Lagrangian Transport Model Forecasts as a Useful Tool for Predicting Intercontinental Pollution Transport During Measurement Campaigns

A contribution to subproject EXPORT-E2

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Summary

In this study, the Lagrangian tracer transport model FLEXPART is shown to be a useful forecasting tool for the flight planning during aircraft measurement campaigns. The advantages of this model are that it requires only a short computation time, has a finer spatial resolution and does not suffer numerical diffusion compared to chemistry transport models (CTMs). It is a compromise between simple trajectory calculations and complex CTMs that makes best use of available computer hardware. During the ITCT 2k2 (Intercontinental Transport and Chemical Transformation 2002) and the CONTRACE (Convective Transport of Trace Gases into the Upper Troposphere over Europe: Budget and Chemistry) campaigns FLEXPART provided three-day forecasts for different anthropogenic carbon monoxide (CO) tracers: Asian, North American, and European. The forecasts were based on data from the Aviation model (AVN) of the National Center for Environmental Prediction (NCEP) and relied on the EDGAR emission inventory for the base year 1990. In several case studies, the forecast abilities of FLEXPART are analysed and discussed. The forecasts are compared with measurement data and FLEXPART post analysis simulations in forward as well as in backward mode based on ECMWF data. It is shown that intercontinental transport and dispersion of pollution plumes were well predicted, and the aircraft could successfully be directed into the polluted air masses.

Measurement Campaigns and Model

The tracer transport model forecasts for several anthropogenic CO tracers (North American, European, and Asian) with FLEXPART have been successfully used within the measurement campaigns CONTRACE (Convective Transport of Trace Gases into the Upper Troposphere over Europe: Budget and Chemistry) and ITCT 2k2 (Intercontinental Transport and Chemical Transformation 2002). During the CONTRACE campaign in November 2001 measurements of North American pollution plumes over Europe were performed with the Falcon aircraft by DLR. The ITCT 2k2 campaign took place at the North American west coast in April/May 2002, where Asian pollution plumes were intercepted by the NOAA P3 aircraft.

FLEXPART is a Lagrangian dispersion model, which simulates the transport and dispersion of non-reactive tracers, e.g. CO, by calculating the trajectories of a multitude of particles (Stohl *et al.*, 1998). Chemical processes are roughly accounted for by assuming an e-folding lifetime of CO of 36 days. The forecasts of an Asian, a North American and a European CO tracer during the measurement campaigns were based on data from the Aviation (AVN) model of the National Center for Environmental Prediction (NCEP) and the EDGAR emission inventory for the base year 1990 (Olivier *et al.*, 1996). For the post-analysis modelling FLEXPART was driven forward as well as backward in time to calculate a CO and NO_x tracer relying on data from the European Centre for Medium-Range Weather Forecasts (ECMWF, 1995) and the EDAGR 1995 emission inventory (Olivier *et al.*, 2001). FLEXPART parameterises turbulence by solving Langevin equations (Stohl and Thomson, 1999) and the ECMWF version is equipped with a subgrid-scale convective parameterization (Emanuel and Zivkovic-Rothman, 1999). The tracer concentrations on a three-dimensional grid are determined by applying a kernel method.

The advantages of FLEXPART as a forecasting tool are that it requires only a short computation time, has a finer spatial resolution and does not suffer numerical diffusion compared to chemical transport models (CTMs). It is a compromise between simple trajectory calculations and complex CTMs that makes best use of available computer hardware (Forster *et. al.*, 2002).

In the following the forecasts and post-analysis modelling of two example flights from CONTRACE and ITCT 2k2 are presented.

