JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. D22, PAGES 28,441-28,452, NOVEMBER 27, 2001

Cross-tropopause and interhemispheric transports into the tropical free troposphere over the Indian Ocean

M. Zachariasse[1], H. G. J. Smit[2], P. F. J. van Velthoven[1], and H. Kelder[1,3]

Abstract. Ozone (O_3) and relative humidity (RH) profiles over the Indian Ocean, obtained during the 1999 Indian Ocean Experiment, were analyzed. Upper-tropospheric O_3 mixing ratios were generally very high (varying from 100 ppbv up to 150 ppbv at the (upper) tropopause). Maxima were observed as laminae (between 14-16 km) and as O_3-rich layers between the chemopause in O_3 and the tropopause (between 15-18 km), resembling a transition zone between tropospheric and stratospheric O_3 mixing ratios. Very dry, high O_3 air is observed in the midtroposphere (between 5-8 km). The 1999 laminae are similar to those observed in 1998 in a pre-INDOEX campaign, although they appear older. This complicates the attribution of an origin but there are indications, i.e., by back trajectory analyses, that the air in all these O_3 maxima originates in the subtropical jet stream (STJ). This is a favored region for stratosphere-troposphere exchange (STE). A new feature is that the transition zone is supplied with air from both the northern and the southern STJ. A pair of anticyclones located over the western Pacific/Australia directs this interhemispheric transport (IHT). IHT also occurs in the midtroposphere where a flow channel along the east coast of Africa connects the upper troposphere of both hemispheres. Although our analysis, involving the ozone profiles, trajectories, and ECMWF model data, supports the idea that all O_3 maxima have sources similar to 1998, the upper-tropospheric flow is anomalously easterly in 1999. This is probably associated with the La Nina phase of the tropospheric quasi-biennial oscillation as opposed to the 1998 El Niño. Thus, although climatological conditions are very different, the tropospheric O_3 budget over the Indian Ocean during the winter monsoon is still largely influenced by stratospheric intrusions.

1. Introduction

O_3, relative humidity (RH), temperature and wind profiles were measured over the Indian Ocean during the 1999 winter monsoon (February-March) as part of the Indian Ocean Experiment (INDOEX). INDOEX is a major international field experiment, primarily designed to investigate the role of natural and anthropogenic aerosols in the global energy balance [*Coakley et al.*, 2001]. INDOEX also provided an opportunity to collect information on O_3 and water vapor concentrations in the data-sparse tropics, one of the Earth's regions most influenced by convection.

Pre-INDOEX campaigns in 1998 and 1995 have shown large O_3 variability over the Indian Ocean in the winter monsoon season [*Zachariasse et al*, 2000; *de Laat et al.*, 1999]. Close to India ozone concentrations are enhanced due to pollution. Once in the marine boundary layer (MBL), O_3 concentrations drop due to efficient O_3 destruction. These O_3-poor air masses were sometimes lifted to the upper troposphere by convection. In 1998, O_3 maxima were often found in the middle and upper troposphere, the latter shaped as shallow layers (1-2 km), called laminae, with very high mixing ratios (up to 120 ppbv). Upper-tropospheric O_3-rich transients were also found over the Atlantic [*Suhre et al.*, 1997], related to convective activity. Suhre et al. have not been able to attribute a definite mechanism but they offer three possibilities of creating high ozone levels: cloud charging processes, extratropical baroclinic wave breaking extending into the tropics, and STE connected to overshooting convection and entrainment into the anvil outflow. Our analyses showed strong indications that the O_3 maxima originated from the stratosphere, with the subtropical jet stream (STJ) playing a central role in the exchange mechanism. We hypothesized that stratosphere-troposphere exchange (STE) near the STJ by either shear-induced differential advection (filament stripping from the SJT) or clear-air turbulence (CAT), resulting from vertical wind shear instabilities, caused the midtropospheric maxima (STE followed by descent) and the upper tropospheric laminae. These stratospheric intrusions were even found deep within the tropics. Similar filament stripping has also been observed near the polar vortex [*Tuck et al.*, 1997], resulting in elongated layers extending over thousands of kilometers.

[1]Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands.
[2]Institute for Chemistry of the Polluted Atmosphere (ICG-2), Research Centre Jülich, Jülich, Germany.
[3]Department of Applied Physics, University of Eindhoven, Eindhoven, The Netherlands.

Paper number 2001JD900061.
0148-0227/01/2001JD900061$09.00

The purpose of this paper is to perform the same analyses as in 1998 and to investigate how differences in climatological conditions, such as La Nina (1999) versus El Niño (1998) and the different phases of the QBO, affect the O_3 profiles (especially the laminae). We will concentrate on the mid and upper troposphere. The lower troposphere will be described by H. G. J. Smit et al. [manuscript in preparation, 2001]. An elaborate description of the meteorological conditions during INDOEX is given by *Verver et al.* [this issue].

Since O_3 changes are most effective in forcing climate change when they occur in the upper troposphere/lower stratosphere region [*Lacis et al.*, 1990], it is important to carefully document O_3 behavior in those regions. A previous study by *Tuck et al.* [1997] showed that the tropical upper troposphere often contained midlatitude stratospheric air masses resulting from isentropic transport. Other research on upper-tropospheric O_3 concentrations in the tropics are, for example, studies by *Newell et al.* [1996, 1999], *Browell et al.* [1996], *Wu et al.* [1997], and *Fenn et al.* [1999]. *Folkins et al.* [1999] found that O_3 mixing ratios usually start increasing toward stratospheric values already a few kilometers below the tropopause. According to Folkins et al. this is mainly due to slow upward ascent in this so-called transition zone, associated with radiative warming, together with in situ O_3 production. In addition, they argue that some of the O_3 originates from the stratosphere. We are interested to see if this transition zone shows up in our profiles and if the same conclusions follow from our analyses.

Another topic that is relevant for the tropical tropospheric O_3 distribution is transport from one hemisphere to the other. The transport across the equator of pollutants emitted by man mostly on the Northern Hemisphere continents mainly determines the concentrations of those pollutants in the Southern Hemisphere troposphere. Not much is known about the meteorological processes leading to interhemispheric exchange. A model intercomparison study [*van Velthoven et al.*, 1997] focusing on aircraft emissions gave indications that pollutants emitted in the Northern Hemisphere flight corridors preferably enter the Southern Hemisphere in the upper troposphere (above roughly 500 hPa). Since we have 61 profiles over an extensive area of the Indian Ocean (from 15°S to 17°N) at our disposal, it is interesting to investigate this interhemispheric exchange.

We apply the same analysis technique as in 1998. This means that meteorological data from the European Centre for Medium-Range Weather Forecasts (ECMWF) model will be used, and back trajectories, based on data from the same model, will be calculated to determine the origin of the air masses.

2. Measurements

From February 23 to March 30, 1999, 61 combined ozonesondes and radiosondes were launched from the NOAA research vessel '*Ronald H. Brown*' over an extensive area of the Indian Ocean. Profiles were obtained twice a day from 15°S near Mauritius to 17°N in the southeastern Arabian Sea. The frequency of sampling increased when the ship approached the southwestern Bay of Bengal. An overview of the data will be given as a technical report by H. G. J. Smit et al. (manuscript in preparation, 2001).

