well below the tropical tropopause near 100 hPa and the coldest point in tropical temperature profiles at about 80 hPa (Highwood and Hoskins, 1998), indicate that convective overshooting is unlikely to be plausible pathways. Thus, the proposition that air enters the stratosphere primarily by slow ascent through stratospheric fountain regions and only during specific seasons of the year appears to gain weight. However, the entry of air into the stratosphere in fountain regions has been questioned (Dessler, 1998), and later it became clear that air can enter the stratosphere throughout the year. Michelsen et al. (2000) and Zhou et al. (2001), on the other hand, argue against slow and continuous entry mechanism. Moreover, according to Selkirk (1993), the slow ascent associated with the stratospheric fountain would likely cause large cirrus sheets in the tropics which are not visible. This hypothesis is now partly questionable due to detection of large subvisible cirrus clouds (McFarquhar et al., 2000). Also, several studies, (e.g., Gettelman et al. (2000)), indicate that there is net subsidence at the tropopause in the stratospheric fountain region, not ascent.

As a result, there are several alternative hypotheses of stratospheric dehydration (e.g. Danielsen, 1982; Potter and Holton, 1995; Holton et al., 1995; Holton and Gettelman, 2001) ranging from radiatively triggered turbulence in cirrus anvils of the highest and the coldest cumulonimbus clouds to gravity waves that triger the formation of clouds in the stratosphere. However, Highwood and Hoskins (1998) favour the picture of a transition zone between the top of the convective outflow of the Hadley cell, and the stratospheric Brewer–Dobson circulation above the cold point, over a single tropopause surface. In this transition zone, substantial exchange with air from the extratropics can occur, further complicating the picture. The exact nature of the transfer of air through the transition zone, however, is still another unsettled research topic.

Others have also suggested the importance of large scale dynamical systems in the enhancement of tropospheric ozone. For instance, breaking Kelvin waves (Fujiwara et al., 1998), or tropical cyclones (Baray et al., 1999) could episodically transport airmass across the tropical tropopause from stratosphere to the troposphere. Baray et al. (2003) have also found regional scale circulation patterns such as cut-off lows that can play significant role in ozone enhancement in tropical troposphere. Specifically, they have shown that tropical cut-off low over Southern Africa can be detached from stratospheric reservoir both horizontally and vertically in an irreversible manner thereby leading to O_3 enhancements in the troposphere. Furthermore, Rossby wave breaking at the subtropical tropopause in the vicinity of the subtropical jet stream can transport stratospheric air into the tropical upper and middle troposphere (Zachariasse et al., 2001).

Stratospheric air intrudes into the tropics preferably in the westerly ducts (Waugh and Polvani, 2000) and can trigger convection there. Studies confirm that enhanced ozone is introduced into troposphere during thunderstorm events. For instance, significant positive correlation between lightning frequency and tropospheric column ozone has been established from climatology of the two observations (e.g. Ryu and Jenkins, 2005). Moreover, recent studies on O_3 enhancement over Equatorial Southern Indian Ocean by Zhang et al. (2012) have shown that upto 62% O_3 tropospheric column could come from O_3 production driven by lightning NO_x emissions. Convection could also be responsible for low level O_3 at upper troposphere due to transport by downdrafts from the upper troposphere as Hu et al. (2010) confirmed from model studies and field observations over West Africa. Moreover, past measurements of O_3 in clouds have indicated that both production and loss mechanisms exist. For example, Dickerson et al. (1987) measured higher O_3 mixing ratios inside a cloud than in the boundary layer while Stenchikov et al. (1996) found higher O_3 near than within a thunderstorm anvil, both of which have attributed this effect to intrusion of stratospheric air. Similar measurements by Ridley et al. (1994), and Highwood and Hoskins (1998) also showed no systematic increase of in-cloud O_3 concentrations.

Funatsu and Waugh (2008) have studied coupling of PV intrusion and deep convection over subtropical eastern pacific based on model and observation. They have proposed plausible mechanism on the coupling of PV intrusion and deep convection. The potential application of their concept for stratosphere–troposphere exchange and the composition of subtropical upper troposphere is very important. Although transport of high ozone, low water vapour stratospheric air into subtropical middle-upper troposphere (e.g. Scott et al., 2001; Waugh and Funatsu, 2003; Cooper et al., 2005) and transport of low ozone, high water vapour into the upper troposphere by convection (Waugh, 2005) have been reported from model and coarse resolution satellite observations, these processes have not yet confirmed by in-situ high resolution measurements. Moreover, the net impact of these processes on ozone distribution over equatorial tropics is not yet known.

The main objective of this work is to investigate whether the enhanced ozone over upper tropospheric equatorial Africa from MOZAIC and ERA-Interim observations can be explained by PV intrusions accompanied by deep convections, as well as to understand the mechanisms involved at different times during sequences of temporal cycle at which coherent variations of variables characterizing PV, deep convection and ozone are expected. The rest of the paper is organized such that descriptions of data sets and methodologies are given in Section 2; results and discussion are presented in Section 3 whereas conclusions are given in Section 4.

2. Data and methodology

2.1. Data

Measurements of ozone in the MOZAIC programme are taken every four seconds from take-off to landing. Based on the dual-beam UV absorption principle (Model 49-103 from Thermo Environment Instruments, USA), the ozone measurement accuracy is