Flight on 19 November 2001 during CONTRACE

The left panel in Figure 1 shows the FLEXPART forecast of the mixing ratio of the North American CO tracer at 500 hPa. A North American plume is predicted to arrive over southern Scandinavia on 19 November 2001. According to this forecast the flight track of the DLR falcon was planned to go from Oberpfaffenhofen (southern Germany) to Oslo, then to Stockholm and back to Oberpfaffenhofen at this day. The right panel shows 4-days FLEXTRA forward trajectories, which fulfil a warm conveyor belt (WCB) criterion (ascent over more than 5 km altitude in 4 days, endpoint of trajectory NE of startpoint), started in the domain -110°-20° E and 20°-60°N. The trajectories show transport of North American boundary layer air to Europe within a WCB

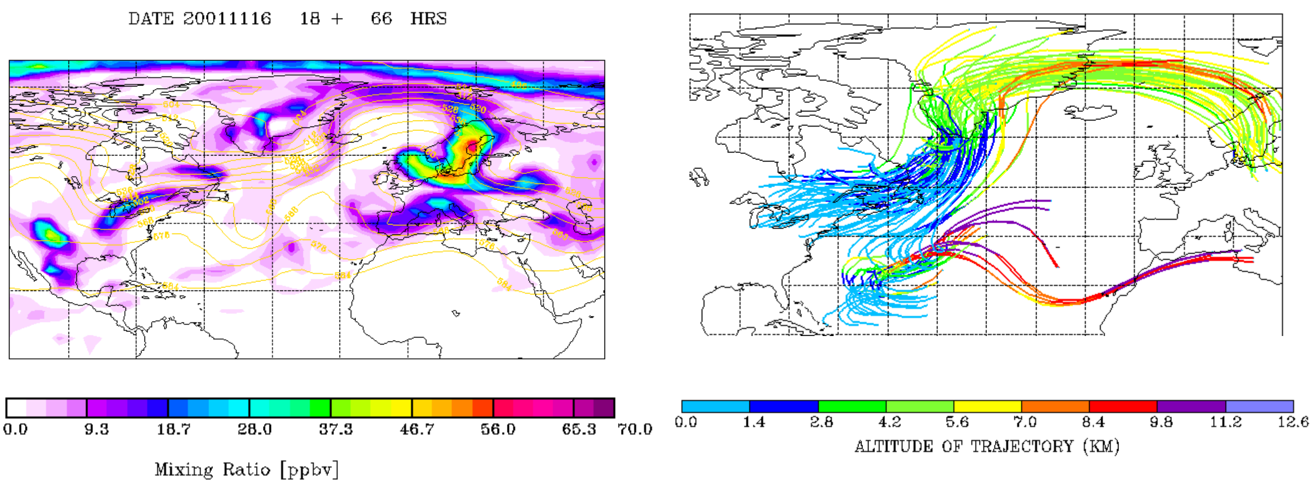

Figure 1. Left panel: FLEXPART forecast of the mixing ratio of the North American CO tracer at 500 hPa. Right panel: FLEXTRA forward trajectories, which fulfill a warm conveyor belt (WCB) criterion (see text). The ending time of the trajectories corresponds to the time in the left panel.

In Figure 2 the FLEXPART results from the post-analysis modelling are shown for the flight on 19 November 2001. The concentrations of the North American CO and NO_x tracers were interpolated to the flight track, so that the impact of the different emission sources can be estimated along the flight track and compared to measurement data (Stohl *et al.*, 2002b). In addition, the tracer age was determined, which enables the investigation of chemical processes that took place in aged air masses. The North American NO_x and CO tracers show four peaks at 12, 13, 14:30 and 16:15 UTC with tracer ages mainly between 3 and 10 days. At all these times the NO_y and CO measurements show clear enhancements over the background, i.e. the locations of the peaks are in good agreement with the measurements, but FLEXPART overestimates the increases in the plumes somewhat. NO is very low, which implies that a substantial part of NO_x has been oxidized to another species of the NO_y family and confirms a plume age of at least a few days.