The sondes used were balloon-borne Electrochemical Concentration Cell (ECC) ozone sondes (Model SPC-6A, Science Pump Corporation, New Jersey, United States) coupled to Väisälä radiosondes (Model RS80-15 H, Väisälä Finland). The accuracy error of the ECC ozone sensor increases from ±1-2 ppbv below 5 km to ±5 ppbv at 10 km and ±20 ppbv at 20 km altitude [*Smit et al.*, 1994, 1998]. The response time of the ozone sensor is within 25-30 s, which gives an altitude resolution of about 125-150 m for an average ascent velocity of about 5 m/s.

The uncertainties in the temperature and pressure measurements below 20 km are ±0.3°C and ±0.5 hPa, respectively. The accuracy error of the humidity sensor (HUMICAP-H) increases from ±2% near the surface to ±15-30% between 5-15 km altitude [*Kley et al.*,1997]. At low temperatures the response time of the sensor increases from about 200 s at -60°C to 400 s at −70°C [*Antikainen et al.*, 1994]. Above 15 km altitude the performance of the sensor is not reliable anymore [*Kley et al.*, 1997].

3. Trajectory Model

Trajectories were calculated with the KNMI trajectory model [*Scheele et al.*, 1996]. The model uses 6 hour forecast wind fields from ECMWF to calculate the displacements of air parcels. Using forecast instead of analyzed data rules out imbalances due to data assimilation in the model analyses. The data are available at 50 hybrid sigma-p model levels at a 1°x1° horizontal resolution. For more details on trajectory calculations we refer to *Scheele et al.* [1996] and *Stohl* [1998].

For all calculations we applied clustered 5 or 10-day (depending on whether the trajectories pass through convection) backward and forward kinematic trajectories. A cluster consists of multiple trajectories starting from 8 corners and 19 midpoints of a three-dimensional (3-D) box around the air mass of interest. The length and width of the box are 1°, and the height varies from 10-80 hPa. To illustrate, say that a profile shows an O_3-rich layer of thickness dp (with the boundaries also within the layer) at pressure *p*, latitude *y* and longitude *x*. Then the box surrounding this layer, from which the cluster of trajectories is calculated, extends from <*x*-0.5°, *x*-0.5°>, <*y*-0.5°, *y*+0.5°>, <*p*-½dp, *p*+½dp>. This cluster technique gives an impression of the accuracy of the trajectories related to spatial gradients in the wind. For two reasons we chose a maximum of 10 days for trajectory calculations. First, in the tropics long calculations are not recommended due to a lack of a dynamical balance. This may create small imbalances in the analyzed wind fields, which grow substantially with time. Ten days is an upper limit as experience and testing has showed. Second, if STE had taken place more than 10 days prior to observation time, the dynamical, and perhaps even chemical, signatures would almost certainly have disappeared.

Various steps in the trajectory calculations can produce errors. The largest error source is caused by the wind fields [*Stohl*, 1998]. It cannot be excluded that the ECMWF analyses are inaccurate, since the tropics, especially over the oceans, are a data-sparse region where the dynamics calculations are difficult due to the absence of a large-scale dynamical balance (such as the geostrophic balance for the extratropics) [*Heckley*, 1985]. ECMWF data postprocessing as well as conversion from spherical harmonics space to grid point space for trajectory calculations can also introduce some errors. Moreover, the vertical resolution of the used 50-layer model (20 hPa in the tropopause region) may also introduce difficulties when dealing with small-scale features. We believe, however, that ECMWF provides the best quality and finest resolution analyses around the world. Comparison of ECMWF temperature profiles with sondes showed few deviations. Generally, tropopause heights, as determined by the temperature minimum, matched to within 5-10 hPa (although one should keep in mind the 20 hPa resolution of the ECMWF analyses), with no more than 2 K difference between tropopause temperatures from sondes and analyses. A study by *Simmons et al.* [1999] also illustrates a good mean fit of the recent operational ECMWF analyses to radiosonde temperatures at 100 hPa. In the same study the authors affirm that the humidity analyses contain some significant remaining flaws near the tropical tropopause but they appear realistic enough both in overall amount of water vapor and in its geographical and seasonal distributions. In addition, we have compared ECMWF analyses of cloud parameters and convection (total column water, convective precipitation, cloud cover) to actual METEOSAT5 satellite observations. Small-scale features were not represented by the coarser analyses but the main features were captured. These comparisons yielded confidence in the ECMWF analyses. Furthermore, the KNMI trajectory model has been intercompared with two other state-of-the-art trajectory models, and it has been found that all models agreed very well [*Stohl et al.*, 2001].

In this study we used data with a resolution of 1°x1°, which is similar to that of the model simulations. At this resolution the model resolves the larger convective cells of the ITCZ, although it probably underestimates the vertical motions therein. Smaller-scale convection is not captured. Thus the actual path of an air parcel becomes unreliable if the trajectory passes through a convective area. Close to the ITCZ this becomes important since many turrets in the ITCZ are smaller than the model resolution. METEOSAT5 satellite images provided a useful tool to determine when trajectories passed through convection. Animations were made consisting of hourly plots of a combination of trajectories plotted over these images with the location of the trajectory at that time highlighted. The height of the trajectory was indicated by interpolating ECMWF temperature analyses to the trajectory latitude/longitude and pressure. At the same time, brightness temperatures of the satellite images were calculated to indicate the height of the clouds. From the temperatures of the trajectory and the corresponding satellite image it can be determined whether the trajectory is at that point in space and time below, in or above the clouds and convection. This has proven to be a useful tool in determining the reliability of a trajectory. Once it passes through clouds, the trajectory was not used in the analyses for earlier times.

4. Results

Before discussing the O_3 maxima of the profiles measured during INDOEX, the description of a reference O_3 profile merits some attention. It is rather difficult to define such a profile for the tropics since vigorous localized dynamics and active chemistry interplay in a complex manner to form a profile. However, when studying tropical profiles over the Indian Ocean during pre-INDOEX campaigns in 1995 and 1998 and over Atlantic Oceans [*Smit et al.*, 1989], the following rough description of a "background" or reference profile over the tropical ocean can be obtained. It must be kept in mind that profiles over land can differ quite substantially. At the surface, background O_3 concentrations are usually low (less than 10-20 ppbv) due to efficient photochemical destruction during long-range transport from sources. Background concentrations in the free troposphere increase up to 40-50 ppbv, depending on the amount of vertical mixing. Toward the tropopause these concentrations increase up to 70-80 ppbv in absence of active recent transport from the stratosphere. In the light of this description we will describe O_3 deviations in the INDOEX 99 profiles. It must be kept in mind that we study the influence of dynamics on the O_3 profiles so we are mainly interested in differences between the slope of the reference profile and individual measured profiles.

