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Climatologies of subtropical mixing derived from 3D models

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Abstract. Fingerlike structures reaching from lower into extra-tropical latitudes significantly contribute to the tropical-extratropical exchange of air masses. This is also an exchange of upper tropospheric and stratospheric air. Those so called streamers can, on a horizontal plane, be detected in N_2O or O_3 since they are characterised by high N_2O or low O_3 values compared to undisturbed mid-latitude values. 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 geographical distribution of streamer frequencies has been determined on the basis of 9 years of meteorological analyses.

For the current investigation, a meridional gradient criterion has been newly formulated and applied to the N_2O distributions calculated with KASIMA. A climatology has been derived by counting all streamer events between 21 and 25 km for the years 1990 to 1998. The results have been compared with 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). Both climatologies are qualitatively in agreement, in particular in the northern hemisphere, where much higher streamer frequencies are found in winter than in summer. In the southern hemisphere, the KASIMA analyses indicate strongest streamer activity in September. E39/C streamer frequencies clearly displays an offset from June to October, pointing to model deficiencies with respect to tropospheric dynamics. KASIMA and E39/C results agree well 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 atmospheric conditions, have been employed to answer the question how climate change would alter streamer frequencies. This shows 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 the mid-latitude distribution of chemical tracers and compounds.

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1 Introduction

The stratospheric ozone distribution is influenced not only by in-situ chemistry but also by a broad variety of different dynamical processes like tropospheric dynamics (e.g. Perlwitz and Graf, 1995, 2001; Appenzeller et al., 2000; Hu and Tung, 2002), 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 Callagham, 1993; Waugh, 1997). Observations of chemical tracers made 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 sub-tropical transport barrier (Plumb, 1996). Therefore, (quasi-) horizontal mass exchange between the tropics and mid-latitudes is restricted. But observations of chemical compounds and analyses of meteorological quantities like Ertel's potential vorticity do indicate that transport occurs in form of pronounced fingerlike structures, so-called streamers. Those frequently appear over the Atlantic and the Pacific Ocean near the storm tracks. Large areas characterised by low ozone and HNO_3 or high N_2O 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 N_2O (Version 5) at 30 hPa on November 6, 1994 is shown in Fig. 1 (Offermann et al., 1999).