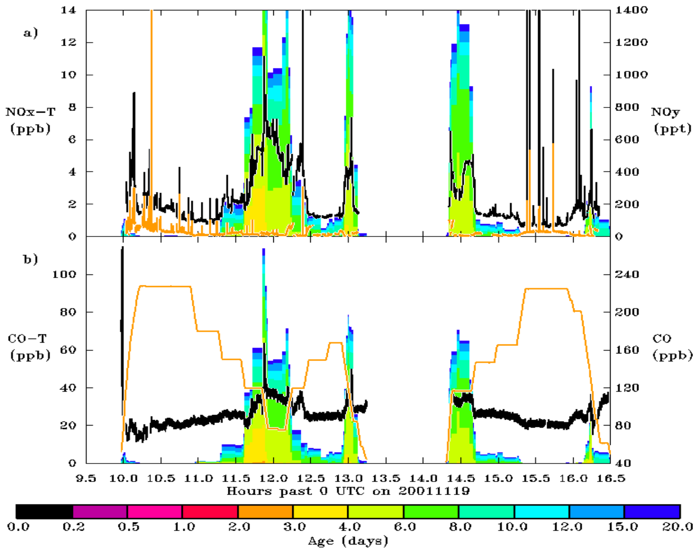

Figure 2: Age spectra (colored bars) of a North American (a) NO_x and (b) CO tracer along the flight track for the flight on 19 November 2001 calculated with FLEXPART. Aircraft measurements of (a) NO (orange line), NO_y (black line) and (b) CO (black line) are superimposed. The orange line in (b) denotes the flight altitude in km in units of 10% of the units on the CO-T axis.

Backward simulations with FLEXPART were preformed in order to establish a detailed analysis of the sources of the trace gases measured along the flight tracks (Stohl *et al.*, 2002b).

A large number of particles with unit mixing ratio are released from receptor boxes along the flight tracks and their trajectories are calculated backward in time. This is a more accurate method than traditional backward trajectory calculations (Stohl *et al.*, 2002a), as it accounts not only for advection, but also for processes like turbulence and convection. For each receptor the residence times of these particles are determined on a uniform grid (here 1x1 degree). Multiplying the residence times of the lowest 300 m (footprint layer) by the tracer's source strengths (ppbm/s) in a grid cell of an emission inventory (here EDGAR 1995) reveals the source contribution per grid cell to the tracer-mixing ratio at the receptor. Summing up these contributions finally gives the tracer-mixing ratio at the receptor.

Figure 3 shows the residence time distribution in the footprint layer and the source contribution per grid cell for particles arriving on 19 November 2001 at 11:53 UTC, where a CO peak in both model and measurements is seen (compare Figure 2). The highest residence times can be found at the east coast of North America (left panel in Figure 3). The maximum source contribution is from the New York region (right panel in Figure 3), i.e. the CO peak measured at 11:53 UTC on

19 November 2001 is part of a New York City plume that has travelled from North America to Europe.

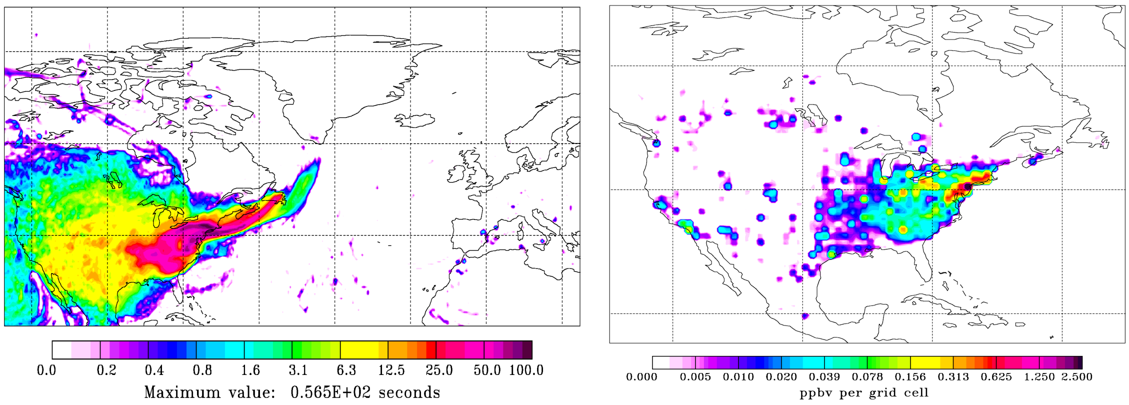

Figure 3: The left panel shows the footprint residence time distribution for particles arriving in a small receptor box (0.005° x 0.035° x 200m) along the flight track on 19 November 2001 at 11:53 UTC. The units are given in percentages of the maximum residence time. The right panel displays the source contribution per 0.5° grid box to the total CO tracer mixing ratio for the same receptor box.