Nearly all of the 61 observed O_3 profiles (H. G. J. Smit et al., manuscript in preparation, 2001) showed enhanced O_3 mixing ratios in the upper troposphere. Sometimes these take the form of very thin layers at pressures between 110-160 hPa (14-16 km) with a typical thickness of 1-3 km and mixing ratios up to 120 ppbv (e.g., Figure 1a). We will call these layers laminae. Other profiles (e.g. Figure 1b) did not show this layered structure, but rather a steep increase toward the tropopause (defined as the minimum in temperature), which was typically found between 80-100 hPa (17-18 km). In most cases the O_3 increase in these profiles was not smooth but occurred in a stepwise manner coincident with small irregularities in the temperature profile. Often a double tropopause was observed. O_3 mixing ratios in these so-called transition zones (the region bounded by the double tropopause where there is a transition from tropospheric to stratospheric O_3 values) increased up to over a 150 ppbv at the (upper) tropopause level. Only a minor fraction of the profiles (<10%) showed a relatively O_3-poor upper troposphere (approximately 70 ppbv or less) compared to the other profiles.

The midtroposphere also exhibits O_3-enhanced layers (e.g. Figure 1c). In almost a third of the profiles a dry, midtropospheric O_3 maximum is visible, with O_3 mixing ratios varying between 60-100 ppbv and with relative humidities (RH) sometimes as low as 10% or less. These layers are usually thicker than those in the upper troposphere, i.e., about 2-5 km.

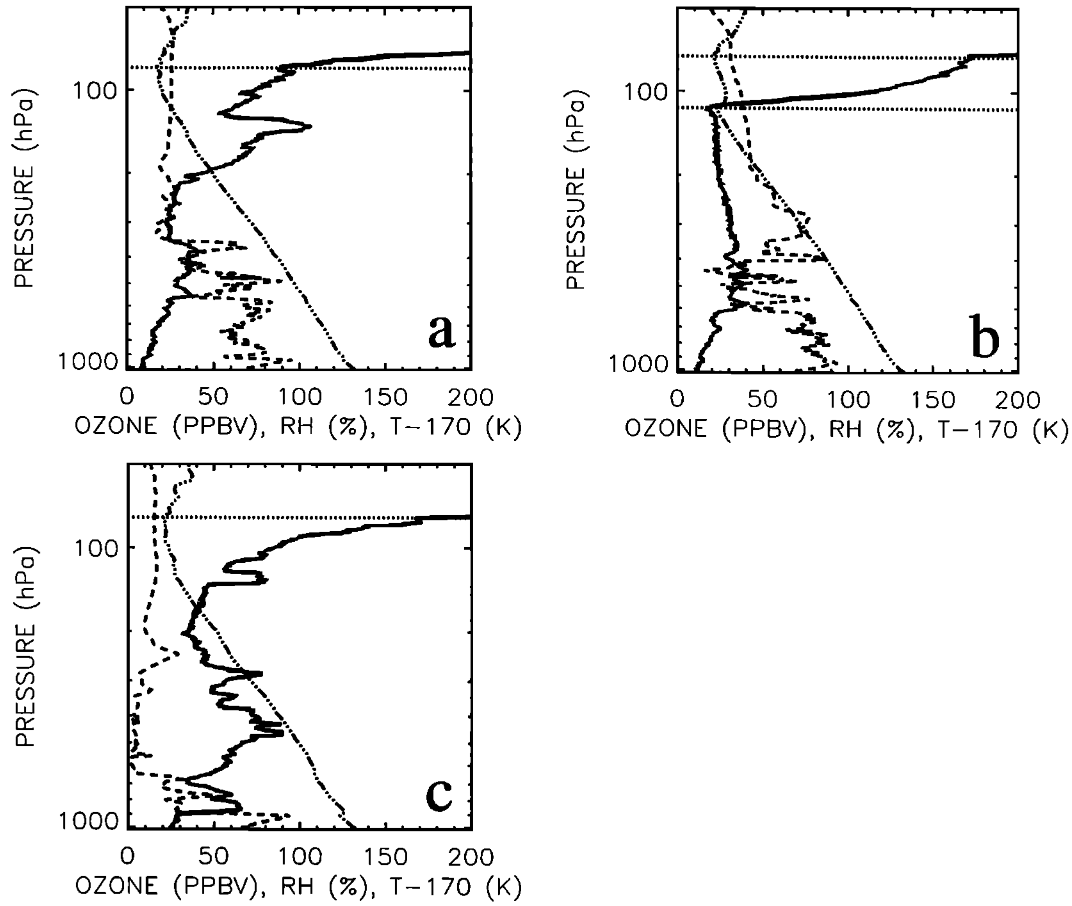

Figure 1. O_3, RH and temperature profiles as examples of (a) upper-tropospheric laminae, (b) upper-tropospheric transition zones, and (c) midtropospheric maxima. Solid line; O_3 (in ppbv); dash-dotted line: temperature (in K) offset by 170 K in order to fit into the plot; dashed line; RH (in %). The horizontal axis runs from 0-200. The vertical axis denotes the pressure from 1000-50 hPa. The tropopause (temperature minimum) is indicated by the dotted line. The latitude/location and date of the profiles are as follows: 2.5°S/66°E/February 26, 1999 (Figure 1a); 0.2°S/73.7°E/March 22, 1999 (Figure 1b); 7.5°N/69. 6°E/March 6, 1999 (Figure 1c).

The origins and characteristics of all these O_3-enhanced layers, both in the midtroposphere as well as in the upper troposphere, will be investigated in the subsections below. The investigations will be based on trajectory calculations and ECMWF analyses. Throughout the discussion, we will often compare the findings of this study to those of measurements from the 1998 pre-INDOEX campaign as described by *Zachariasse et al.* [2000], hereafter referred to as Z2000.

4.1. Upper-Tropospheric Ozone Laminae

At first sight the laminae just below the tropopause are very similar (in thickness, height at which they occur, maximum concentrations, shape and meteorological location) to those found in 1998 (compare Figure 1a to Figure 2 by Z2000). They appear as distinct layers and are typically found between roughly 110-160 hPa, with high O_3 mixing ratios indicating a stratospheric origin. Five-day backward trajectories from all laminae are presented in Plate 1, together with the trajectories from laminae from pre-INDOEX campaigns. Contrary to the findings of 1998 by Z2000 (e.g., Plate 4), none of the trajectories for 1999 originate in the subtropical jet stream (for example, shown in Figure 2), where CAT or shear-induced differential advection could bring stratospheric air to the upper troposphere (see Z2000). In fact, while residing in the upper troposphere for a large part, almost all trajectories come from the Indonesia/New Guinea area and are transported by upper-tropospheric easterlies to the INDOEX domain. This is in sharp contrast to the eastward transport that usually occurred in the upper troposphere during February and March 1998 over the INDOEX area.