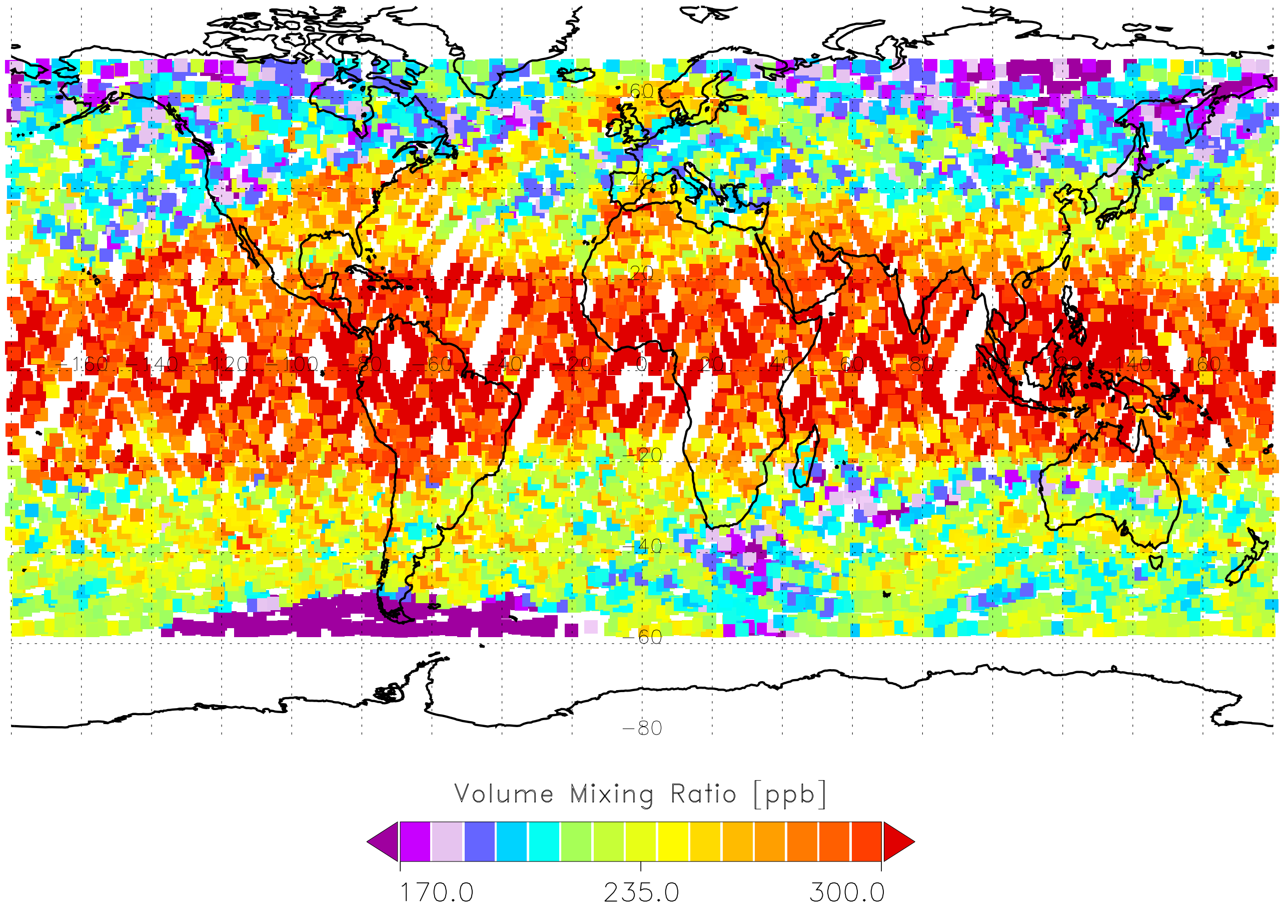

Fig. 1. CRISTA-1 measurements of N_2O (Version 5) at 30 hPa on 6 November 1994 (Offermann et al., 1999).

It is still an open question how streamers are related to large-scale dynamics. The role of the variability of the stratospheric polar vortex, which is directly connected to the activity of (quasi-stationary) planetary waves is still not well understood. There are hints that the frequency of occurrence as well as the intensity (spatial size) of streamers might be linked to enhanced wave activity (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 in ozone concentration, and therefore, parts of the smaller scale ozone variability is due to streamer events. Streamers have been identified at all altitudes from the tropopause up to the middle stratosphere (Waugh, 1996; Orsolini and Grant, 2000).

As mentioned above, a considerable number of papers have been published which deal with individual observed 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 (Waugh, 1996; Orsolini and Grant, 2000). In the current paper a 9-year data record is used to determine a streamer frequency climatology. It is based on calculations of a chemical transport model which uses ECMWF re-analyses (ERA) and operational analyses. Most of the currently available models, in particular chemical-transport models (CTMs) and chemistry-climate models (CCMs) underestimate the observed ozone trend in the northern hemisphere mid-latitudes during the last two decades. Several possible explanations for this underestimation are possible (Becker et al., 1998; Grewe et al., 1998; Solomon et al., 1998; Steinbrecht et al., 1998), but no definite conclusion about the missing or insufficiently represented processes in the models have been reached.

In this paper a numerical method is developed to detect and to count streamers (Sect. 2.1). A description of the chemical transport model KASIMA and the coupled chemistry-climate model ECHAM4.L39(DLR)/CHEM (hereafter E39/C), is given in Sect. 2.1 and Sect. 2.2. In Sect. 3, the streamer climatology obtained from KASIMA is presented and discussed. In addition, a streamer climatology

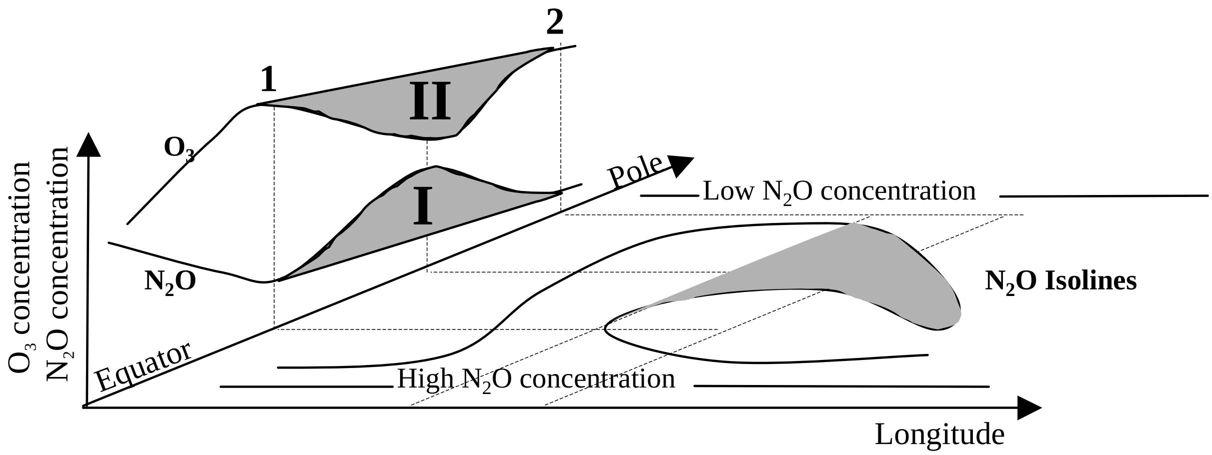

Fig. 2. Schematic longitude-latitude distribution of N_2O concentration. The shaded area is the region where the meridional criterion as defined in Sect. 2.1 detects a streamer. For the chemical perturbation study, ozone gradients are additionally regarded. The shaded area I (II) is the area, where the N_2O (O_3)-values are higher (lower) than the undisturbed mid-latitude values (see text for detail).

has been derived from E39/C, which uses the same counting algorithm. The results gained from E39/C have been compared to KASIMA. This inter-comparison aims at checking the abilities and deficiencies of E39/C with respect to the temporal and spatial distribution of streamers. 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). A summary and concluding remarks are given in Sect. 5.

