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**Climatologies of  
streamer events**

V. Eyring et al.

# Climatologies of streamer events derived from a transport model and a coupled chemistry-climate model

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Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2002

## Abstract

Streamers, i.e. finger-like structures, reach from lower into extra-tropical latitudes. They can be detected in  $N_2O$  or  $O_3$  distributions on single lower stratospheric layers in mid-latitudes since they are characterised by high  $N_2O$  or low  $O_3$  values compared to undisturbed mid-latitude values. If irreversible mixing occurs, streamer events significantly contribute to the transfer of tropical air masses to mid-latitudes which is also an exchange of upper tropospheric and stratospheric air. A climatology of streamer events has been established, employing the chemical-transport model KASIMA, which is driven by ECMWF re-analyses (ERA) and operational analyses. For the first time, the seasonal and the geographical distribution of streamer frequencies has been determined on the basis of 9 years of observations.

For the current investigation, a meridional gradient criterion has been newly formulated and applied to the  $N_2O$  distributions calculated with KASIMA. The climatology has been derived by counting all streamer events between 21 and 25 km for the years 1990 to 1998. It has been further used for the validation of a streamer climatology which has been established in the same way employing data of a multi-year simulation with the coupled chemistry-climate model ECHAM4.L39(DLR)/CHEM (E39/C). It turned out that both climatologies are qualitatively in fair agreement, in particular in the northern hemisphere, where much higher streamer frequencies are found in winter than in summer. In the southern hemisphere, KASIMA analyses indicate strongest streamer activity in September. E39/C streamer frequencies clearly offers an offset from June to October, pointing to model deficiencies with respect to tropospheric dynamics. KASIMA and E39/C results fairly agree from November to May. Some of the findings give strong indications that the streamer events found in the altitude region between 21 and 25 km are mainly forced from the troposphere and are not directly related to the dynamics of the stratosphere, in particular not to the dynamics of the polar vortex.

Sensitivity simulations with E39/C, which represent recent and possible future atmo-

## Climatologies of streamer events

V. Eyring et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

**Climatologies of streamer events**

V. Eyring et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2002

spheric conditions, have been employed to answer the question how climate change would alter streamer frequencies. It is shown that the seasonal cycle does not change but that significant changes occur in months of minimum and maximum streamer frequencies. This could have an impact on mid-latitude distribution of chemical tracers and compounds.

The influence of streamers on the mid-latitude ozone budget has been assessed by applying a special E39/C model configuration. The streamer transport of low ozone is simply inhibited by filling up its ozone content according to the surrounding air masses. It shows that the importance of streamers for the ozone budget strongly decreases with altitude. At 15 km streamers lead to a decrease of ozone by 80%, whereas around 25 km it is only 1 to 5% and at mid-latitude tropopause, ozone decreases by 30% (summer) to 50% (winter).

## 1. Introduction

The stratospheric ozone distribution is influenced not only by in-situ chemistry but also by a broad variety of different dynamic processes, for example tropospheric dynamics (e.g. [Reed, 1950](#); [Dameris et al., 1995](#)), stratosphere-troposphere exchange (e.g. [Holton et al., 1995](#); [Grewe and Dameris, 1996](#); [Kowol-Santen et al., 2000](#)), or meridional transport in the stratosphere (e.g. [Salby and Callaghan, 1993](#); [Waugh, 1997](#)). Observations of chemical tracers like  $N_2O$  and  $HNO_3$  by the CRISTA instrument ([Offermann et al., 1999](#)) or from the UARS satellite ([Randel et al., 1993](#)) indicated a strong latitudinal gradient in these trace species, which confirmed the existence of a subtropical transport barrier ([Plumb, 1996](#)). Therefore, (quasi-) horizontal mass exchange between the tropics and mid-latitudes is restricted. Those structures are superimposed with tongues of tropical air (stretching from tropical latitudes to the extra-tropics), which transport tropical air masses into the mid-latitudes. Satellite-based observations of chemical compounds and analyses of meteorological quantities (e.g. Ertel's potential vorticity) indicate that the remaining transport occurs in form of pronounced finger-like

**Climatologies of streamer events**

V. Eyring et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2002

structures, so-called streamers, which frequently appear over the Atlantic Ocean. For example, large areas characterised by low ozone and  $\text{HNO}_3$  or high  $\text{N}_2\text{O}$  mixing ratios are advected (quasi-) horizontally towards mid-latitudes and are partly irreversibly mixed with surrounding air masses. An example of a CRISTA-1 measurement of  $\text{N}_2\text{O}$  (Version 5) at 30 hPa on November 6, 1994 is shown in Fig. 1 (Offermann et al., 1999).

It is still an open question how streamers are related to large-scale dynamics, i.e. the variability of the stratospheric polar vortex, which is directly connected to the activity of (quasi-stationary) planetary waves. There are hints that the frequency of occurrence as well as the intensity (spatial size) of streamers might be linked to enhanced wave activity (e.g. Waugh, 1993). Rossby wave breaking events are capable of eroding the polar vortex, which can cause irreversible mixing. Streamers are often linked to strong vertical and horizontal advection processes. This can cause considerable horizontal gradients, e.g. in ozone concentration, and therefore, parts of the smaller scale ozone variability is due to streamer events. Streamers have been identified at all altitudes between the tropopause and the middle stratosphere (e.g. Waugh, 1996; Orsolini and Grant, 2000; Waugh and Polvani, 2000).

As mentioned above, a considerable number of papers have been published which deal with individual streamer events (e.g. Offermann et al., 1999; Kouker et al., 1999a) or discuss streamer events during shorter (seasonal) episodes (e.g. Chen et al., 1994). A reliable streamer climatology, which requires long-term data series, is currently not available. The seasonal and geographical variations have been determined only on data records of at most 3 years (e.g. Waugh, 1996; Orsolini and Grant, 2000) which are different in detail.

In the current paper a numerical method has newly been developed to detect and to count streamers. It focuses on streamers that are mainly caused by horizontal advection and lead to substantial meridional displacements. This method is described in Sect. 2.1. For the first time a 9-year data record has been used to determine a streamer frequency climatology. It is based on calculations of the chemical transport model KASIMA (Sect. 2.2) which uses ECMWF re-analyses (ERA) and operational

**Climatologies of streamer events**

V. Eyring et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2002

analyses. In Sect. 3, the streamer climatology obtained from KASIMA is presented and discussed. In addition, a respective streamer climatology has been derived from the coupled chemistry-climate model ECHAM4.L39(DLR)/CHEM (hereafter E39/C), which uses the same counting algorithm. The results gained from E39/C have been compared to KASIMA. This inter-comparison aims to check the abilities and deficiencies of E39/C with respect to the temporal and spatial distribution of streamers.

Most of the currently available models, in particular chemical-transport models (CTMs) and chemistry-climate models (CCMs) underestimate the observed ozone trend in northern hemisphere mid-latitudes during the last two decades. Certainly, no definite conclusion about the missing processes in the models can be given, although there are several possible explanations (e.g. Becker et al., 1998; Grewe et al., 1998; Solomon et al., 1998; Steinbrecht et al., 1998). A change of streamer occurrence could also have an impact on mid-latitude ozone changes (trends). Therefore, based on distinct model sensitivity studies with E39/C an analysis of the frequency of streamer events under recent (1960, 1980, 1990) and possible future (2015) atmospheric conditions is carried out (Sect. 4). After examination of E39/C and considering its limitations, it is employed to quantify the importance of streamers to meridional transport of ozone low air to extra-tropical latitudes and for the mid-latitude ozone budget using an artificial E39/C experiment design (Sect. 5). A summary and concluding remarks are given in Sect. 6.

## 2. Method and model description

In this section, a detailed description of the meridional streamer criterion and a comparison to other methods is given. Brief summaries of the employed model systems are presented which are used for the current investigations.

## 2.1. Definition of a streamer criterion

### 2.1.1. The meridional streamer criterion

This study first aims to find an objective criterion to identify streamer events in observed and modelled data sets and to derive a global streamer climatology for all seasons. Use can be made of chemical and dynamical tracers like  $N_2O$ ,  $O_3$ ,  $HNO_3$ , and (Ertel's) potential vorticity (EPV), which have strong latitudinal gradients but a pronounced zonally symmetric structure under undisturbed atmospheric conditions. The entry of air masses from different latitudes is therefore accompanied by a change of the vertical and the meridional gradient of those tracer fields. Deviations of the gradient can be used to identify regions where horizontal transport processes from the (sub-) tropics to extra-tropical latitudes occur. In this study a criterion based on the meridional gradient of  $N_2O$ -data in a horizontal plane has been newly developed.