Analysis of the difference in winds between 1999 and 1998 at 200 hPa in March (Figure 3) shows that during the entire 1999 INDOEX measurement period the flow in the upper troposphere is anomalously easterly compared to 1998, with wind speed anomalies of 5-10 m/s or more. The flow is not only anomalously easterly compared to 1998 but also in the climatological sense. When compared to the 10-year mean flow at 200 hPa from 1990-1999, anomalous easterlies prevail as well. This easterly flow in the upper troposphere is probably associated with the tropospheric quasi-biennial oscillation (QBO). It has long been observed that winds

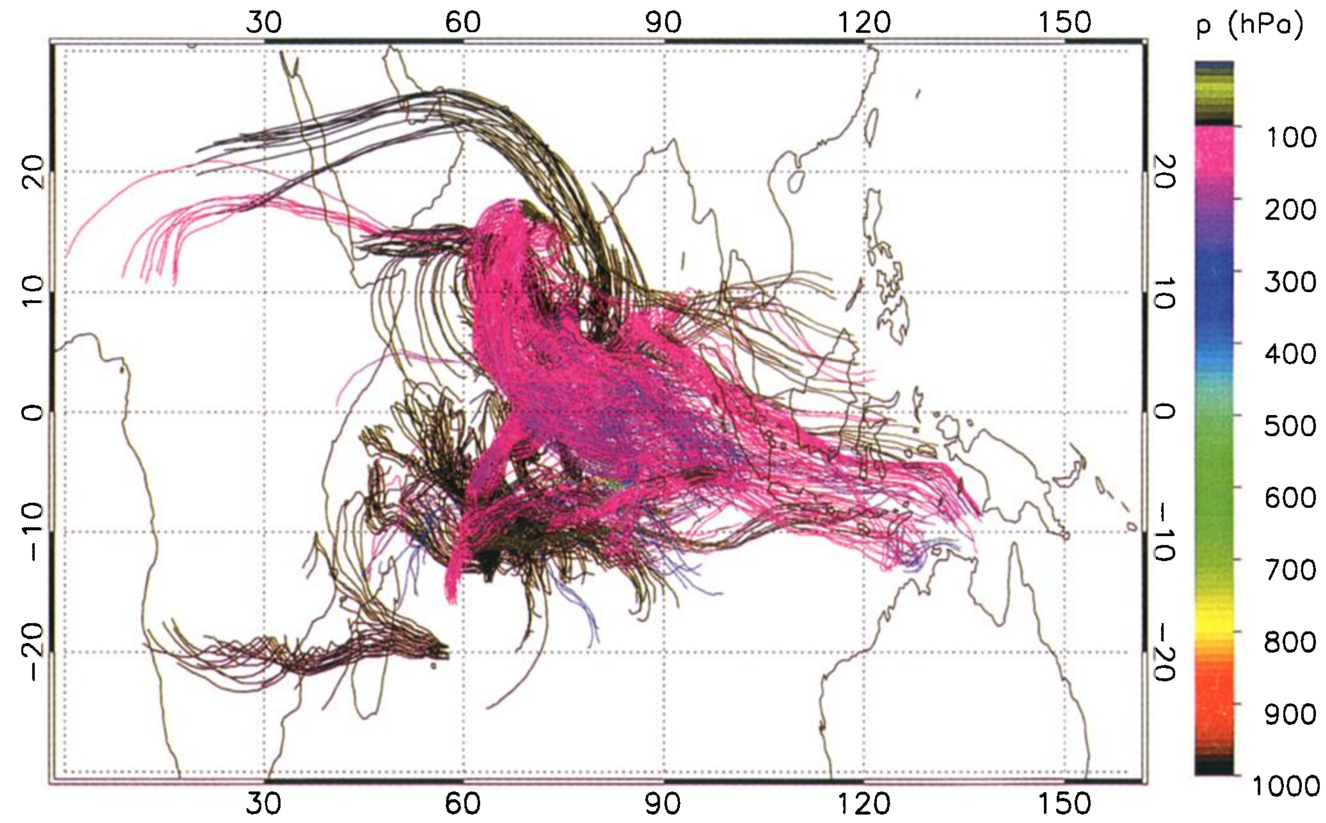

Plate 1. Five-day back trajectories from 1°x1° boxes surrounding all the upper-tropospheric O_3 laminae of 1999 (colored) and pre-INDOEX campaigns (black). Colors indicate the pressure of the trajectories. See section 3 for further details

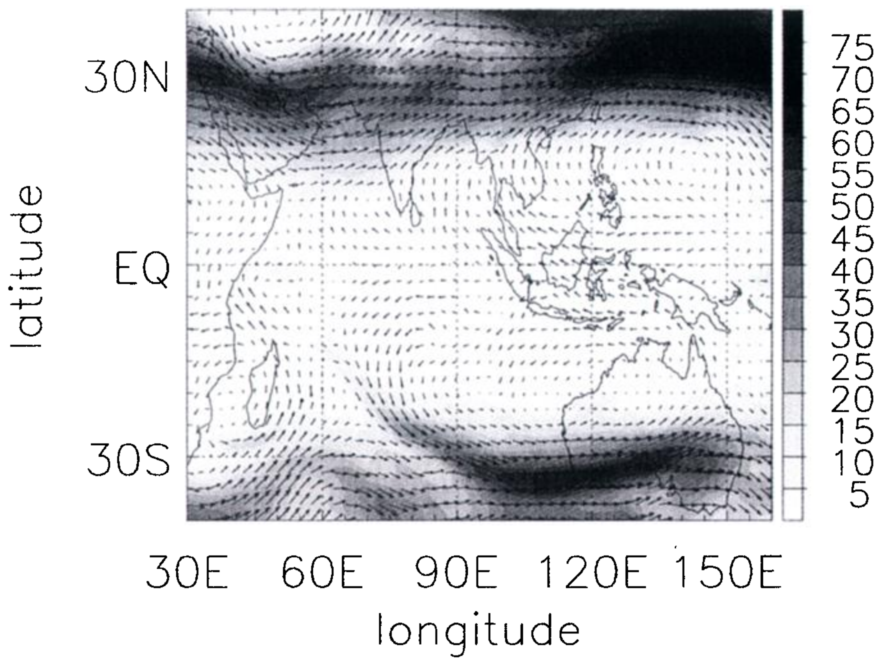

Figure 2. ECMWF horizontal wind and wind speed at March 4, 1999, at 200 hPa. The vertical bar indicates the wind speed. The subtropical jet streams are indicated by the wind speed maxima (dark colors) in the Northern and Southern Hemisphere.