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 at finding 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 at almost the same location for the different tracers and 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. The newly formulated meridional criterion detects a change in the meridional gradient of a tracer distribution averaged over a 5 km pressure altitude. The vertical averaging over this domain allows the investigation on pressure levels rather than on isentropic levels even in the presence of adiabatic wave disturbances, because the variation of pressure altitude of a typical stratospheric wave disturbance does not exceed 2–3 km even for large amplitude events like stratospheric warmings (e.g. Hsu, 1980; Kouker and Brasseur, 1986). 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 10 ppbv/rad or smaller than −10 ppbv/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 shows the robustness of this method. Whenever the criterion is fulfilled, the corresponding streamer field is set to one, otherwise zero. The following reasons limit the regions of applicability of the algorithm: (1) It is possible that the algorithm counts a streamer event, if the polar vortex is shifted off the pole, but has a simple circular structure. If the N_2O structures follows, a streamer will be detected between the pole and the center of the polar vortex because of the formal reversal of the N_2O gradient. (2) The highest N_2O 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_2O gradient. To avoid these problems in our comparison we have applied this criterion only between ±20° and ±70° latitude and not below 21 km. To derive a full streamer climatology the algorithm is applied to the N_2O-data on the respective model grid twice a day (at 00:00 and 12:00 UTC) on all vertical layers between 21 and 25 km (in E39/C: 30, 40, and 50 hPa; in KASIMA: 21, 22, 23, 24, 25 km). The distribution is normalised with the number of time steps employed and is integrated over the above mentioned altitude range.

An example of a 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 can be seen 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 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 towards Europe. The meridional streamer criterion identifies only the rising and not the trailing edge of the N_2O-finger like structures. Therefore the area in the streamer field is smaller and narrower than that of the corresponding N_2O-area.

2.1.2 Discussion of different methods

In recent studies (Orsolini and Grant, 2000; Manney et al., 2000) changes in the vertical profile were used to detect streamer events. The vertical criterion detects a streamer, whenever the local perturbation of the N_2O-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 investigation three algorithms (meridional, vertical, and zonal anomaly) have been compared (not shown). By applying each algorithm to short test periods of the 1990 E39/C time slice experiment (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.

The vertical criterion has two considerable disadvantages compared to the meridional:

1. If 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 in 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. Appenzeller and Holton (1997) investigated the time rate of change of vertical tracer gradients by advection due to vertical shear of the horizontal wind. At the onset of horizontal tracer gradients, the method accounts for the production rate of vertical gradients. This 1-dimensional problem was extended on a 2-dimensional horizontal plane by Kouker et al. (1999b) for the discussion on the advective nature of the streamer evolution. This study, however, focuses on the existence of the streamers independently of their nature. Moreover, we intend to investigate horizontal transport processes. Therefore it is not surprising 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 (not shown) 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 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 pressure altitude $z = -H \ln(p/p_0)$ as vertical coordinate where $H = 7\,\text{km}$ is a constant atmospheric scale height, p is the pressure, and $p_0 = 1013\,\text{hPa}$ is a constant reference pressure. 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 (ERA-15, until 1994) and operational analyses thereafter. Thus a consistent dataset based on the same ECMWF analyses scheme is used. 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 altitude. The model is initialised in 1990 with an atmosphere at rest and