The meridional criterion detects a change in the meridional gradient of a tracer distribution in a horizontal plane.  $N_2O$  values at a certain pressure level usually decrease from the equator towards the pole in both hemispheres, which means that the  $N_2O$  gradient is in general negative in the northern and positive in the southern hemisphere. A streamer can therefore be defined by a change of sign in the  $N_2O$  gradient (see Fig. 2). A streamer is counted, if the gradient in the northern hemisphere is greater than 10ppbv/rad and smaller than -10ppbv/rad in the southern hemisphere. This is a slightly weaker criterion than a change in sign. A change of the threshold by about 30% did not alter the resulting climatology, which states the robustness of this method. Whenever the criterion is fulfilled, the corresponding streamer field is set to one, otherwise zero. An example of an  $N_2O$ -,  $O_3$ , and  $HNO_3$ -distribution at 40 hPa and the corresponding streamer field derived with the meridional criterion at a single time step of E39/C is given in Fig. 3. Three big streamer events can clearly be identified in all tracer distributions as well as in the streamer field: one streamer event over the West-coast of America, where comparatively high  $N_2O$  or low  $O_3$  and  $HNO_3$  values with respect to the undisturbed mid-latitude values are detected. A second event extends

## Climatologies of streamer events

V. Eyring et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

**Climatologies of streamer events**

V. Eyring et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2002

from the West-coast of Mexico over Florida further northwards towards the Atlantic Ocean, which transports air masses from tropical to extra-tropical latitudes. A third big event starts over the Atlantic Ocean at the West-Coast of Mauritania and brings tropical air masses over Europe. The meridional streamer criterion identifies only the raising and not the trailing edge of the N<sub>2</sub>O-finger like structures. Therefore the area in the streamer field is smaller and narrower than that of the corresponding N<sub>2</sub>O-area. The following reasons limit the availability of the algorithm (see also Sect. 5): (1) It is possible that the algorithm counts a streamer event, if the polar vortex is shifted towards lower latitudes. In this case the algorithm identifies increasing N<sub>2</sub>O values with latitude. This rise is not due to streamer events, but to non-vortex air at high latitudes. (2) The highest N<sub>2</sub>O values are typically not found exactly at the equator, but are usually displaced some degrees north- or southwards. (3) At lower altitudes upper tropospheric high pressure systems can cause a change in the N<sub>2</sub>O gradient. To avoid these problems in our study we have therefore applied the criterion only between ±20° and ±70° and latitude and not below 100 hPa.

To derive a full streamer climatology the algorithm is applied to the N<sub>2</sub>O-data of each model grid (96 in E39/C, 128 in KASIMA) twice a day (at 00:00 and 12:00 UTC) of the evaluation period and all vertical layers between 21 and 25 km. The distribution is normalised to the number of time steps employed and is integrated over the above mentioned altitude range.

### 2.1.2. Comparison of different methods

In former studies (e.g. Orsolini and Grant, 2000; Manney et al., 2000) changes in the vertical profile were used to detect streamer events. The vertical criterion counts a streamer, whenever the local perturbation of the N<sub>2</sub>O-profile, which is defined as the difference between the actual vertical profile and a 5-point vertical running-mean for every evaluated time step, exceeds more than 5% (Pierce and Grant, 1998). Also a perturbation from the zonal mean or a combination of a change in the vertical and horizontal gradient might be a possible way to detect streamers. In the current investi-

**Climatologies of streamer events**

V. Eyring et al.

gation three algorithms (meridional, vertical, and zonal anomaly) have been compared in detail. By applying each algorithm to short test phases (e.g. a single November or March of the E39/C model simulation) the streamer fields for a single time step have been compared to the corresponding  $N_2O$  data. First of all, applying different methods yields different streamer fields. It was found that the results of the meridional streamer criterion at different altitudes and seasons matched best with streamers seen in the  $N_2O$  data for the following reasons:

The vertical criterion has two considerable disadvantages compared to the meridional, if meridional displacements due to horizontal advection are concentrated on:

1. In case the undisturbed vertical profile has a considerable curvature (i.e. the second derivative of the mixing ratio with height is significant), the running mean profile is located systematically at the interior of the curved profile. Thus, in one direction small deviations from the curved profile count as streamers whereas in the other direction large deviations are necessary.
2. In case the vertical profile has a steep gradient independently of its curvature, only a small vertical displacement leads to a streamer, whereas a large displacement is necessary for a small vertical gradient.

Therefore the vertical criterion might not be an adequate approach. In order to avoid these problems, [Ehhalt et al. \(1983\)](#) normalized the local standard deviation with the local vertical gradient. This so-called 'equivalent displacement height' is used to examine the temporal variance of stratospheric tracers. A different possibility is to look at the change in time of these gradients ([Appenzeller and Holton, 1997](#)). Moreover, we intend to investigate horizontal transport processes. Therefore it does not seem to be a surprise that a method based on a change in the horizontal distribution of tracers is better able to reproduce those events than a vertical method. The zonal criterion has problems in reproducing streamers seen in the  $N_2O$ -data mainly due to the fact that it is difficult to define a robust threshold which is applicable for all latitudes. The meridional criterion was able to reproduce these streamer structures, why we will use this criterion

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

in our study.

## 2.2. The 3-D-chemical transport model KASIMA

KASIMA is a global chemical transport model configuration for the simulation of the behaviour of physical and chemical processes of the middle atmosphere (Kouker et al., 1999b). The meteorological component is based on a spectral architecture with the logarithm of pressure as vertical coordinate. The model has previously been used for studies of stratospheric transport and chemistry (e.g. Kouker et al., 1995; Ruhnke et al., 1999; Reddmann et al., 2001).

For this study the model is nudged towards the ECMWF re-analyses (until 1994) and operational analyses thereafter. After integrating the primitive equations in the prognostic model, a correction is applied to the temperature field nudging the calculated temperature towards the ECMWF analysed temperature using a Newtonian cooling like algorithm. The setup of the nudging coefficient is taken from the experience obtained from sensitivity studies described by Kouker et al. (1999a).

The model is used with a horizontal triangular truncation T42 and 63 levels between 10 and 120 km pressure altitude. The model is initialised in 1990 with an atmosphere at rest and a barotropic temperature field equal to the U.S. Standard Atmosphere (1976). Some experiments showed that the model results yield reasonable atmospheric structures after approximately 5–10 days (see Kouker et al., 1999a and references therein). The model runs continuously until 1998.

To study transport characteristics related to the streamer phenomena, an idealised tracer representing stratospheric N<sub>2</sub>O is transported by the model winds: The tracer has a source region in the equatorial lower stratosphere (equator-wards of 15° latitude and below 100 hPa) and a prescribed photolysis coefficient depending on altitude and zenith angle only.

### Climatologies of streamer events

V. Eyring et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

### 2.3. The coupled chemistry-climate model E39/C

A detailed description of the coupled chemistry-climate model E39/C has been given by [Hein et al. \(2001\)](#), who also discussed the main features of the model climatology. The model horizontal resolution is T30 with a corresponding Gaussian transform latitude-longitude grid, on which model physics, chemistry, and tracer transport are calculated, with mesh size  $3.75^\circ \times 3.75^\circ$ . In the vertical, the model has 39 layers (L39) from the surface to the top layer centered at 10 hPa ([Land et al., 1999](#)). Water vapour, cloud water, and tracers are advected by the semi-Lagrangian scheme of [Williamson and Rasch \(1994\)](#), while spectral Eulerian advection is applied to the other prognostic variables. Parameterisation schemes for radiation ([Fouquart and Bonnel, 1980](#); [Morcrette, 1991](#); [van Dorland et al., 1997](#)), convection ([Tiedke, 1989](#)), large-scale cloud formation ([Roeckner, 1995](#)), land surface processes, vertical turbulent diffusion ([Louis, 1979](#); [Brinkop and Roeckner, 1995](#)), and orographic gravity wave drag ([Miller et al., 1989](#)) are employed. The effects of non-orographic gravity waves are not considered. The chemistry module CHEM ([Steil et al., 1998](#)), updated in ([Hein et al., 2001](#)) is based on the family concept, containing the most relevant chemical compounds and reactions necessary to simulate upper tropospheric and lower stratospheric ozone chemistry, including heterogeneous chemical reactions on polar stratospheric clouds (PSCs) and sulfate aerosol, as well as tropospheric  $\text{NO}_x$ - $\text{HO}_x$ - $\text{CO}$ - $\text{CH}_4$ - $\text{O}_3$  chemistry. Physical, chemical, and transport processes are calculated simultaneously at each time step, which is fixed to 30 min. Stratospheric sulfuric acid aerosol surface areas are based on background conditions ([WMO, 1992](#)) with a coarse zonal average. Sea surface temperature and sea ice distributions are prescribed for the various time slices according to the transient climate change simulations of [Roeckner et al. \(1999\)](#).

Main features of both models are listed in Table 1.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

### 3. Comparison of streamer climatologies in the lower stratosphere

#### 3.1. Setup of experiments

For the first time a 9-year streamer climatology based on ECMWF re-analyses (ERA) from 1990 to 1994 and operational analyses thereafter until 1998 is derived using the KASIMA model. The climatology is employed to test the ability of the E39/C model to reproduce the seasonal and geographical dependence of the frequency of streamer events. In this case the KASIMA results are taken as reference although some model dependent assumptions can slightly influence the derived streamer climatology (see Sect. 2.2). In KASIMA, a passive idealised tracer, which represents stratospheric N<sub>2</sub>O, is transported by model winds. To check the accuracy of this method, model results have been episodically compared with values of Ertel's potential vorticity (EPV), which can be directly derived from ECMWF data. It turned out that the agreement was satisfactory which justifies the procedure described above.

The E39/C data are taken from a 20-year time-slice experiment representing atmospheric conditions of the early 1990s (for details see Hein et al., 2001). The boundary conditions for this model simulation are briefly summarised in Table 2.

For both data sets, KASIMA and E39/C, the same meridional criterion for the identification and counting of streamer events (Sect. 2.1.1) has been used to derive climatologies. The resulting climatologies are presented in Fig. 4.