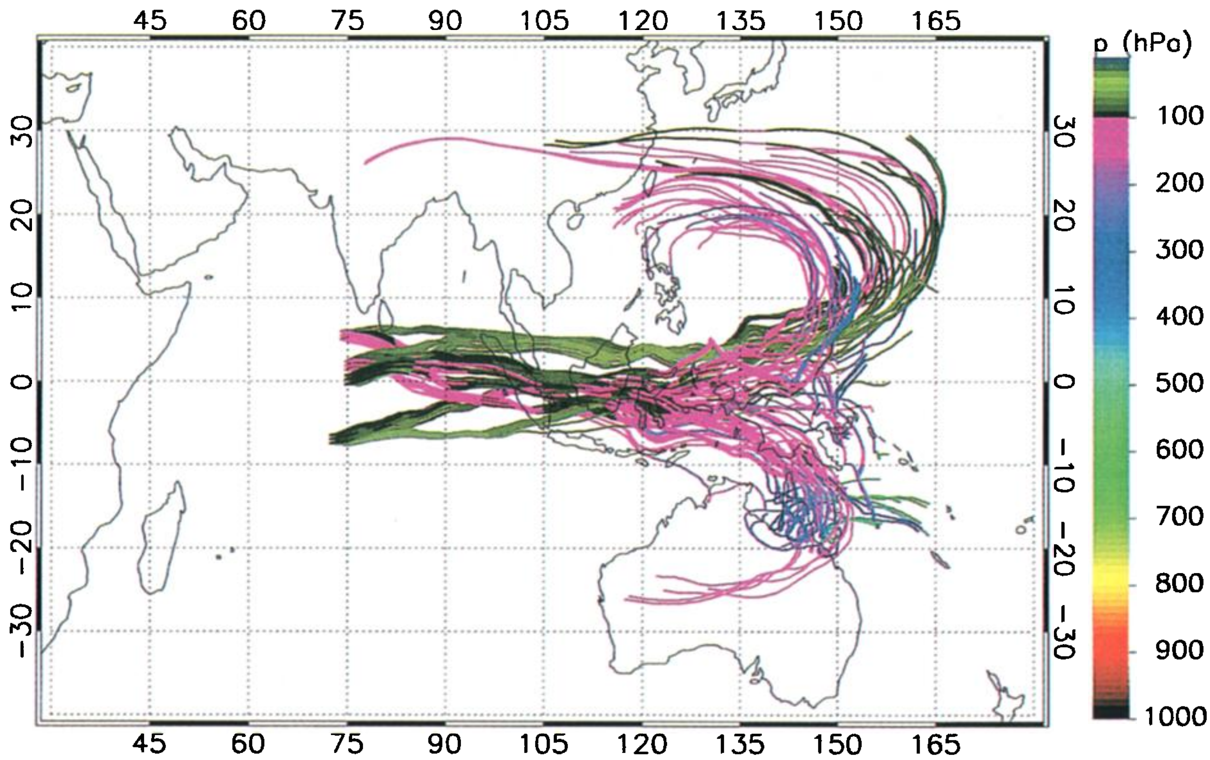

Plate 2. Examples of 10-day back trajectories from 1°x1° boxes surrounding the upper-tropospheric O_3-rich transition zones. Colors indicate the pressure of the trajectories.

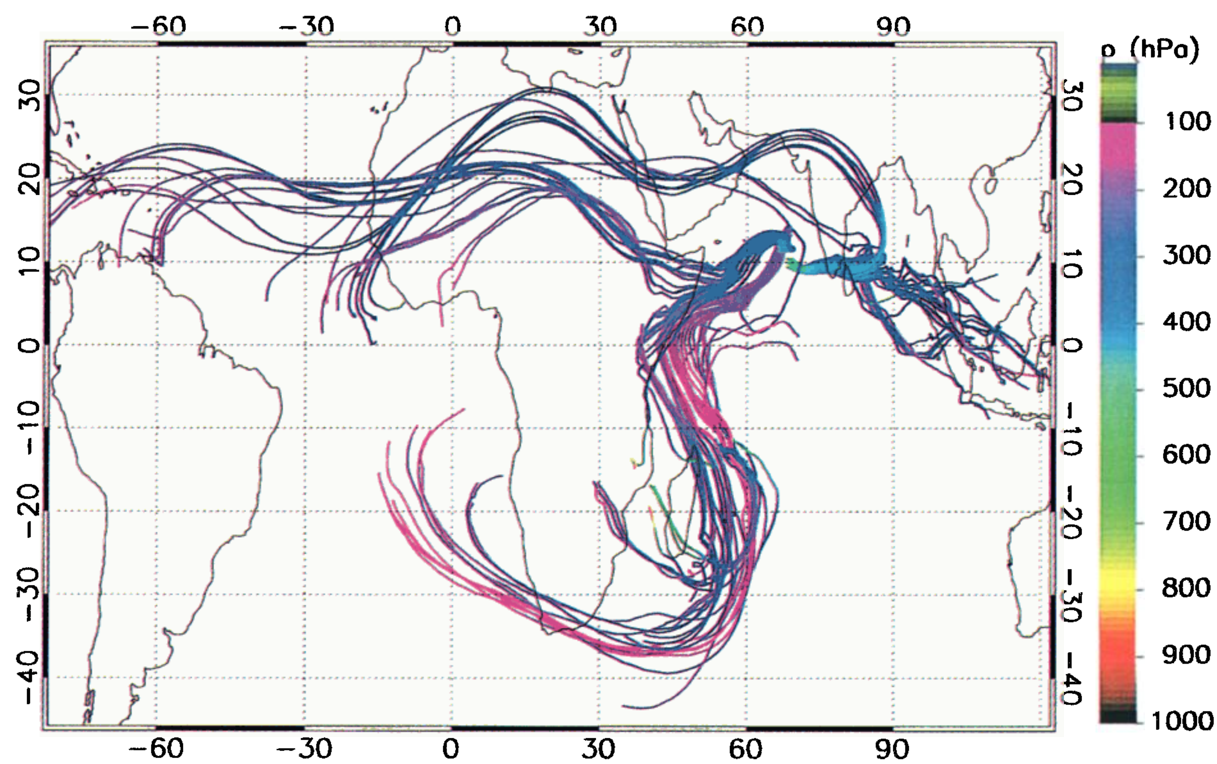

Plate 3. Examples of 10-day back trajectories from 1°x1° boxes surrounding the midtropospheric O_3 maxima. Colors indicate the pressure of the trajectories.

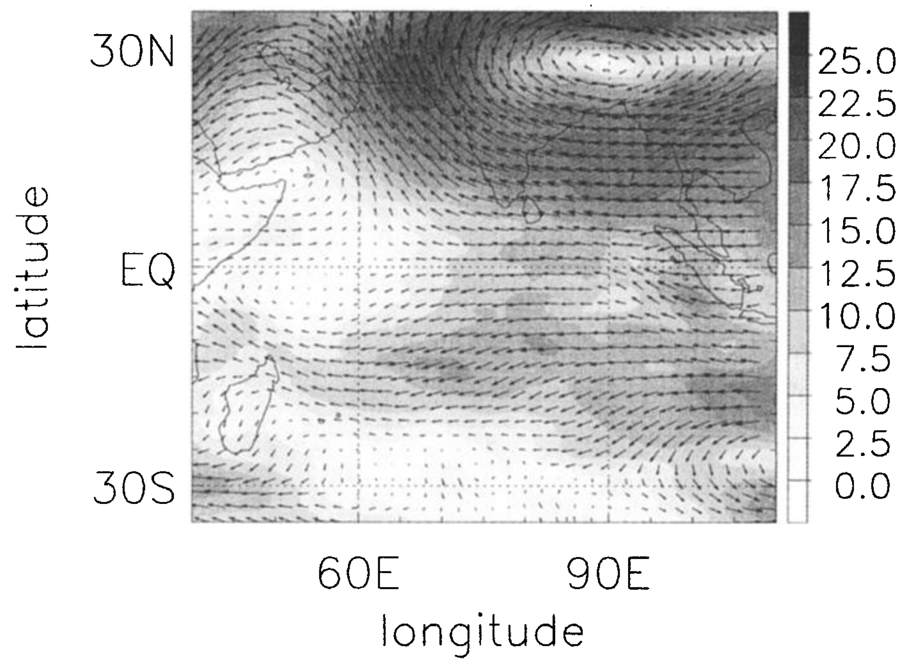

Figure 3. Wind and wind speed difference between March 1999 and March 1998 at 200 hPa from ECMWF analyses.