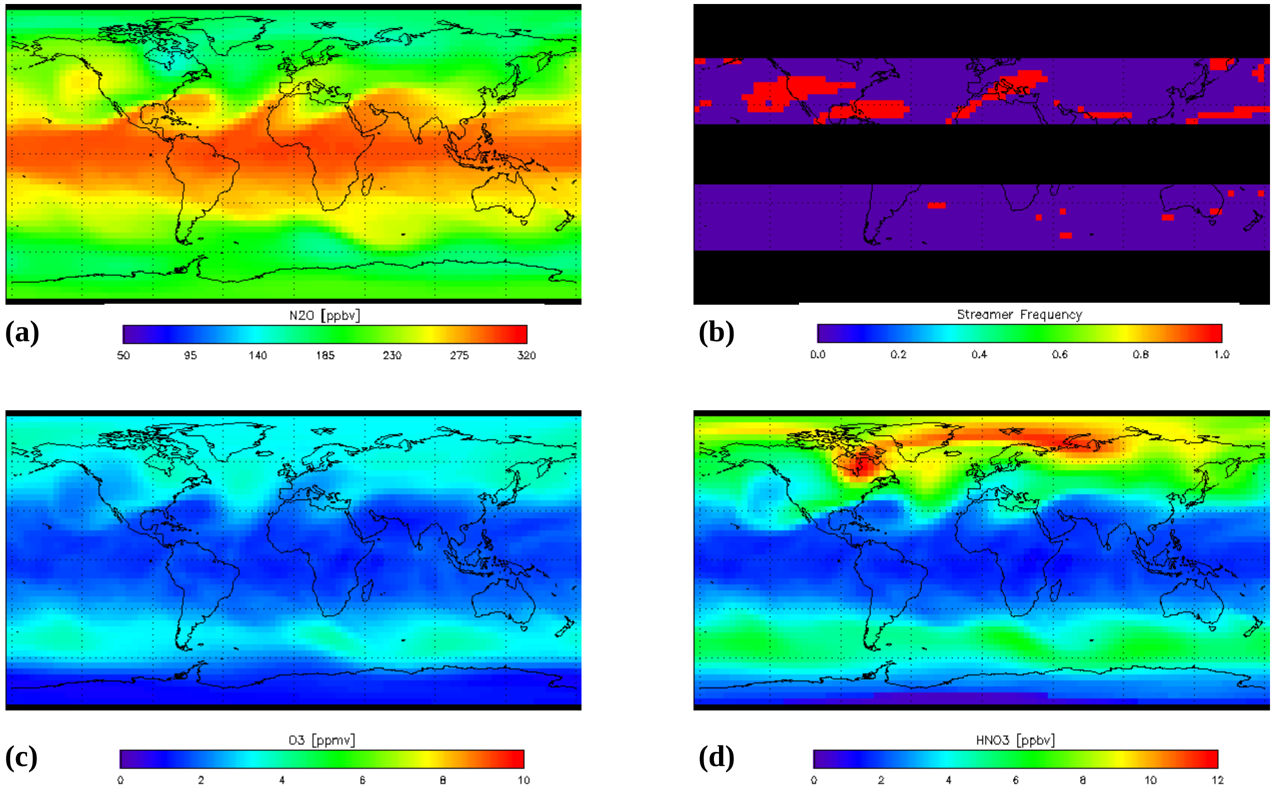

Fig. 3. **(a)** N_2O-field at 40 hPa as calculated by E39/C for a single time step in November. **(b)** Corresponding streamer-field as it is deduced from the N_2O-distribution using a meridional streamer criterion. Same time step, but for O_3 **(c)** and HNO_3 **(d)**.

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.

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's horizontal resolution is T30 with a corresponding Gaussian transform latitude-longitude grid of 3.75° × 3.75°, on which model physics, chemistry, and tracer transport are calculated. In the vertical, the model has 39 levels (L39) extending from the surface to the top level centered at 10 hPa (Land et al., 2002). 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. 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 NO_x-HO_x-CO-CH_4-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 for the "1990" simulation are prescribed according to a climatological mean of observed data between 1974 and 1994 (Gates et al., 1999). For the simulations "1960", "1980" and "2015" the transient climate change simulations with ECHA4/OPYC3 (Roeckner et al., 1999) have been additionally used.

Main features of both models are listed in Table 1.

3 Comparison of streamer climatologies in the lower stratosphere in a present climate

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

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

Model	Model type	Horiz. Resol.	Vertical Levels	Lower Boundary	Upper Boundary	Tracer	Simulation
E39/C	Coupled chemistry-climate model (CCM)	T30	39	0 km	30 km	N_2O	20-year time-slice experiment under conditions of the early 1990s
KASIMA	Combination of diagnotic and prognostic model (CTM)	T42	63	10 km	120 km	Idealised tracer representing stratospheric N_2O	Temperature field nudged towards ECMWF analysis: 1990-98

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). To study transport characteristics related to the streamer phenomena, an idealised tracer representing stratospheric N_2O is transported by the model winds: The tracer has a source region in the equatorial lower stratosphere (equator-wards of 15° latitude and at altitudes below 100 hPa) and a prescribed photolysis coefficient depending on altitude and zenith angle only. To check the accuracy of this method, model results for specific episodes have been 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 northern winter hemisphere than in the southern summer 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 region. The KASIMA as well as the E39/C results show little interannual variability. 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 notedly reduced in the northern hemisphere (spring season) compared to DJF. Both climatologies indicate smaller frequency values than in DJF. Higher values are found in the southern (fall) hemisphere, which are again systematically lower in E39/C than in KASIMA. As in DJF in MAM in the northern hemisphere there is a satisfactory agreement between KASIMA and E39/C with regard to the main activity centers, except in the western part of North America, where E39/C simulates nearly no streamers at all. 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 over South Africa, whereas in E39/C it is shifted eastward and is located between South Africa and Australia. Again, the maximum values are smaller in E39/C. Generally, the streamer events simulated by E39/C