#### 3.2. Seasonal and geographical distribution of streamers

During December, January, and February (DJF; Fig. 4a) both climatologies indicate much higher streamer frequencies in the winter (northern) hemisphere than in the summer (southern) hemisphere. The horizontal distributions derived from KASIMA and E39/C both indicate a clear zonal asymmetry. There is an overall agreement with regard to the main activity centers which can be identified over the western part of North America, the Eastern Atlantic/Western Europe, and the Far East/Western Pacific

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

**Climatologies of streamer events**

V. Eyring et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2002

region. Individual years of the KASIMA analysis and the E39/C results do not differ significantly from each other, i.e. the climatological mean streamer distributions do not differ from those derived for cold (stable polar vortex) and warm (unstable polar vortex) winters (not shown). However, there are obvious quantitative differences between KASIMA and E39/C. E39/C generally simulates lower streamer frequencies during the DJF season. This can also be seen in Fig. 5. It shows the longitudinal distribution of the mean meridional (20° N–70° N) streamer frequency in the northern hemisphere. The maximum value is 0.23 at 0° longitude in KASIMA, whereas it is only 0.17 in E39/C.

The streamer activity during March, April, and May (MAM; Fig. 4b) is notably reduced in the northern hemisphere (spring season) compared to DJF. Both climatologies indicate smaller frequency values. Higher values are found in the southern (fall) hemisphere, which are again systematically lower in E39/C. As in DJF in the northern hemisphere there is a satisfactory agreement between KASIMA and E39/C with regard to the main activity centers, except the western part of North America, where E39/C simulates nearly no streamers during this season. In the southern hemisphere the two climatologies agree well not only qualitatively but also quantitatively.

Considering June, July, and August (JJA; Fig. 4c), the number of streamer events in the winter (southern) hemisphere is obviously higher than in the summer (northern) hemisphere in both climatologies which is qualitatively the same result as that found for DJF (e.g. higher frequencies in the winter season). Two centers of main activity are identified in the KASIMA and the E39/C climatologies, but they differ clearly with respect to the geographical location. KASIMA shows a pronounced center of action westward of the southern part of South America. In E39/C, this region is shifted northward. Moreover, the maximum frequency values are approximately a factor of 2 smaller than in KASIMA. The second region showing high streamer frequencies is centered above South Africa, whereas in E39/C it is shifted eastward and is located in the middle between South Africa and Australia. Again, the maximum values are smaller in E39/C. Generally, the streamer events simulated by E39/C are concentrated in a smaller latitudinal belt (20° S–70° S) as indicated by the KASIMA results. The much

**Climatologies of streamer events**

V. Eyring et al.

higher streamer frequency in southern winter can also be seen in Fig. 5, which indicates that the total number of streamer events counted in KASIMA is approximately a factor of two higher than in E39/C. The longitudinal variance of the mean meridional ( $20^{\circ}$  S– $70^{\circ}$  S) streamer frequency in the southern hemisphere during winter time is smaller than in the northern winter season. In the northern hemisphere in summer, the number of streamer events is very low in E39/C; it is considerably higher in KASIMA with a pronounced activity center east of the Mediterranean Sea, which is only weakly represented by E39/C (see Fig. 4c).

For September, October, and November (SON) the differences between the KASIMA and the E39/C climatologies are largest in the southern hemisphere spring season (Fig. 4d). Here, the region of streamer activity in E39/C is simulated in a smaller latitudinal band than it is calculated by KASIMA. Also as was discussed for the other seasons, KASIMA results show higher values of streamer frequencies in both hemispheres, but it is most obvious in the southern hemisphere for this season. Nevertheless, the main center of activity which lies west of South America is identical for both climatologies. In the northern hemisphere, the location of strongest activity are similar to those found during DJF.

A quantitative summary of the seasonal dependency of the mean streamer frequencies for  $20^{\circ}$ – $70^{\circ}$  latitude in both hemispheres is given in Table 3, for KASIMA and E39/C, respectively. As formerly described, the frequency values derived from KASIMA are larger than those calculated from E39/C, except for summer (DJF) and fall (MAM) conditions in the southern hemisphere. The differences between KASIMA and E39/C are most obvious during southern winter (JJA) and spring (SON) season. During summer months, streamer frequencies are smallest in both climatologies and both hemispheres.

A closer inspection of the seasonal cycle of streamer frequencies on a monthly mean basis can be obtained from Fig. 6. The annual cycle of the two models agree very well in the northern hemisphere. In the southern hemisphere there is a distinct discrepancy between the KASIMA analysis and the E39/C results especially for the period between

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2002

June and October indicating deficiencies in the dynamics of E39/C during that time.

The annual cycle of the KASIMA streamer frequency climatology shows a clear signature: maximum streamer frequencies are found near winter solstice (pronounced peak in December in the northern hemisphere) with a shift towards spring in the southern hemisphere (broad maximum from June to September). Interestingly, the maximum values are of the same order of magnitude in both hemispheres (approx. 0.22). Minimum streamer frequencies are detected in the months after summer solstice, i.e. July in the northern hemisphere and January in the southern hemisphere, with slightly higher values in the northern hemisphere (approx. 0.05 in the northern hemisphere, approx. 0.04 in the southern hemisphere). In summary, the shape of the annual cycle of streamer frequencies seems to indicate a link to the seasonality of the stratospheric polar vortex.

Whereas the annual cycle of streamer frequencies in the northern hemisphere is in fair agreement between E39/C and KASIMA analysis (Fig. 6), significant differences are found in the southern hemisphere for the months from June to October. At this time of the year, E39/C, as most climate models, shows marked temperature deviations with respect to observations, a phenomenon known as the cold bias (Pawson et al., 2000; Austin et al., 2002). In the model, the southern hemisphere winter and spring polar stratosphere is much too cold and the stratospheric vortex is too strong. An important question is how the cold bias of the model and the streamer climatology are related to each other. Are both deficiencies of E39/C caused by the same missing (dynamic) process, or is the poor reproduction of streamer frequencies in winter and spring a direct consequence of the cold bias?

As mentioned above, the annual cycle of streamer events seems to be related to the dynamics of the stratosphere with high streamer activity in winter months. The results presented here do not show higher frequency values during the formation or the decay of the polar vortex as shown in previously published analyses (e.g. Waugh, 1996). Moreover, for northern winter months neither the KASIMA analysis nor the results of E39/C show different streamer frequencies in warm and cold winters, which

Climatologies of streamer events

V. Eyring et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

**Climatologies of streamer events**

V. Eyring et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2002

is also indicated by the relatively small standard deviations of the frequency values in winter (Fig. 6). Therefore, the dynamics of the polar vortex (stretching of the vortex, displacement from polar latitudes during a minor warming event, decay during a major stratospheric warming) seems not to be the primary process which forces streamer events in the analysed altitude region. Much more plausible is that large-scale planetary (Rossby) waves which originate in the troposphere vertically propagate into the stratosphere and directly generate streamer events. From linear theory it follows that only during the west wind phase in the stratosphere (all seasons except summer) these waves can propagate upward from the troposphere into the stratosphere (Charney and Drazin, 1961). The upward propagation of those Rossby-waves and the breaking of these waves at higher altitudes is one of the main causes for horizontal transport in that altitude range (e.g. Trepte et al., 1993; Chen et al., 1994; Waugh, 1996). In E39/C, the deficiencies detected in the southern hemisphere might partly be caused by the horizontal resolution (T30) which may not be sufficient to resolve the relevant tropospheric dynamic processes which generate planetary waves there (see discussion below). The systematic underestimation of (large-scale) wave activity in the southern hemisphere might be one reason for the cold bias (missing dynamical heating of the polar stratosphere), and it could also be the cause for the too small extra-tropical streamer frequencies in winter and spring season.

### 3.3. Discussion

The seasonal dependency of streamer activity found in KASIMA and E39/C partly agrees with formerly published studies (e.g. Chen et al., 1994; Waugh, 1996). For example, Chen et al. (1994) also found that the bulk of transport out of the tropics at the 600 K-level is into the winter hemisphere and only little transport into the summer hemisphere. For winter in the northern hemisphere at the 400 K-level, Chen et al. showed that roughly equal amounts of air masses are transported into both mid-latitudes, whereas during winter in the southern hemisphere most transport is found into southern hemisphere mid-latitudes. Waugh (1996) analysed the seasonal variation

**Climatologies of streamer events**

V. Eyring et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2002

of the isentropic transport out of the tropical stratosphere for the three-year period July 1991 to June 1994. Strong transport out of the tropics was found to occur whenever there are westerlies throughout middle latitudes, which is consistent with the KASIMA results. It was concluded that in the northern hemisphere the transport out of the tropics fluctuates about an approximately constant value during the fall to spring period (late September to early May), a finding which is not supported by the current analysis. A different result was also found in the southern hemisphere: Waugh detected maximum transport of air mass in early and late winter with a relatively quiet midwinter period. The KASIMA results do neither show an early and/or late winter maximum nor a reduced activity in mid-winter. Both studies (Chen et al., 1994; Waugh, 1996) also investigated the altitude dependence of tropical mass exchange. Chen et al. showed that the tropics are most isolated in the middle stratosphere (600 K, approx. 25 km in the tropics) and that much more air of tropical origin is transported into mid-latitudes of the winter hemisphere in the upper (1100 K, approx. 38 km in the tropics) and lower (400 K, approx. 17 km in the tropics) stratosphere. Qualitatively, the same result was gained by Waugh, considering 425 K, 500 K, and 850 K. A reasonable explanation for this behaviour was given by Chen and co-workers: in the lower stratosphere (tropopause region) there are more synoptic-scale waves originating in the troposphere than in the middle stratosphere (500–600 K) while the amplitude of planetary-scale disturbances in the upper stratosphere is much larger than in the middle stratosphere due to the density effect. The findings discussed so far in the current paper, which are based on data only for altitudes between 21 and 25 km, fit well with this hypothesis, since we do not find a clear relation between the dynamics of the polar winter vortex and streamer events.