over the western Pacific and eastern Indian Ocean change sign with a quasi-biennial period [*Arkin*, 1982: *Gutzler and Harrison* 1987; *Yasunari*, 1987, 1989; *Ropelewski and Halpert*, 1988]. The lower and upper troposphere are negatively correlated. This is consistent with the flow in March 1999 where anomalous westerlies prevail in the lower troposphere [*Verver et al.*, this issue]. While the exact nature of the tropospheric QBO is uncertain, it seems to correlate quite well with the QBO mode of El Niño-Southern Oscillation (ENSO) indices [*Barnett*, 1991; *Yasunari*, 1987, 1989; *Ropelewski et al.*, 1992; *Kane*, 1992]. For additional references we refer to *Trenberth* [1975] and *Kane* [1992]. Observations [*Arkin*, 1982; *Gutzler and Harrison*, 1987] show that during La Nina the wind at 200 hPa is anomalously easterly while lower tropospheric winds are westerly. The same is observed during INDOEX, which corresponds well considering that 1999 was a La Nina year. The laminae are transported by the easterly winds from the convectively active area from Indonesia/New Guinea to the Indian Ocean, apparently without having been in contact with the STJ in either the Northern or Southern Hemisphere. However, the similarity of the laminae to those of 1998 suggests that the layers do eventually originate in the STJ but 5-day backward trajectories are too short. Unfortunately, longer backward trajectory calculations are not reliable since the trajectories pass through convection in 5 days. The following, however, supports the presumption of an origin from the STJ. First, a slight shift upward of say, 10-20 hPa, often showed trajectories typical for the laminae as we've seen in 1998 (for example those shown in section 4.2). Since this shift is of the order of the vertical resolution of the wind data, we believe that these slightly higher trajectories might be representative for those from the laminae. Second, enhanced potential vorticity (PV) structures in the ECMWF PV maps are present at the locations of the laminae in some cases (see Z2000 for a more elaborate discussion on the use of PV maps to investigate stratospheric influences). Laminae with enhanced PV values appear to be stripped off the STJ although they are less pronounced than in 1998. This absence of a pronounced PV signature points toward older laminae in 1999 than in 1998. This is further supported by a lack of a dynamical signature (wind shear) of the laminae in the wind data of the profiles.

Another indication that the upper-tropospheric O_3 maxima (also those described in section 4.2) are of stratospheric origin is presented in Figure 4. This figure depicts the equivalent potential temperature (θe, [*Reid and Gage*, 1981]) of the marine boundary layer (MBL) of all profiles plotted against the θe of the upper troposphere. Purely based on its moist static energy, an air parcel could not be lifted to a level beyond its equilibrium level (tropopause), which is based on its surface θe. This does not take into account overshooting of the tropopause level which occurs in the real tropical atmosphere [*Selkirk*, 1983]. A large positive deviation of the upper tropospheric θe from that of the MBL points to a stratospheric influx [*Reid and Gage*, 1996]. Small positive differences can be caused by radiative heating in the upper troposphere (above roughly 150 hPa), which is of the order of 0.2 K/day in the tropics [*Folkins et al.*, 1999]. Figure 4 has been split into O_3 enhanced layers (plusses) and profiles with less enhanced O_3 (relative to the reference profile) in the upper troposphere (squares). The profiles with a large O_3 enhancement in the upper troposphere exhibit the largest θe difference between the upper troposphere and the MBL.

It is interesting to investigate the fate of the laminae. Ten-day forward trajectories (not shown) indicate that a large part of the air masses in the laminae is pulled into the STJ of either the Northern or the Southern Hemisphere . The trajectories remain close together and follow the latitudinal meandering of the STJ (10-20°). There is no variation with latitude, that is trajectories starting close to the equator were just as likely to get pulled into the STJ as those from the edges of the tropics. In 10 days the air masses can be transported as far away as the eastern Pacific or even the Caribbean by the strong westerlies of the STJ.

4.2. The Upper Troposphere in Profiles With a Double Tropopause

In almost a third of the soundings the height of the chemopause in O_3 (steep increase of O_3) and the lapse-rate tropopause do not match. The temperature profile in those cases shows two inversions ("double tropopause") in the upper troposphere, one below and one above 100 hPa. The chemopause matches with the lower inversion, from here O_3 increases to stratospheric mixing ratios at the upper tropopause. A clear maximum or minimum in the form of a thin layer is not present.

Plate 2 depicts the 10-day backward trajectories from the transition zone. Apparently, in most cases the air between the temperature inversions consists of air masses coming from the STJ in the Northern or the Southern Hemisphere , or even both. If transport from both STJs takes place then for all cases trajectories show that the upper part of the transition zone is fed by the northern STJ and the lower part is fed by the southern STJ. This transport from two regions about 50° apart with different tropopause temperatures could explain the existence of the double temperature inversion. Often a pronounced maximum in the wind shear coincides with the O_3-rich transition zone, pointing to the relatively recent formation of the feature. In Figure 2 the ECMWF wind field at 200 hPa is presented for March 4. This wind field is representative for the other cases with a double tropopause where both STJs feed the transition zone. A pair of anticyclones, one over northern Australia and one just east of the Philippines, determines the inflow into the eastern Indian Ocean upper troposphere. These anticyclones transport air from the STJ, where STE can take place (Z2000). The region in the eastern Indian Ocean where the air from both anticyclones converges seems a preferred region for interhemispheric mixing. A slight shift of the anticyclones and one or both of the branches will disappear. Even when one branch of the STJ disappears, there is still transport from two separate regions. This double branch transport contrasts with the trajectories from the laminae discussed in section 4.1, which only have a single branch. This may contribute to the different character of the upper tropospheric laminae, especially since a double tropopause is present when transport from two separate regions takes place. Unfortunately, due to the problems with convection discussed in the previous section we cannot state without doubt what causes the difference in character between these laminae and those discussed in section 4.1 Despite the difference in character, we believe that the underlying process of STE most likely is the same.

Forward trajectories show that, similar to the laminae, a large part of the air in the transition zones is pulled back into the STJ, followed by eastward transport. Others show transport in the direction of Africa and the mid-Atlantic. There is no difference between trajectories started from the edges of the tropics and the deep tropics.