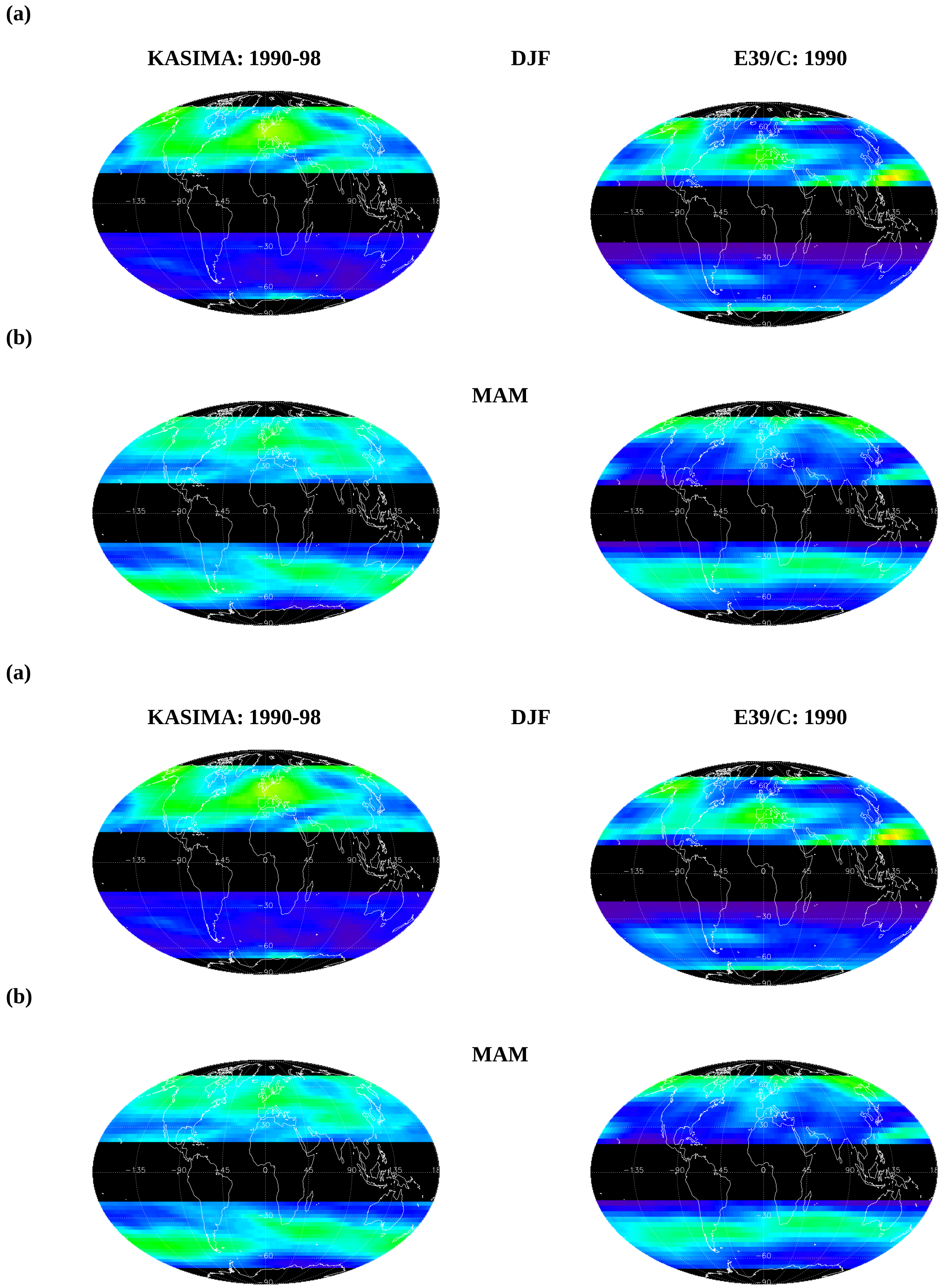

Fig. 4. Comparison of KASIMA (left side) and E39/C (right side) streamer-climatologies averaged between 21 and 25 km for different seasons. From top to bottom: DJF, MAM, JJA, SON-season.

Table 2. Mixing ratios of greenhouse gases and NO_x emissions of different natural and anthropogenic sources adopted for the model simulations

		1960	1980	1990	2015
CO_2	[ppmv]	317	337	353	405
CH_4	[ppmv]	1.26	1.57	1.69	2.05
N_2O	[ppmv]	295	303	310	333
Cl_y	[ppmv]	0.7	2.3	3.4	3.1
NO_x lightning	(Tg(N)/year)	5.1	5.2	5.3	5.6
NO_x air traffic	(Tg(N)/year)	0.0	0.3	0.6	1.1
NO_x surface (total)	(Tg(N)/year)	21.9	29.9	33.1	43.8
NO_x surface (industry, traffic)	(Tg(N)/year)	11.8	19.5	22.6	32.9
NO_x surface (soils)	(Tg(N)/year)	5.5	5.5	5.5	5.5
NO_x surface (biomass burning)	(Tg(N)/year)	4.6	4.9	5.0	5.5

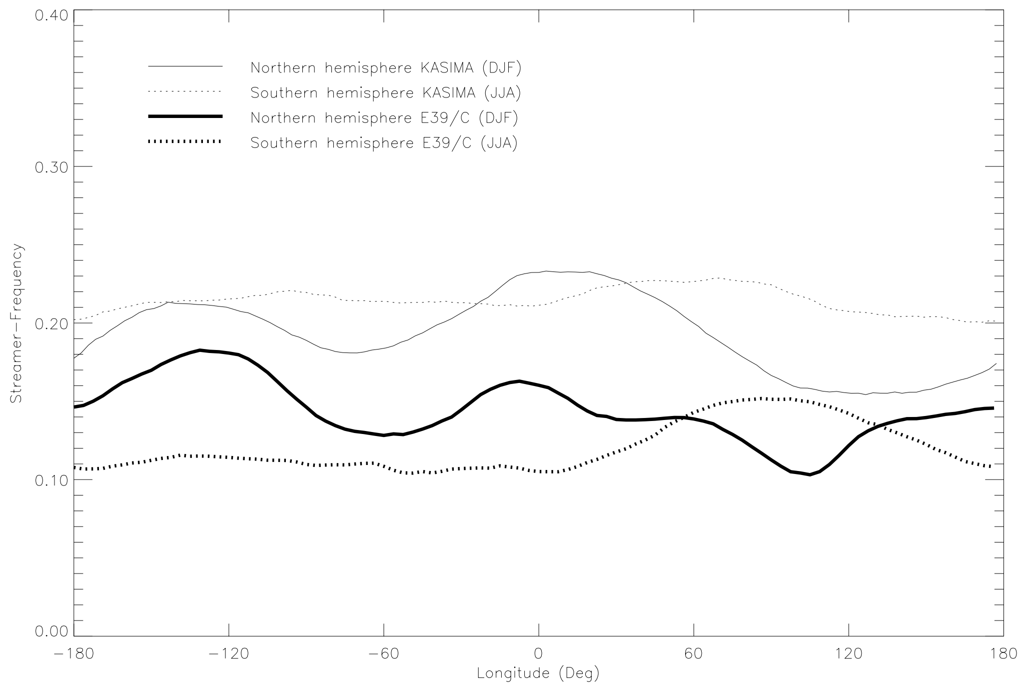

Fig. 5. Longitudinal distribution of streamer frequencies averaged between 20° and 70° for the altitude region 21 to 25 km as calculated by KASIMA (thin lines) and E39/C (bold lines) for the northern (solid) hemisphere in DJF and the southern (dashed) hemisphere in JJA.

