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Interim report on the KNMI contributions to the second phase of the AERO-project

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Introduction

The RLD (Dutch Civil Aviation Department) has started a policy analysis in order to find the best strategy to reduce the impacts of air traffic on the atmosphere taking into account the environmental benefits, as well as the economic impacts for the aviation industry. This is done in the AERO-project (Aviation Emissions and Evaluation of Reduction Options). The project is executed by the KNMI (Royal Netherlands Meteorological Institute), MVA-Consultancy, the NLR (National Aerospace Laboratory), Resource Analysis, and the RLD. A description of the project is given by Pulles *et al.* (1995). The AERO-project will lead to the construction of AIMS (Aviation Immission Modelling System), which is a software-shell integrating all AERO modules. A user interface will allow for the specification of scenarios, different policy measures, as well as various other assumptions. This AIMS system will be used in order to asses the environmental and economic impacts of air traffic policies.

The KNMI investigates the environmental and climatic consequences of the aircraft emissions and contributes to the APDI and ENVI modules of AIMS. APDI (Atmospheric Processes and Dispersion model) determines the 3D concentrations for all relevant substances based on repro-functions. ENVI (Direct and indirect Environmental Impact model) assesses impacts of e.g. global warming and changes in UV-radiation at the ground. In this report the KNMI contributions to the second phase of the AERO-project are presented. This includes various test and preparatory calculations for the development of the parametrizations for APDI and ENVI.

Atmospheric processes and dispersion calculations

In the first phase of the AERO-project the global 3D CTMK-model (Chemistry Transport Model KNMI) has been used to study changes in atmospheric NO_x and ozone concentrations due to aircraft emissions (cf. Wauben *et al.*, 1995a). The complex CTMK-model is not suitable for use in AIMS. Therefore repro-models will be constructed which give the 3D concentrations for all relevant atmospheric constituents. Atmospheric constituents like CO_2 with long chemical life times accumulate in the atmosphere. These substances can be homogeneously distributed in the atmosphere taking into account the past emissions of the substance (see Fortuin *et al.*, 1995). Constituents like NO_x and ozone with shorter life times are more difficult to parametrize since both chemistry and transport need to be considered. For these tracers the CTMK-model will be used to construct repro-models. Such a repro-model can be a transfer matrix that gives the change in the 3D concentration of a tracer when emissions occurs in an individual grid cell. In order to construct such a transfer matrix many runs with the CTMK-model are required. In this second phase of the AERO-project test calculations for the development of the transfer matrices were performed. During the third and last phase of the AERO-project the transfer matrices will be constructed and implemented in AIMS.

Linearity and superposition

The transfer matrix gives the global perturbation of a tracer which results from emissions in each grid cell individually. This matrix is used to obtain the perturbation of atmospheric constituents for future emission scenarios. In order to apply such an approach the linearity and superposition principles must be valid for the range of emission levels under consideration. For the base situation the 1990 emission level is considered. This situation is perturbed with the European Renaissance emission scenario for 2003, i.e. the emissions level is increased from the 1990 to the 2003 level for each individual grid cell separately. Such an additional emission is small compared to the global emissions and the resulting increase in NO_x and ozone is small compared to the background concentrations. Therefore, the effects of natural variability of the

constituents and the dependence on the initial condition were eliminated by performing a perturbation run that was identical to the base run, except for the additional emission.