The identified seasonal cycle of streamer activity differs substantially from the one derived by the SLIMCAT chemical transport model (Chipperfield, 1999), where a period between February 1996 to February 1999 was analysed (Orsolini and Grant, 2000). The main difference is a higher activity in the summer season than in winter season in both hemispheres (Orsolini and Grant, 2000; their Fig. 2). In this study the vertical

**Climatologies of streamer events**

V. Eyring et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2002

streamer criterion discussed in Sect. 2.1.2 was applied to the N<sub>2</sub>O data. The altitude range between 500 and 600 K (roughly 20–25 km) was averaged. To examine the differences between the annual cycles of the KASIMA and the E39/C streamer climatologies presented in the current paper and the one of (Orsolini and Grant, 2000), we have applied the same vertical criterion to the “1990” E39/C time slice experiment. Surprisingly the resulting annual cycle is then in much better agreement with the SLIMCAT study (not shown). In particular, we also find higher activity in the summer hemispheres, which conflicts with the climatologies derived with the meridional criterion. Since E39/C is able to reproduce the climatology obtained with SLIMCAT using the vertical criterion and the climatology derived with KASIMA using the meridional criterion, it must be concluded that the differences in the climatologies are mainly due to the different criteria. The formal differences including an interpretation have already been described in Sect. 2.1. Therefore, an interpretation based on the expectation from the middle atmosphere circulation follows: It is well known from many climatologies (e.g. CIRA, 1992) that planetary wave activity is much smaller in summer than in winter, the wave activity in northern hemisphere winter is larger than in southern hemisphere winter. Since planetary waves are a major cause for streamers (see Kouker et al., 1999a and references therein), it is expected from the arguments above that the streamer frequency is considerable larger in winter than in summer. Consequently the vertical criterion seems not to be appropriate for the detection of streamers.

In summary, although there are some differences with regards to formerly published analyses, the climatology of streamer frequencies based on KASIMA results seems to be reliable, not at last since it employs 9 years of ECMWF re-analysis and operational analyses. The agreement with the corresponding climatology derived from E39/C is satisfactory, except for winter and spring season in the southern hemisphere. Therefore, in the following E39/C results of sensitivity experiments are used to assess possible changes in streamer distributions and frequencies related to climate change and to estimate the influence of streamers on the mid-latitude ozone budget.

#### 4. Streamer activity in a changing climate

As shown before, streamer frequencies vary clearly with season, and streamers can significantly modify the ozone budget at mid-latitudes due to irreversible mixing of (sub-) tropical air (see Sect. 5). This gives rise to the question, if the streamer frequencies are different in a changing climate. To get some first hints, four different time-slice experiments of the past and future have been carried out (e.g. [Hein et al., 2001](#); [Schnadt et al., 2002](#)). They represent 1960, 1980, 1990 and 2015 conditions. Prescribed boundary conditions for the four simulations are given in Table 2. Boundary values for the most important greenhouse gases ( $\text{CO}_2$ ,  $\text{N}_2\text{O}$ ,  $\text{CH}_4$ ) for “1960”, “1980”, and “1990” are taken from ([IPCC, 1990](#)), those for “2015” according to the IPCC-scenario IS92a (business as usual, [IPCC, 1996](#)). Upper boundary values for  $\text{NO}_y$  and CIX and the zonal CFC fields are adapted to observations for the present and past simulations and follow projected changes for “2015” ([WMO, 1999](#)). Each model experiment was integrated for 20 model years. The model results representing recent atmospheric conditions have been intensively compared with respective observations. It turned out that the model is able to simulate not only mean conditions in fair agreement with observations but also intra- and inter-annual changes of dynamic and chemical values and parameters, particularly in the northern hemisphere. These findings have been taken as justification to employ E39/C also for an assessment of possible near future changes. The results of the four model experiments were provided for an international model inter-comparison ([Austin et al., 2002](#)) which indicates the abilities and deficiencies of the currently used chemistry-climate models. Streamer climatologies for 1960, 1980, 1990 and 2015 for the altitude region from 21 to 25 km are shown in Fig. 7.

First of all, it indicates no principle changes in the annual cycle, i.e. the maximum and minimum streamer frequencies in the four model simulations are always found in the same months, they are not shifted to other months.

Comparing the results of the different time-slice simulations it is obvious that the inter-annual standard deviation (1 sigma) within a month of one specific model experi-

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

**Climatologies of streamer events**

V. Eyring et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2002

ment is mostly larger than the changes in streamer frequencies of one month between the four simulations. But there are a few exceptions which yield interesting facts: In both hemispheres, the streamer frequencies are found to increase in the summer months. Comparing the values of the “1960” and the “2015” simulations, this increase is statistically significant, for July in the northern hemisphere and for February in the southern hemisphere, respectively. As already discussed by Schnadt et al. (2002), the model shows a systematic decrease of lower stratospheric temperatures in summer due to enhanced greenhouse gas concentrations which is in agreement with cooling trends estimated on the basis of long-term measurements (Ramaswamy et al., 2001). The cooling in the model is much more pronounced at high- than at mid- and low latitudes (due to the decrease of polar ozone) which yields a reduced meridional temperature gradient in the extra-tropical lowermost stratosphere. This effect could be responsible for more streamer events since the lower stratosphere is more susceptible to synoptic-scale causing perturbations generated in the (sub-)tropical troposphere. Moreover, in a warmer troposphere, the generation of tropospheric waves could be different. Even more synoptic-scale waves could be generated. Since easterly winds dominate the middle and upper stratosphere in summer (which is out of the model domain) and prevent the upward propagation of planetary waves, we expect no significant changes of streamer activity in that altitude region due to climate change.

A reduction of streamer frequencies in E39/C (from “1960” to “2015”) can be detected in both hemispheres in early winter, i.e. in the months of maximum streamer activity. In the southern hemisphere a significant reduction of streamer frequencies is found in May; in the northern hemisphere a decrease of streamer events can be identified in November. Although the changes in the northern hemisphere are not statistically significant, it is interesting that again both hemispheres show the same behaviour. Since both hemispheres react in the same way, stratospheric dynamics (variability) which are different in both hemispheres, especially in winter, might play a minor role in this altitude region (21–25 km). Another aspect supporting this theory is that the standard deviation of the streamer frequencies are of comparable magnitude in both

hemispheres. If stratospheric dynamics played a major role, the standard deviations should clearly be larger in the northern hemisphere.

The results presented in this section yield some interesting model behaviour. There are some first hints that the streamer frequency in both hemisphere might alter in a changing climate. This would certainly have an impact on the ozone budget at mid-latitudes, and possibly small parts of the observed ozone changes in mid-latitudes in recent years could be related to changes in streamer activity. Some aspects support the idea that dynamics of the stratospheric polar vortex might be of minor importance and tropospheric dynamics could have a stronger impact on the development of streamers in the lower stratosphere. The results of this model study are not convincing proofs but indications which are in line with formerly published investigations. Further analyses of long-term observations and respective model simulations are required to get more reliable conclusions.

## 5. Influence of streamers on mid-latitude ozone budget

Streamers, as discussed in the previous sections, transport tropical air masses to mid and high latitudes, i.e. air masses, which are characterised by high  $N_2O$  and low ozone values compared to mid-latitude values. Therefore, they can reduce the ozone content in the mid-latitudes. In this section, we address two questions: (1) If these streamers had the same ozone mixing ratios like mid-latitude air masses, how much ozone would be additionally released in the mid-latitudes by streamers in comparison to the photochemical ozone production? (2) Does this additional ozone have any impact on the mid-latitude ozone distribution via long-range transport? To answer these questions we apply the coupled chemistry-climate model E39/C. We use a non-feedback (off-line) simulation of the 1990s (e.g. Hein et al., 2001; Grewe et al., 2001) and compare it with the results of a sensitivity simulation, where we fill-up streamers with ozone according to the surrounding air masses. Three years are analysed after a spin-up period of 2 years. A feedback of the ozone changes on the dynamics is excluded in

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

**Climatologies of streamer events**

V. Eyring et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2002

either simulation, i.e. they have identical meteorology. By comparing the results of this simulation with those of the standard 1990 simulation, we are able to detect and to quantify the effects of streamers on the ozone distribution. For these simulations the detection criterion has to be adapted, since not only a change of the  $N_2O$  gradient has to be detected (point 1 in Fig. 2), but also the point where  $N_2O$  reaches the mid-latitude value again (point 2), which is the first poleward data point with at least the same  $N_2O$  value like point 1. Between these points 1 and 2 ozone values are linearly interpolated and adjusted to this value whenever the actual ozone mixing ratio is less than this interpolated value (shaded area II in Fig. 2). This criterion is then applied to 7 model levels, which represent approximately 30 to 100 hPa.