Flight on 5 May 2002 during ITCT 2k2

At the beginning of May 2002 a CO plume was forecasted to travel over the Pacific towards the west coast of North America and was supposed to arrive there on 5 May 2002 (Figure 4).

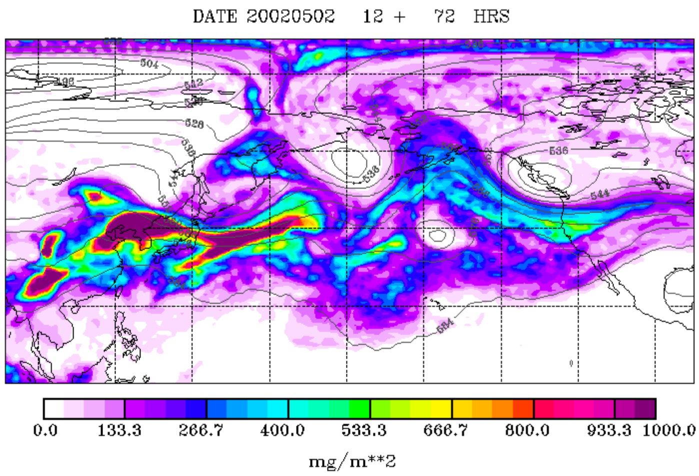

Figure 4. FLEXPART total column CO tracer forecast for the flight on 5 May 2002. Contours of geopotential height (in gpdm) are overlayed in dark grey.

According to this forecast the P3 aircraft was guided into the pollution plume on 5 May 2002. In Figure 5 the FLEXPART CO model tracer forecasts interpolated to the flight track are displayed. The forecast suggests only low and very aged European tracer (Figure 5a) and North American tracer peaks during take-off and landing (Figure 5b). The Asian CO tracer forecast (Figure 5c) shows enhancements in the tracer between 23:00 and 24:30 UTC almost exactly where CO enhancements were measured by the aircraft. NO_y is enhanced in the plume as well (Figure 5b), but NO is very low, indicating that a substantial part of NO_x has been transformed into a species of the NO_y family and suggests a plume age of several days. This is in good agreement with the FLEXPART forecasts which show a tracer age of 10 to 20 days. However, the enhancements suggested by the model are much lower (about 30 to 40 ppb) than the enhancements seen in the measurement data (about 100 ppb). This phenomenon can be traced back to several reasons.

First, a part of the measured CO might be due to forest fires which were not simulated with FLEXPART. Second, the emission inventories might underestimate the emissions in some parts of Asia. Third, FLEXPART simulates transport only and we account for chemical processes by assuming an e-folding lifetime of CO of 36 days. However, the lifetime of CO is shorter at lower latitudes than at higher latitudes, and transport often occurs from tropical regions up to high latitudes, i.e. CO lifetime is variable during transport, which might lead to errors in our simulations.