4.3. Dry, Midtropospheric Maxima

Profile 1c shows a layer of enhanced O_3 with peak mixing ratios of almost 100 ppbv at 400-500 hPa. This type of O_3 maximum is frequently observed in profiles over the Indian Ocean and coincides with a minimum in the RH. In the work of Z2000 it has been shown that this combination of high O_3 and low RH is due to STE in the

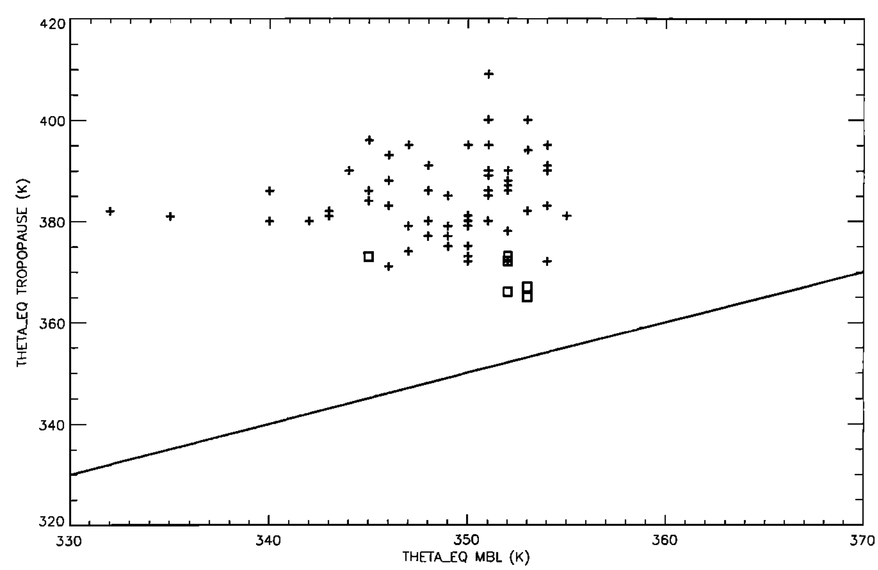

Figure 4. Equivalent potential temperature (θ_e, in K) of the tropopause (vertical axis) versus the MBL (horizontal axis). Pluses indicate profiles with an O_3-enhanced upper troposphere, and squares indicate profiles with a not-so-enhanced upper troposphere. The 1:1 line is also shown.

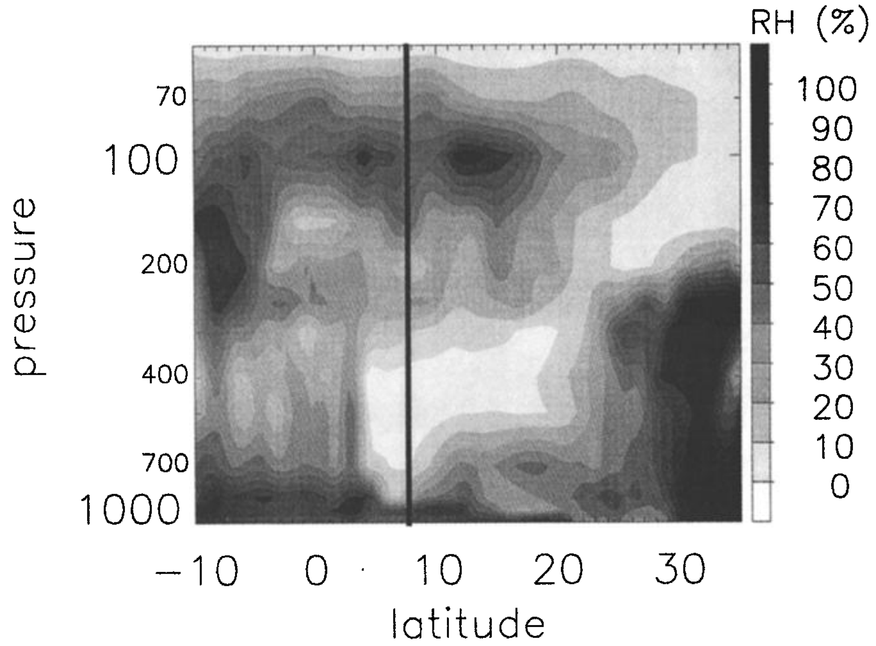

Figure 5. ECMWF RH cross section (in %) for profile 1c on March 6, 1200 UTC at 70°E. The position of the profile is indicated by the vertical line at 7.5°N.

upper troposphere near the STJ. The mechanism most likely is either shear-induced filament stripping from the STJ or CAT followed by shear-induced differential advection. Transport toward the midtroposphere and the deep tropics is channeled by anticyclones. While descending, mixing with tropospheric air dilutes the O_3-enriched air mass.

As in 1998, most of the midtropospheric maxima originate in the upper troposphere near the STJ (for example Plate 3). In the midtroposphere (300 hPa and below) there is a transport belt from the vicinity of the northern STJ into the tropics (eastward from Saudi Arabia over the Arabian Sea to the west coast of India where it turns to the southwest). This belt transports O_3-rich air from the upper troposphere over Arabia to the midtroposphere of the deep tropics. This belt was also responsible for the 1998 midtropospheric maxima. This transport belt is not present at 200 hPa, the level previously discussed. For all maxima, ECMWF vertical RH cross sections (such as shown in Figure 5) depict the dry layers sloping upwards to the STJ region. This descending branch from the upper to the middle troposphere is part of a synoptic structure and explains the extremely low RH in the maxima. O_3 mixing ratios are not entirely stratospheric (i.e., 100 ppbv or more), indicating that mixing along the way possibly plays a more important role for the midtropospheric maxima than for the upper-tropospheric laminae.

Another interesting new feature, which was not present in the 1998 data, is that several of the trajectories show interhemispheric exchange in the upper to midtroposphere. Some trajectories, mainly from the higher-altitude maxima around 450-400 hPa, move from the STJ at roughly 35°S to as far north as 10°N. They remain in the upper troposphere for the largest part of this journey and descend to the midtroposphere (approximately 400 hPa) only during the last few days. Some midtropospheric maxima are even fed by both the northern and the southern STJ (Plate 3). The interhemispheric flow regime from the Southern to the Northern Hemisphere along Madagascar and the east coast of Africa is quite pronounced on several days. From the ECMWF wind analyses at 200 hPa (Figure 2) it can be seen that this flow regime is the result of anticyclonic motion between Madagascar and the east coast of Africa. This particular feature extended down below 300 hPa. This (transient) channel is very pronounced in 1999 and shows up in deviations of the 200-hPa wind from 1998 (Figure 3) and the 10-year mean 1990-1999.

A minor fraction of the trajectories shown in Plate 3 originates from 600-900 hPa. These were released from the corners of the 3-D box surrounding the maximum, thus being farthest away (in latitude/longitude/pressure) from the actual location of the maximum. Therefore they probably represent air just outside the maxima and not that part of the maxima comes from the CBL over or near east Africa.

Forward trajectories show that the maxima remained at midtropospheric levels. Some were transported eastward almost around the Earth back to the western Indian Ocean. The trajectories starting close to the equator are more likely to remain over the Indian Ocean/western Pacific warm pool during the 10 days.