Figure 8 (left) shows the frequency of streamers detected in the E39/C simulation. Applying the on-line detection without any regional restrictions results in the detection of different phenomena as streamers (see Sect. 2.1.1). By scanning sequences of latitude and longitude plots of  $N_2O$ , and the streamer frequency at different heights, three regions were detected in each hemisphere, which have the same characteristics like streamers, in terms of the meridional gradient of  $N_2O$ . A region A, where upper tropospheric high pressure systems lead to a high tropopause and disturbances of the stratospheric  $N_2O$  field, which are not related to streamers. A region B, which is influenced by the polar vortex. Cut-offs of the polar vortex and also displacements of the polar vortex can lead to similar structures of the meridional gradient of  $N_2O$ , which are also not related to streamers. And a region C, which finally is characterised by streamers. The characterisation has been done on a daily basis for 4 representative months of each season. To avoid an impact of these high pressure systems and of the polar vortex, in the following we only concentrate on the region C and we are aware that we may lose some streamers, which can reach to high latitudes. Therefore, this on-line detection should lead to a lower boundary of the number of streamers and the chemical effects.

Figure 8 (right) clearly shows the vertical structure of streamer events, with a maximum at 70 hPa and decreasing values above, agreeing well with previous findings (see

**Climatologies of streamer events**

V. Eyring et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2002

Sect. 3.3). It also indicates a tendency of higher streamer frequencies with deep poleward intrusion at higher altitudes. The air masses detected between 30 and 100 hPa during a year amount to  $155.5 \cdot 10^{15}$  kg (Table 4) with higher contributions from the northern hemisphere than from the southern hemisphere. The seasonal cycle in the southern hemisphere is much less pronounced than in the northern hemisphere. Minimum (maximum) values are found in the spring (fall) season of both hemispheres. However, this result is largely dominated by the streamer events at lower altitudes (60 to 100 hPa), which represent around 65% of all detected streamers (30 to 100 hPa). At higher altitudes (30 to 40 hPa) streamers mainly transport air masses into the winter hemisphere (NH for DJF and SH for JJA) with a very pronounced seasonal cycle. The region 30 to 50 hPa (approx. 21–25 km) shows the same with a less pronounced seasonal cycle, though. Below 60 hPa this air mass exchange pattern changes: Streamers transport more mass into the summer hemisphere. As expected, the results for the altitude region 30 to 50 hPa (Table 4) confirm the results presented in Table 3.

The additional ozone source in the perturbation simulation depends on two factors (see Fig. 9), the detected air volume (Table 4) and the surrounding ozone concentration. The larger the detected volume the more ozone is released in the perturbation simulation and the flatter the latitudinal ozone gradient the less ozone is released. This artificial source has the same pattern as the streamer frequency (Fig. 10, shaded areas). Figure 9 shows the strength of the photochemical ozone source in the region of the streamers in comparison to the streamer ozone source. In general, the mean photochemical ozone source (photolysis of  $O_2$  and subsequent reaction with  $O_2$ ) of 0.10 to 0.12 pptv/s is smaller in all seasons than this artificial streamer ozone source of 0.30 to 0.48 pptv/s. The region, where streamers occur, i.e. around 70 hPa at mid-latitudes (Fig. 8), is characterised by minimal ozone production. The hemispheric deviations from mean photochemical ozone production are quite large and mirror the variations of the solar zenith angle. The hemispheric variations in the streamer ozone source are much less pronounced. In all seasons, more ozone is released in northern hemisphere streamers than in the southern hemisphere.

**Climatologies of  
streamer events**

V. Eyring et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2002

The comparison of the simulation with the additional ozone source with the standard simulations is presented in Fig. 10. The additional ozone source affects the ozone concentration only below 40 hPa. In the region above that height the short lifetime inhibits a transport of the ozone perturbation. Two regions with maximum perturbation can be found at around 100 hPa and 20° N and 20° S, resulting from the location of the additional ozone source and the maximum of the ozone lifetime at 100 hPa. The ozone released in the streamers yields an increase in the mid-latitude lowermost stratosphere of 100% in the winter hemisphere and around 75% in the summer hemisphere. Stratosphere-troposphere exchange leads to an increase of tropospheric ozone values of roughly 40 to 50% in the southern winter hemisphere (JJA) and 50 to 75% in the northern winter hemisphere (DJF). In the summer hemisphere and in the tropics, vertical mixing (convection) leads to a faster destruction of ozone yielding an increase of roughly 30%.

From our simulations it seems that the importance of the streamers for the ozone concentration strongly depends on the altitude of the steamer occurrences. The additional steamer ozone at around 25 km (30 hPa) lead to an increase in the order of 1 to 5%, whereas at around 15 km (100 hPa) it can be as high as 400%, which means that locally ozone can be reduced by 80% through steamer mass exchange. Consequently, the lowermost stratosphere and the ozone content is not only determined by stratospheric ozone transported downwards from the stratosphere, but also by ozone at tropical tropopause levels transported towards higher latitudes. At the tropopause ozone increases by roughly 40% in the summer hemispheres and 100% in the winter hemispheres. This means that streamers lead to a decrease of approximately 30% and 50% of the ozone at the tropopause in the standard simulation for summer and winter hemispheres, respectively. Other sources of the tropopause ozone budget are the polar stratosphere, the troposphere, as well as in situ ozone production, e.g. by nitrogen oxides from tropical lightning (Grewé et al., 2002).

## 6. Conclusions

A new criterion has been applied to establish a climatology of streamer frequencies. For the first time, a 9 year data record has been used to get more reliable information about the geographical distribution and the annual cycle of streamer activity in the altitude region from 21 to 25 km. The results from the KASIMA model, which employs ECMWF re-analyses between 1990 and 1994 and operational analyses thereafter until 1998, show a pronounced seasonal dependence of streamer activity with highest frequency values in northern mid-winter and late southern winter. Very low streamer frequencies have been found during summer months in both hemispheres. The KASIMA climatology has been employed to evaluate the corresponding results of the coupled chemistry-climate model E39/C. It shows a satisfactory agreement, except for southern winter and spring conditions where E39/C clearly underestimates the number of streamer events. Neither the streamer frequency climatology of KASIMA nor that of E39/C indicate strong standard deviations, in particular not for northern winter, i.e. the streamer frequencies and also the geographical distribution do not differ for different stratospheric conditions, i.e. years with a cold and stable polar vortex and those with a warm and unstable polar vortex. This indicates that the direct impact of the dynamics of the stratospheric polar vortex, which is well described by E39/C (Hein et al., 2001), is weak for the generation and development of streamers in the lower stratosphere. In agreement with formerly published investigations (e.g. Chen et al., 1994; Waugh, 1996) it seems that synoptic-scale waves originating in the troposphere are the main drivers for streamer events in the lower stratosphere. This gives an important hint for the possible origin of the cold bias in E39/C, which is also found in late winter and spring, especially in the southern hemisphere. The coarse horizontal resolution of E39/C (i.e. T30) probably hinders the adequate forcing and development of synoptic-scale waves (stationary and transient eddies) and their vertical propagation into the middle atmosphere. In the northern hemisphere, this model deficiency might be partly compensated due to the consideration of the effects of orographic gravity

### Climatologies of streamer events

V. Eyring et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

---

**Climatologies of streamer events**V. Eyring et al.

---

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2002

waves, which do not play such an important role in the southern hemisphere, yielding more realistic heat and momentum fluxes (Schnadt et al., 2002). As a consequence, planetary wave activity in the southern hemisphere of E39/C, although weak, is underestimated considerably. Therefore, we believe that the cold bias of E39/C in the south polar region in winter and spring and the obvious underestimation of streamer activity in the lower stratosphere during this time of the year, do have the same origin, i.e. the model does not adequately simulate tropospheric synoptic-scale waves in the southern hemisphere.

In literature (e.g. Tibaldi et al., 1990; Hamilton et al., 1999) clear hints have been presented that higher horizontal and vertical model resolutions reduce the (extra-tropical) cold bias in climate models at all stratospheric heights, particularly in the southern hemisphere. In the extra-tropical troposphere, low resolution models (e.g. T21) show a different behaviour from higher resolution models (T42 or even higher), for example, a too weak southern hemisphere zonal flow, or horizontal momentum fluxes which are underestimated in both hemispheres. In Hein et al. (2001) it could be demonstrated that increasing the number of vertical model layers from 19 to 39 in ECHAM/CHEM while keeping the horizontal model resolution constant (T30), yields a much better representation of lower stratospheric dynamics, especially in the northern hemisphere. For example, E39/C shows a satisfactory dynamic variability with cold and stable polar winters as well as warm winters including pronounced warming events. Further model studies are required to give more reliable information about the relation between tropospheric wave forcing, streamer activity in the lower stratosphere, and the cold bias in climate models.

The climate change sensitivity studies employing E39/C do not indicate dramatic changes, neither the geographical distribution of streamer activity nor the number of streamer events. The seasonal cycle does not change in the different simulations (“1960”, “1980”, “1990”, and “2015”), i.e. low streamer activity is always found in summer and maximum activity in winter. A slight increase of streamer frequencies is simulated for summer months and a reduction of streamer activity in winter, comparing the

**Climatologies of streamer events**

V. Eyring et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2002

frequency values of the “1960” simulation with those of “2015”. Although these changes are partly significant, they cannot explain larger parts of observed mid-latitude ozone reduction, which have been underestimated in most models.