are concentrated in a smaller latitudinal belt (20° S–70° S) than indicated by the KASIMA results. The much 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° S–70° 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). Again, the region of streamer activity in E39/C is simulated in a smaller latitudinal band than it is calculated by KASIMA. As discussed for the other seasons, KASIMA results show higher values of streamer frequencies in both

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
NH KASIMA	0.19	0.16	0.07	0.16
NH E39/C	0.14	0.13	0.05	0.15
SH KASIMA	0.05	0.12	0.21	0.17
SH E39/C	0.07	0.12	0.12	0.10

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°–70° latitude in both hemispheres is given in Table 3, for KASIMA and E39/C, respectively. As formerly described, the frequency values derived from KASIMA for the 20°–70° latitude band 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) seasons. 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 cycles 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 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).

Whereas the annual cycle of streamer frequencies in the northern hemisphere is in good 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 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., 2003). 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 (dynamical) process, or is the poor reproduction of streamer frequencies in winter and spring a direct consequence of the cold bias?

3.3 Discussion

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 is also indicated by the relatively small standard deviations of the frequency values in winter (Fig. 6). The standard deviation refers to the interannual variability of monthly mean values. 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). Especially in DJF, the location of the storm tracks shows the same pattern as the streamer frequency (Land, 1999). E39/C storm tracks even reveal the same deviation from observations like the streamer frequencies (e.g. underestimated northward tilt in the North Atlantic region), supporting a strong link between troposphere dynamics and stratospheric streamers.

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 dynamical processes which generate planetary waves (see discussion below). The systematic underestimation of (large-scale) wave activity in the southern hemisphere