5. Discussion and Conclusions

It is remarkable that even if the climatological regime is so different between 1998 and 1999 (tropospheric QBO in the La Nina (1999) versus El Niño (1998) phase), the O_3 profiles still show very similar characteristics. The repeated presence of stratospheric layers just below the tropopause appears to be a permanent feature. The general picture that emerges from our analyses is that the extratropical stratosphere feeds O_3 to the tropical mid and upper troposphere from both the Northern and the Southern Hemisphere. This process takes place over almost the entire north-south cross section of the Indian Ocean as sampled during the 1999 measurement phase. Interhemispheric transport occurs in preferred channels depending on the location of transient anticyclones and cyclones. These synoptic systems usually remain in the same region long enough to channel this interhemispheric flow for some time. This "transport by channels" concept is described by *Verver et al.* [this issue].

Nearly all ozone soundings made during the 1999 INDOEX campaign displayed an O_3-enhanced upper troposphere, most often in the form of thin laminae just below the tropopause or in the form of an O_3-rich layer in between a double temperature inversion (the chemopause in O_3 is lower than the upper tropopause). This latter layer is consistent with the description of the upper troposphere in the tropics by *Folkins et al.* [1999]. These authors found that O_3 mixing ratios usually start increasing toward stratospheric values a few kilometers below the tropopause. According to Folkins et al. this is mainly due to slow upward ascent in this so-called transition zone, associated with radiative warming, together with in-situ O_3 production. In addition, they argue that some of the O_3 originates from the stratosphere. The analyses presented here for 1999 and by Z2000 for 1998 indicate that stratospheric exchange plays a prominent role in the tropical upper troposphere.

O_3-rich transients have also been found over the Atlantic on a relatively small scale (5-80 km) connected to convective activity [*Suhre et al.*, 1997]. We do not believe that these streamers are related to the phenomena we describe. First, there is a difference in the altitude at which the ozone-rich transients are found: 10-12 km in the work of Suhre et al. and directly below the tropopause (14-18 km) in our study. Furthermore, the locations of the laminae in our study are far away from the locations of the major areas of convection. With spatial scales of 80 km it is very unlikely that streamers related to convection could spread over such a large area of the Indian Ocean while remaining in the upper troposphere uninfluenced by anvil descent. Moreover, the layers we find in our research seem to be fairly stable and spread over large distances while retaining (most of) their identity. It seems unlikely that such a continuous supply of stable, O_3-rich layers is related to convection.

The laminae just below the tropopause (section 4.1) are very similar to those measured in 1998, with O_3 mixing ratios indicating a stratospheric origin. The trajectories, on the other hand, are not similar. In 1999, they all originate from the convective area over Indonesia/New Guinea, apparently not from the STJ as in 1998. However, slightly higher trajectories, which passed over the convection, do come from the STJ. We believe these to be representative of the laminae since the vertical difference between the starting points from the trajectories in the laminae and the higher trajectories is on the order of the vertical resolution of the wind fields. PV maps also show enhanced filaments stripped from the STJ at the locations of the laminae. PV and θe sometimes took nearly stratospheric values. These PV signatures are less pronounced than in 1998, and stratospheric PV values were not found in all cases. This indicates that the laminae in 1999 are older than the 1998 laminae. *Tuck et al.* [1997] also found that the ECWMF analyses had difficulty in representing filaments correctly. During transport the PV signature disappears rapidly due to diabatic processes. In this case, the chemical signature remains unaffected. This may be especially important for thin layers in the tropics. Upper-tropospheric layers can probably preserve their chemical identity for a long time because photochemical O_3 destruction is small in the dry upper troposphere and there may even be some O_3 production. There can also be several reasons for a lack of conservation of a PV signal. If stratospheric air is mixed into the troposphere by CAT, then a pronounced PV signal would be lacking. Furthermore, even if the trajectory is perfect, one should realize that the PV is a grid box value. Thus, even if high PV laminae are present in the grid box the PV signal will probably be suppressed by grid box averaging.

Although some trajectories and PV maps indicate air origins near the STJ, it cannot be excluded that convection or local photochemical O_3 production might also play a role. We note, however, that the O_3 mixing ratios are too high to be caused by local production alone. For the same reason, we do not think that photochemically produced O_3 from the polluted continental boundary layer (CBL) can create the observed stable, O_3-rich layers in the upper troposphere. In addition, the prevailing large-scale subsidence over India and SE Asia associated with La Nina inhibited vigorous convective lifting.

Forward trajectories demonstrated that a large part of the ozone intrusions is transported back to the STJ. Without mixing, this would imply that at least part of the ozone transport is reversible. Deformations of the STJ would regularly extend into the deep tropics and after some time are pulled back into the STJ. Part of the intrusions remains in the upper troposphere and part descends to the middle troposphere. However, during the time interval between leaving and reentering the STJ exchange between the filament and the troposphere could occur due to turbulent mixing, differential radiative heating, or interaction with clouds. The relative importance of the reversible versus irreversible transports remains uncertain. Model studies, done with high-resolution regional meteorological models, could perhaps provide an estimate.

Many cases of midtropospheric maxima were observed. In most cases the trajectories showed that the midtropospheric O_3 maxima are supplied with air from the STJ. Usually, only one flow channel from the STJ is active, but in a few cases interhemispheric transport took place, and both the northern and the southern STJ supplied the air in the maxima. This sometimes also occurred in the upper troposphere, in which case the O_3-rich layer is shaped as a transition zone instead of a lamina. The midtropospheric O_3 maxima have lower O_3 mixing ratios than the upper-tropospheric maxima, suggesting that dilution of stratospheric air is more important when descent to the midtroposphere follows the STE near the STJ. The ECMWF model reproduced the dryness of the layers. Similar to the 1998 analyses

(Z2000), the dry layer is part of a synoptic structure that slopes upward toward the STJ again indicative of a stratospheric origin. This lends extra confidence to the back trajectory analyses, which are based on wind fields from this model. The O_3 maxima might also have originated from the polluted CBL. However, this is contradicted by the trajectory analyses. Furthermore, convection was inhibited over India and SE Asia, and the extreme dryness of the layers makes it highly unlikely that these air masses come from the polluted CBL.

The tropical upper and middle troposphere is a location where many different air masses (from the troposphere and the stratosphere, from the Northern and Southern Hemispheric midlatitudes and tropics) converge. The chemical consequences of this should be further explored. For example, simple box models of the tropical troposphere, such as the one presented by *Prather and Jacob* [1997] should include a stratospheric influx of trace gases to correctly represent the photochemistry of the upper tropical troposphere.

Acknowledgments. We'd like to thank a few people who have contributed to this paper. First, we thank Dominik Brunner for developing the software to plot the trajectories over the satellite images. This greatly helped the analysis. Secondly, we'd like to thank Rinus Scheele for assisting with trajectory calculations. We also thank the anonymous reviewers who have critically read the paper and suggested improvements. We greatly appreciated their comments. This work was funded by The Netherlands Organization for Scientific Research (NWO).

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H. Kelder, P.F.J. van Velthoven, and M. Zachariasse, Royal Netherlands Meteorological Institute (KNMI), P.O. Box 201, 3730 AE De Bilt, The Netherlands. (zacharia@knmi.nl)

H.G.J. Smit, Institute for Chemistry of the Polluted Atmosphere (ICG-2), Research Centre Jülich, P.O. Box 1913, D-52425, Jülich, Germany

(Received August 7, 2000; revised January 22, 2001; accepted January 30, 2001.)