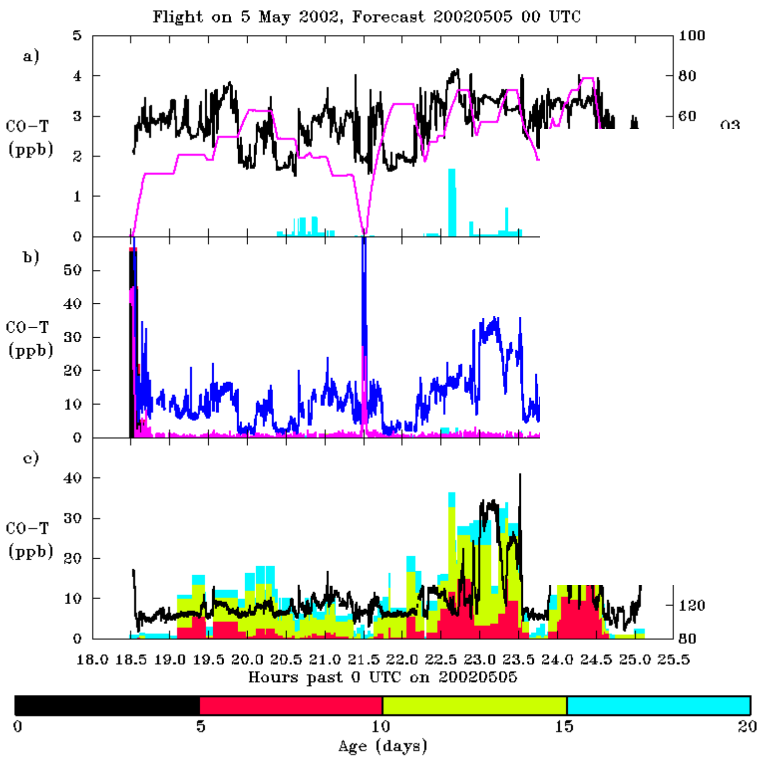

Figure 5. Aircraft measurements (black, blue, and pink lines) and age spectra (coloured bars) of three different CO tracers (Asian, North American, and European) extracted from FLEXPART model forecasts from 5 May 2002 00 UTC for the flight on 5 May 2002. (a) European CO tracer, measured O_3 (black line), and aircraft altitude (pink line). (b) North American tracer, measured NO (pink line) and NO_y (black line). (c) Asian tracer and measured CO.

FLEPXART backward simulations for the CO peak between 23:54 and 24:07 UTC (compare Figure 5c) show that the maximum residence times are in western China and parts of the Himalayan region (left panel in Figure 6). The maximum source contributions can be attributed to the mega cities in central and western China and parts of northern India (right panel in Figure 6).

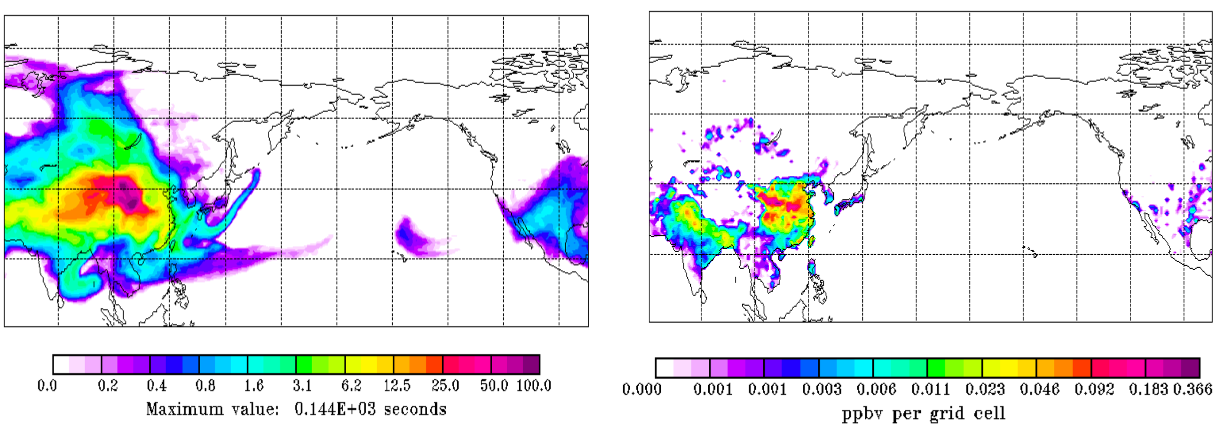

Figure 6: The left panel shows the residence time distribution for particles arriving between 23:54 and 24:07 UTC at the flight track on 5 May 2002. The units are given in percentages of the maximum residence time. The right panel displays the source contribution per 1.0° grid box to the total CO tracer mixing ratio for this time.

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