Sensitivity experiments with E39/C have been used to assess the impact of streamers on the ozone budget at mid-latitudes. As found in recent investigations, an altitude dependency of the mass of streamers has been indicated by E39/C results. A simple model assessment shows that the effects of streamers on the mid-latitude ozone distribution have much larger impacts in the lower stratosphere than in the middle stratosphere. The decrease of ozone at around 25 km is of the order of less than 5% whereas at around 15 km it can reach 80%. Therefore, it is obvious that a realistic simulation of streamers (amount, distribution, seasonal cycle) in CCMs is necessary to calculate the ozone budget at mid-latitudes in a realistic way. The current study indicates that this requires an adequate representation of horizontal transport processes.

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**Climatologies of streamer events**

V. Eyring et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2002

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**Climatologies of  
streamer events**

V. Eyring et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2002

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**Climatologies of streamer events**

V. Eyring et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2002

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**Climatologies of streamer events**

V. Eyring et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2002

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**Climatologies of  
streamer events**

V. Eyring et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2002

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## Climatologies of streamer events

V. Eyring et al.

**Table 1.** Main model features for E39/C and KASIMA

Model	Model type	Horiz. Resol.	Vertical Levels	Lower Boundary	Upper Boundary	Tracer	Simulation
<b>E39/C</b>	Coupled chemistry-climate model (CCM)	T30	39	0 km	30 km	N <sub>2</sub> O	20-year time-slice experiment under conditions of the early 1990s
<b>KASIMA</b>	Combination of diagnostic and prognostic model (CTM)	T42	63	10 km	120 km	Idealised tracer representing stratospheric N <sub>2</sub> O	Temperature field nudged towards ECMWF analysis: 1990-98

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2002

## Climatologies of streamer events

V. Eyring et al.

**Table 2.** Mixing ratios of greenhouse gases and NO<sub>x</sub> emissions of different natural and anthropogenic sources adopted for the model simulations

		1960	1980	1990	2015
CO <sub>2</sub>	[ppmv]	317	337	353	405
CH <sub>4</sub>	[ppmv]	1.26	1.57	1.69	2.05
N <sub>2</sub> O	[ppmv]	295	303	310	333
Cl <sub>y</sub>	[ppmv]	0.7	2.3	3.4	3.1
NO <sub>x</sub> lightning	(Tg(N)/year)	5.1	5.2	5.3	5.6
NO <sub>x</sub> air traffic	(Tg(N)/year)	0.0	0.3	0.6	1.1
NO <sub>x</sub> surface (total)	(Tg(N)/year)	21.9	29.9	33.1	43.8
NO <sub>x</sub> surface (industry, traffic)	(Tg(N)/year)	11.8	19.5	22.6	32.9
NO <sub>x</sub> surface (soils)	(Tg(N)/year)	5.5	5.5	5.5	5.5
NO <sub>x</sub> surface (biomass burning)	(Tg(N)/year)	4.6	4.9	5.0	5.5

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Print Version

Interactive Discussion

© EGU 2002

**Climatologies of streamer events**

V. Eyring et al.

**Table 3.** Mean streamer frequencies between 20° and 70° latitude in the northern (NH) and southern (SH) hemisphere calculated with KASIMA and E39/C for the altitude range between 21 and 25 km

	DJF	MAM	JJA	SON
<b>NH KASIMA</b>	0.19	0.16	0.07	0.16
<b>NH E39/C</b>	0.14	0.13	0.05	0.15
<b>SH KASIMA</b>	0.05	0.12	0.21	0.17
<b>SH E39/C</b>	0.07	0.12	0.12	0.10

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2002

## Climatologies of streamer events

V. Eyring et al.

**Table 4.** Mass of air detected as streamer in the E39/C simulation [ $10^{15}$  kg] for different altitude regions

	SH 30–130 hPa			NH 30–40 hPa			Global 30–50 hPa			SH 60–100 hPa			NH 60–100 hPa			Global 60–100 hPa		
<b>DJF</b>	17.4	19.1	36.5	1.7	6.7	8.4	3.4	9.8	13.2	14.0	9.3	23.3						
<b>MAM</b>	19.3	12.1	31.4	5.9	4.2	10.1	8.7	6.4	15.1	10.6	5.7	16.3						
<b>JJA</b>	18.4	25.3	43.7	7.2	0.4	7.6	10.2	2.0	12.2	8.2	23.3	31.5						
<b>SON</b>	16.7	27.2	43.9	5.2	5.8	11.0	7.7	8.7	16.4	9.0	18.5	27.5						
<b>Annual</b>	71.8	83.7	155.5	20.0	17.1	37.1	30.0	26.9	56.9	41.8	56.8	98.6						

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[I◀](#)
[▶I](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Print Version](#)
[Interactive Discussion](#)

© EGU 2002

Climatologies of  
streamer events

V. Eyring et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

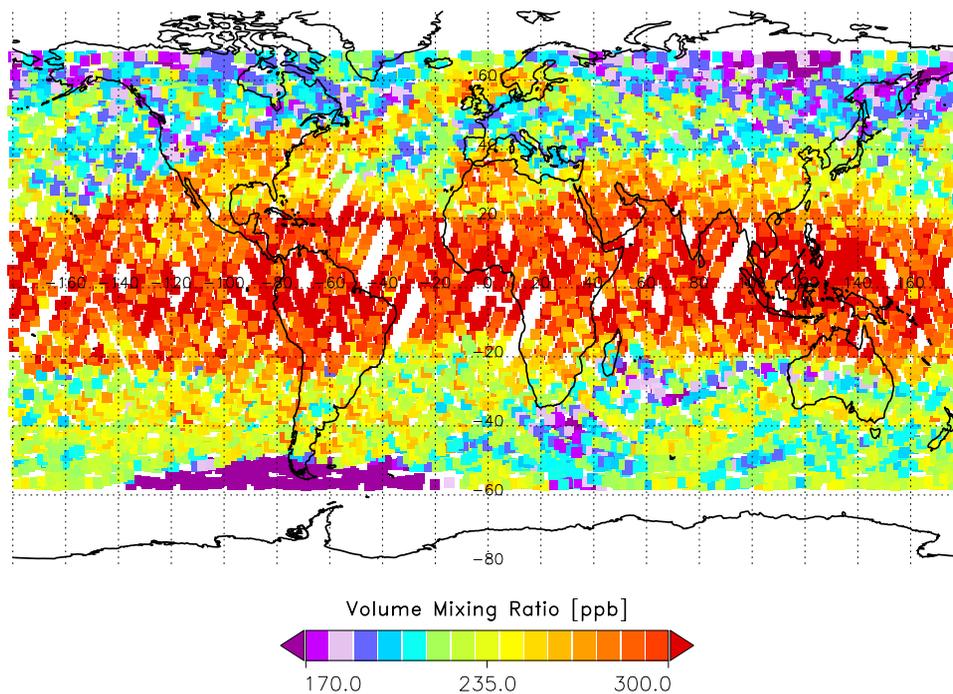
Close

Full Screen / Esc

Print Version

Interactive Discussion

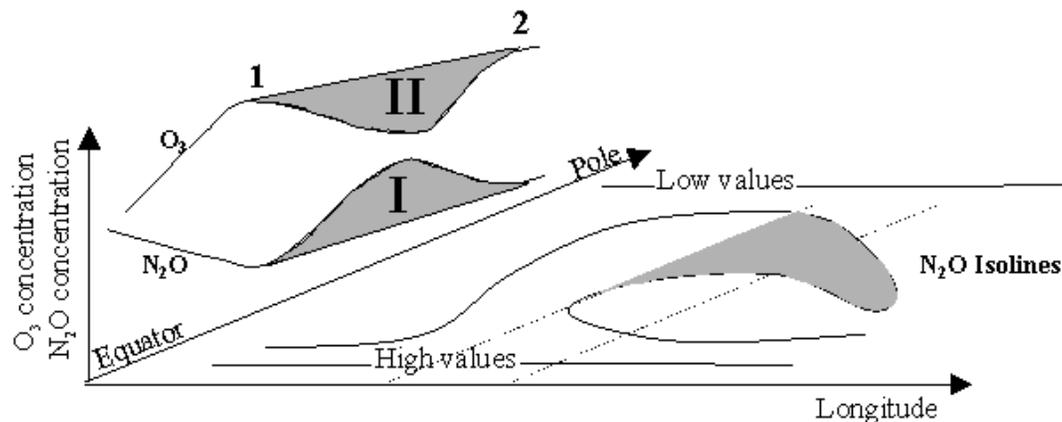
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**Fig. 1.** CRISTA-1 measurements of N<sub>2</sub>O (Version 5) at 30 hPa on November 6, 1994 (Offermann et al., 1999).