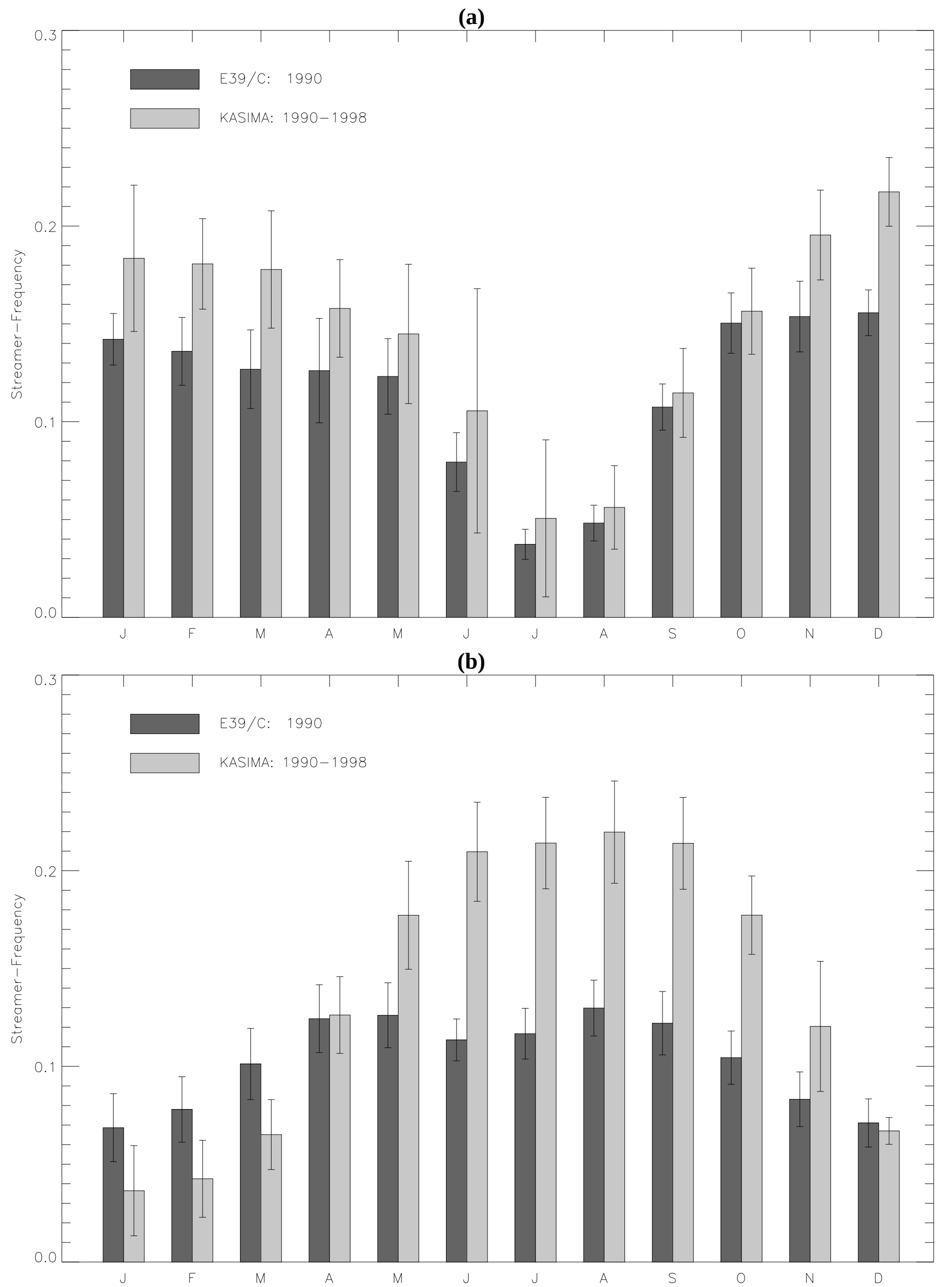

Fig. 6. Seasonal cycle of streamer frequencies for KASIMA (light grey boxes) and E39/C (dark grey boxes) and the corresponding interannual standard deviation averaged between 21 and 25 km. The distribution is a mean of streamer frequencies between 20° and 70° latitude in the northern hemisphere **(a)**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

might be one reason for the cold bias (missing dynamical heating of the polar stratosphere), and it could also be the cause for low subtropical streamer frequencies in winter and spring season.

The seasonal dependency of streamer activity found in KASIMA and E39/C agrees qualitatively well with formerly published studies (Chen et al., 1994; Waugh, 1996). Chen et al. (1994) also found that the bulk of transport out of the tropics at the 600 K-level (approx. 25 km in the tropics) is into the winter hemisphere and only little transport into the summer hemisphere. For winter in the northern hemisphere at the 400 K-level (approx. 17 km in the tropics), Chen et al. (1994) 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 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 the middle latitudes, which is consistent with the KASIMA results. It was concluded that in the northern hemisphere the transport out of the tropics fluctuates around 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 (1996) 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 the exchange of tropical air. Chen et al. showed that the tropics are most isolated in the middle stratosphere (600 K) and that much more air of tropical origin is transported into midlatitudes of the winter hemisphere in the upper (1100 K, approx. 38 km in the tropics) and lower (400 K) stratosphere. Qualitatively, the same result was gained by Waugh (1996), 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 in the current paper 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 streamer criterion discussed in Sect. 2.1.2 was applied to the N_2O 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 between those two criteria can be found in Sect. 2.1. It is well known from many climatologies (e.g. CIRA, 1992) that planetary wave activity is much smaller in summer than in winter, and that 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 above arguments that the streamer frequency is considerably 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 compared to recently published analyses, the climatology of streamer frequencies based on KASIMA results seems to be reliable, not at least since it employs 9 years of ECMWF reanalysis and operational analyses. The agreement with the corresponding climatology derived from E39/C is satisfactory, except for the winter and spring season in the southern hemisphere. Therefore, in the following E39/C sensitivity experiments are conducted to assess possible changes in streamer distributions and frequencies related to climate change.

4 Streamer activity in a changing climate

As shown before, streamer frequencies vary clearly with season, and streamers can significantly modify the ozone budget in the mid-latitudes due to irreversible mixing of (sub-) tropical air (Grewe et al., 2003). This gives rise to the question, if the streamer frequencies are different in a changing climate. To get a first idea, 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 (CO_2, N_2O, CH_4) for “1960”, “1980”, and “1990” are taken from IPCC (1990), those for “2015” are according to the IPCC-scenario IS92a (business as usual, IPCC, 1996). Upper boundary values for total nitrogen, total chlorine and the zonal CFC fields are taken from results of the Mainz two-dimensional model (Brühl and Crutzen, 1993) for all scenarios. For past and present simulations they are adapted to observations and follow projected changes for “2015” (WMO, 1999). Each model experiment was integrated over 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, that agree with observations but also intra- and inter-annual changes of dynamical 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