Climatologies of  
streamer events

V. Eyring et al.



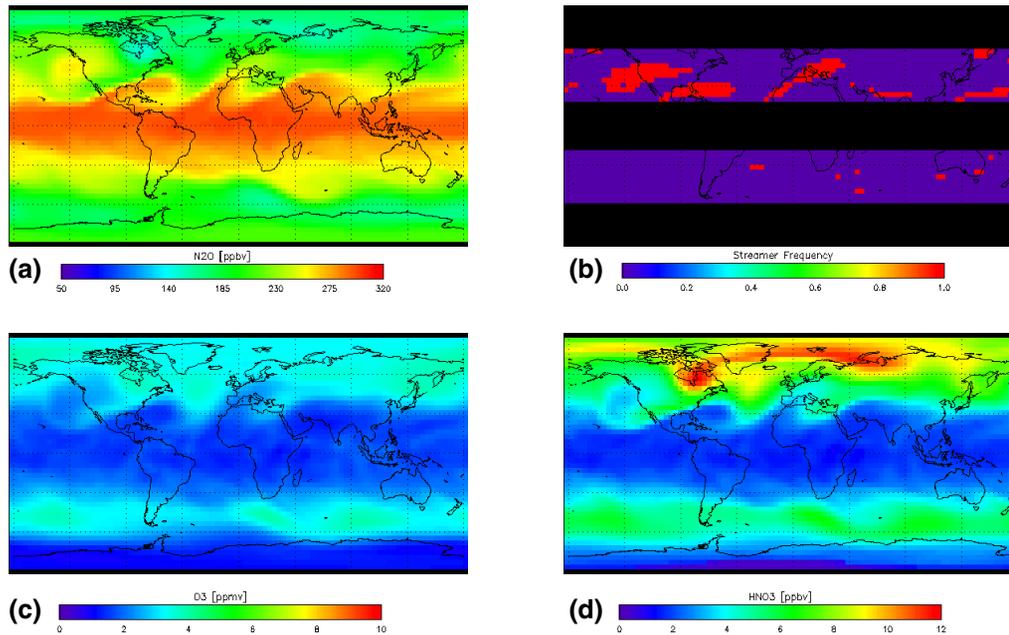
**Fig. 2.** Sketch of the streamer detection algorithm. Meridional gradient changes are used to define streamer events. For the chemical perturbation study, ozone gradients are additionally regarded.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2002

Climatologies of  
streamer events

V. Eyring et al.



**Fig. 3.** (a) N<sub>2</sub>O-field at 40 hPa as calculated by E39/C for a single time step in November. (b) Corresponding streamer-field as it is deduced from the N<sub>2</sub>O-distribution using a meridional streamer criterion. Same time step, but for O<sub>3</sub> (c) and HNO<sub>3</sub> (d).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2002

Climatologies of streamer events

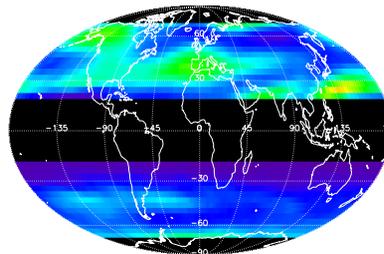
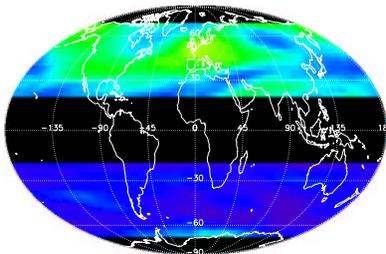
V. Eyring et al.

(a)

KASIMA: 1990-98

DJF

E39/C: 1990



(b)

MAM

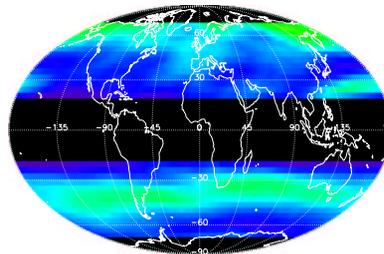
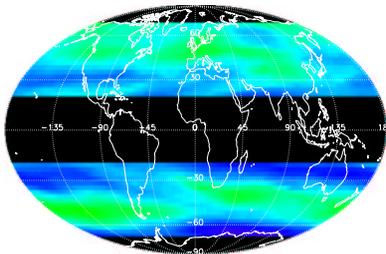


Fig. 4. Continued ....

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Print Version

Interactive Discussion

Climatologies of streamer events

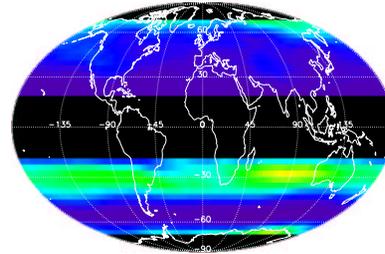
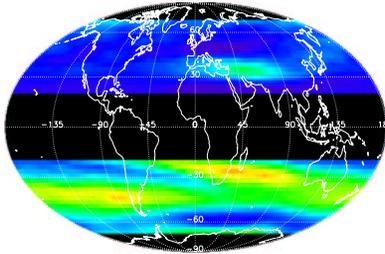
V. Eyring et al.

(c)

KASIMA: 1990-98

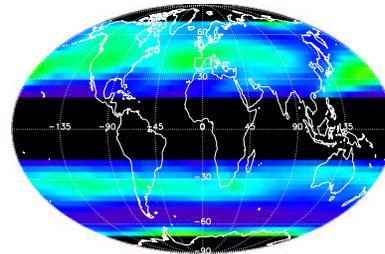
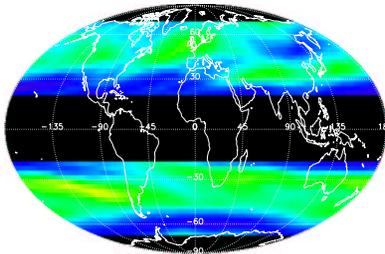
JJA

E39/C: 1990



(d)

SON

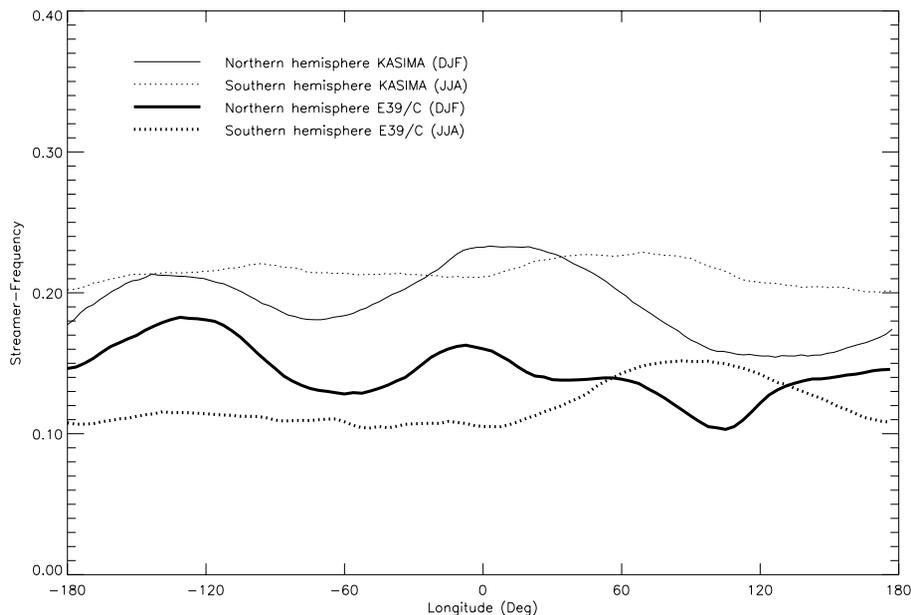


**Fig. 4.** Comparison of KASIMA (left side) and E39/C (right side) streamer-climatologies averaged between 21 and 25 km for different seasons. From top to bottom: DJF, MAM, JJA, SON-season.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Print Version	
Interactive Discussion	

Climatologies of  
streamer events

V. Eyring et al.



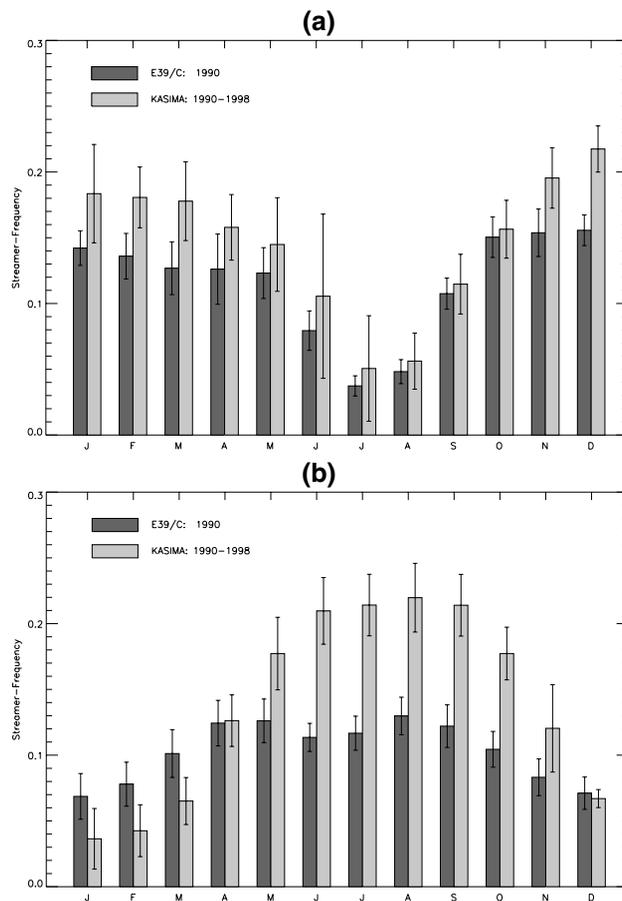
**Fig. 5.** Longitudinal distribution of streamer frequencies averaged between 20° and 70° for the altitude region 21 to 25 km as calculated by KASIMA (thin lines) and E39/C (bold lines) for the northern (solid) hemisphere in DJF and the southern (dashed) hemisphere in JJA.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2002

Climatologies of  
streamer events

V. Eyring et al.



**Fig. 6.** Seasonal cycle of streamer frequencies for KASIMA (light grey boxes) and E39/C (dark grey boxes) and the corresponding interannual standard deviation averaged between 21 and 25 km. The distribution is a mean of streamer frequencies between 20° and 70° latitude in the northern hemisphere **(a)** and southern hemisphere **(b)**.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

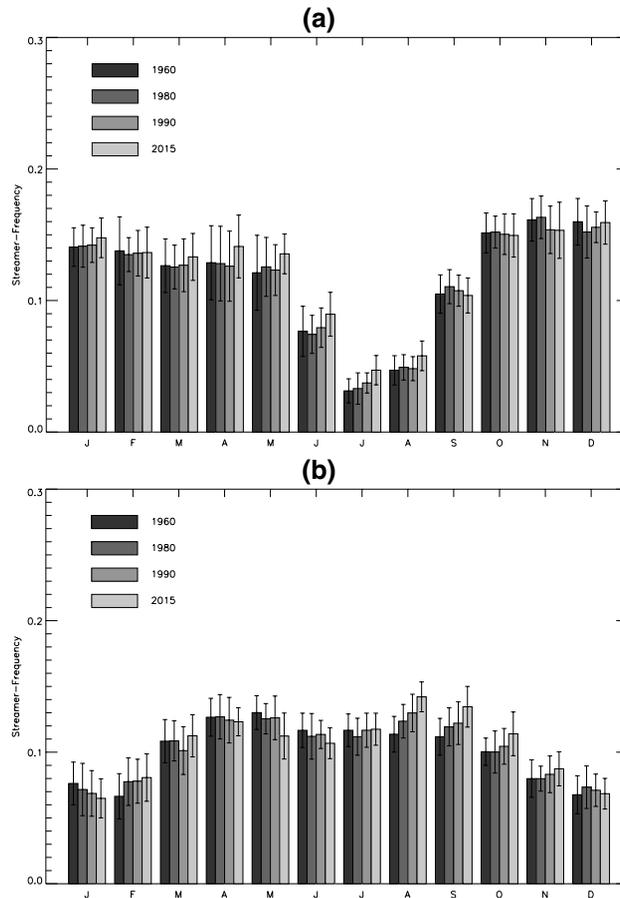
Full Screen / Esc

Print Version

Interactive Discussion

## Climatologies of streamer events

V. Eyring et al.



**Fig. 7.** Mean streamer frequencies between  $20^{\circ}$  and  $70^{\circ}$  latitude and the corresponding inter-annual standard deviation in northern **(a)** and southern **(b)** hemisphere for different time slice experiments of the E39/C model averaged between 21 and 25 km.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

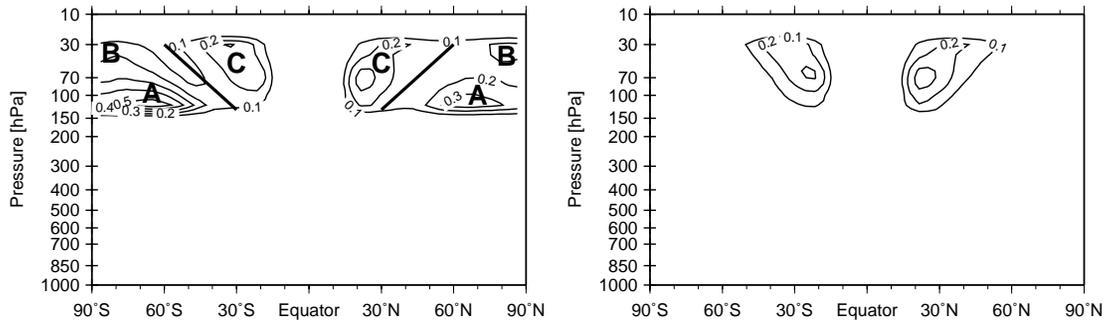
Full Screen / Esc

Print Version

Interactive Discussion

Climatologies of  
streamer events

V. Eyring et al.



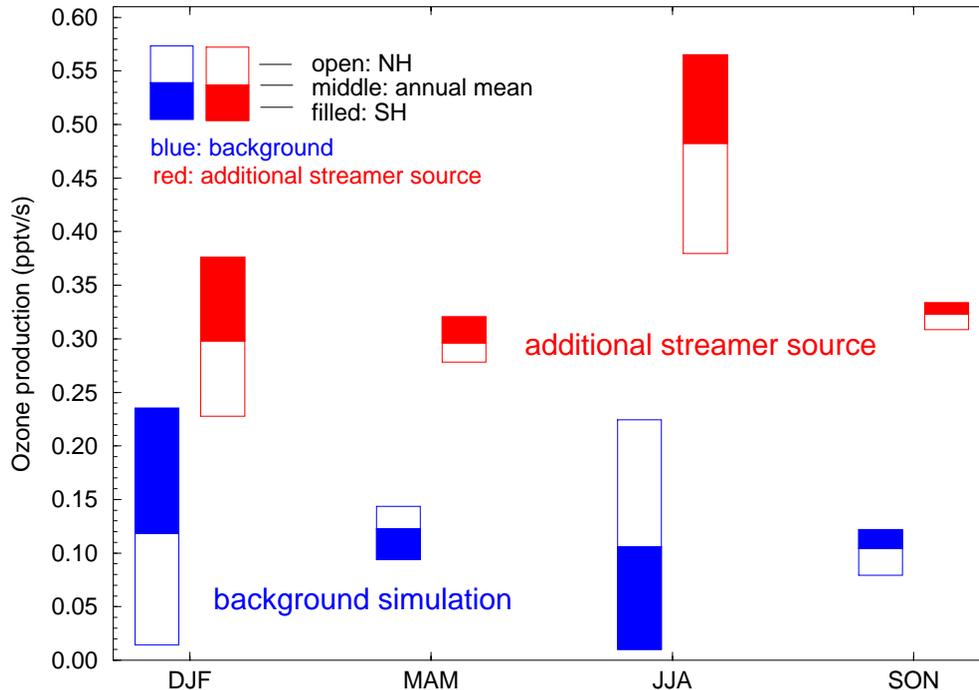
**Fig. 8.** Annual and zonal mean streamer frequency derived with E39/C using an on-line streamer identification. Left: without regional restrictions Right: with regional restrictions. The thick lines indicate the areas for the detection of the streamers. A, B, C denote areas discussed in the text.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2002

Climatologies of  
streamer events

V. Eyring et al.



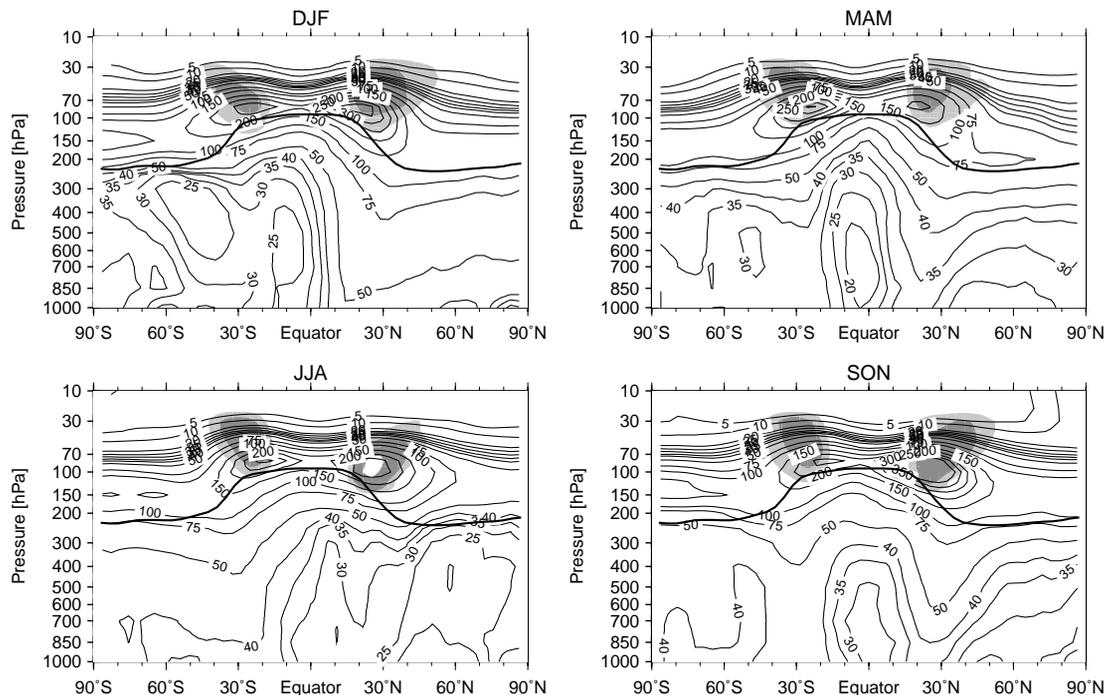
**Fig. 9.** Strength of photochemical ozone source in the region of the streamers compared to artificial streamer ozone source in the northern (open boxes) and southern (filled boxes). The mean of the additional streamer ozone source (red) is higher than the photochemical ozone source (blue) for all seasons.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

© EGU 2002

Climatologies of  
streamer events

V. Eyring et al.



**Fig. 10.** Zonal mean ozone changes [%] caused by an additional ozone source and calculated with the coupled climate-chemistry model E39/C. In reality, stratospheric streamers of ozone cause a decrease of the mid-latitude ozone concentration. These streamers are filled up with ozone according to the surrounding air masses, which represents an additional ozone source (for details see text). This ozone source is shown as shaded areas: Light grey > 0.1 pptv/s; dark grey: > 0.3 pptv/s.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)