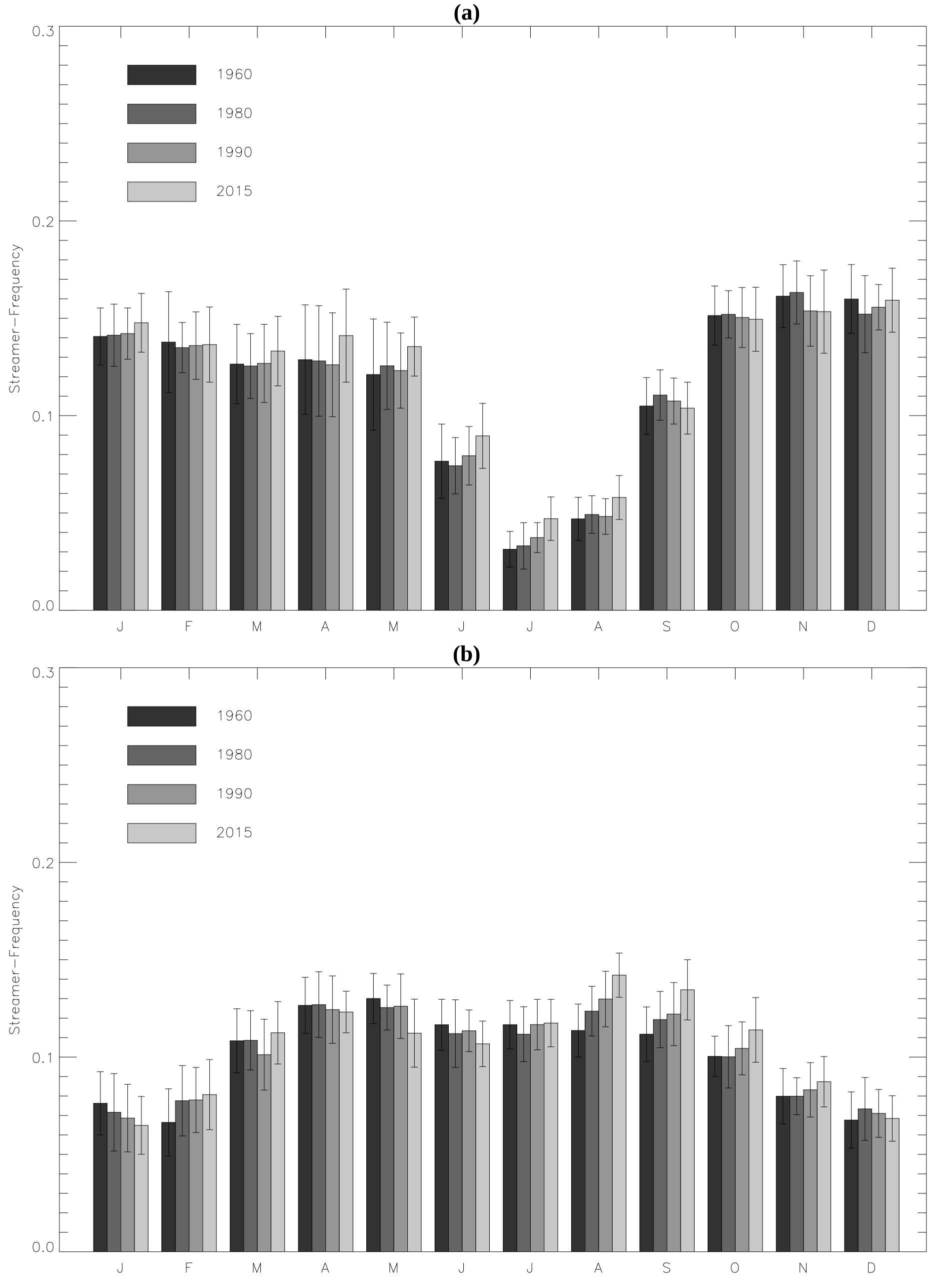

Fig. 7. Mean streamer frequencies between 20° and 70° latitude and the corresponding interannual standard deviation in northern **(a)** and southern **(b)** hemisphere for different time slice experiments of the E39/C model averaged between 21 and 25 km.

provided for an international model inter-comparison (Austin et al., 2003) which assessed 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, no principle changes in the annual cycle are indicated. It is obvious that the inter-annual standard deviation (1 sigma) within a month of one specific model experiment is mostly larger than the changes in streamer frequencies of one month between the four simulations. But there are a few exceptions: In the northern hemisphere, a significant increase in streamer frequencies is only found in the summer months (May to August), whereas in the southern hemisphere a significant increase can be found in late summer (February) and in late winter/early spring (August to October).

An obvious 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 slight decrease of streamer events can be identified in November. Although the changes in the northern hemisphere are not as clear as in the southern hemisphere, it is interesting that again both hemispheres show the same behaviour (see discussion in Sect. 5).

5 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 obtain 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 cycle 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 reasonable 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 interannual variability, in particular not for northern winter, such as 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 mainly drive streamer events in the lower stratosphere. This gives a 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 prohibits 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 waves, which do not play such an important role in the southern hemisphere, yielding more realistic heat and momentum fluxes (Schnadt et al., 2002). 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 the literature (e.g. Tibaldi et al., 1990; Hamilton et al., 1999) clear hints have been presented that a higher horizontal and vertical model resolution reduces the (extra-tropical) cold bias in climate models at all stratospheric heights, particularly in the southern hemisphere. In Hein et al. (2001) it was demonstrated that increasing the number of vertical model levels 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.

The climate change sensitivity studies employing E39/C do not indicate dramatic changes regarding 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 frequency values of the “1960” simulation with those of “2015”. Although these changes are statistically significant, they cannot explain larger parts of observed mid-latitude ozone reduction, which has been underestimated in most models. In both hemispheres, the streamer frequencies are found to increase in the summer months. 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 disturbances causing perturbations generated in the (sub-)tropical troposphere. Moreover, in a warmer troposphere, the generation of tropospheric waves may be different. More synoptic-scale waves may be generated. Since easterly winds dominate the middle and upper stratosphere in summer (which is outside 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. The northern and southern hemisphere show reduced streamer frequencies in early winter. Since both hemispheres react in the same way, stratospheric dynamics (variability) which is different in both hemispheres, especially in winter, might play only a minor role in this altitude region (21–25 km). Another aspect supporting this theory is that the interannual variability 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. Further analysis of long-term observations and model simulations are required to get more reliable conclusions.

Sensitivity experiments with E39/C have been used to assess the impact of streamers on the ozone budget at midlatitudes (Grewe et al., 2003). As found in recent investigations, an altitude dependency of the mass of streamers has been indicated by those E39/C results. A simple model assessment shows that the effects of streamers on the midlatitude ozone distribution have a much larger impact in the lower stratosphere than in the middle stratosphere. The decrease of ozone at around 25 km is below 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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