The effect of such a perturbation is shown in Fig. 1. for an additional emission of 0.990 $Gg(NO_2)$/yr, i.e. 70%, in a grid cell in the NAFC (North Atlantic Flight Corridor). Due to the relatively short chemical life time of NO_x its perturbation is situated close to the place of emission. The increase in ozone is distributed more widely due to its longer chemical life time. The annual global increase is 77.8 ton (NO_2) for NO_x and 47.0 kton for ozone.
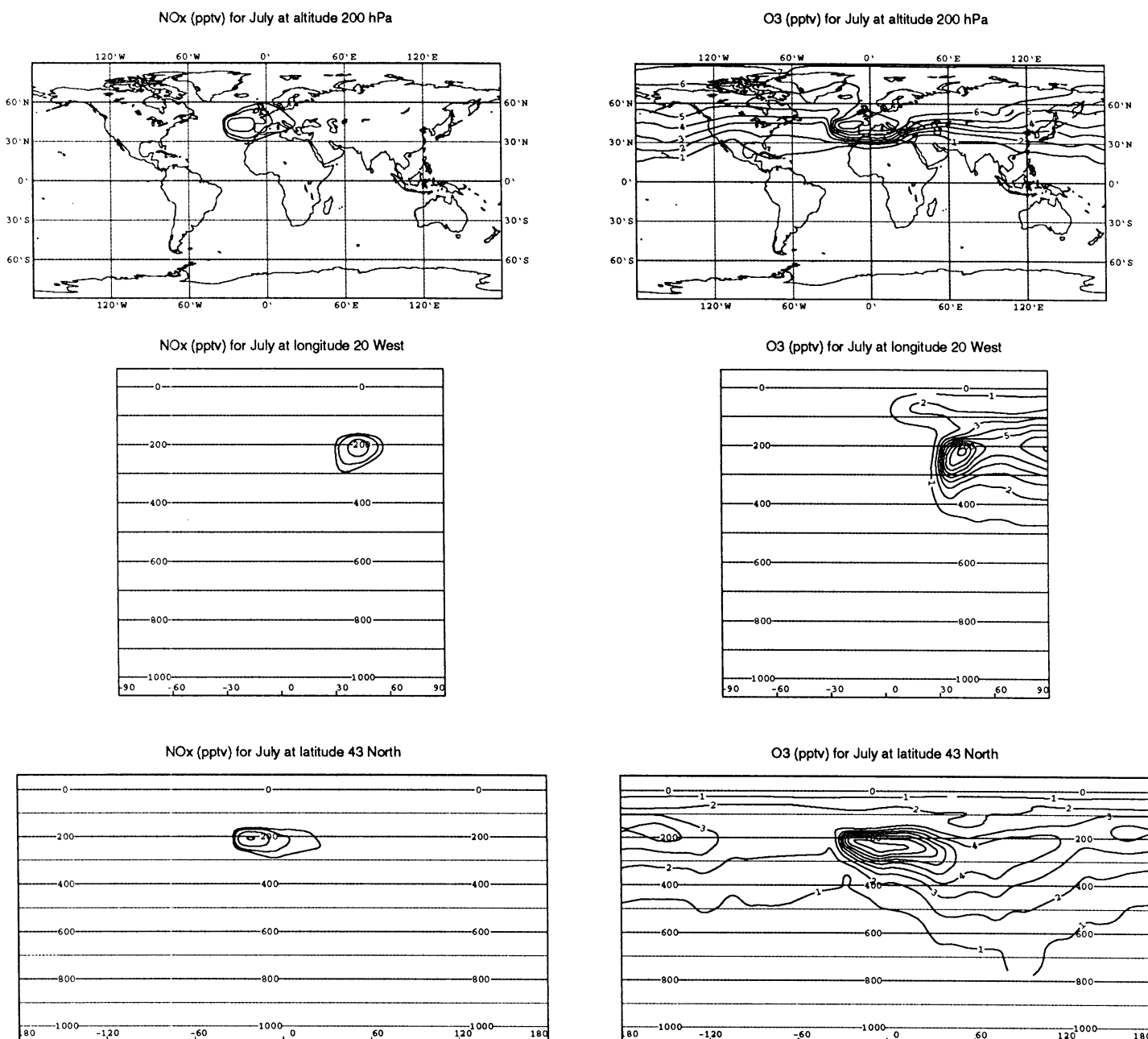

Figure 1. Perturbation of NO_x (left) and ozone (right) due to an additional emission of 0.990 $Gg(NO_2)$/yr in the grid cell near 30 West, 43 North and 200 hPa. Cross sections are given at 200 hPa (top), 20 West (middle) and 43 North (bottom). The isolines are 0.1, 0.2, 0.5, 1 pptv for NO_x and 1, 2, ..., 9 pptv for ozone.
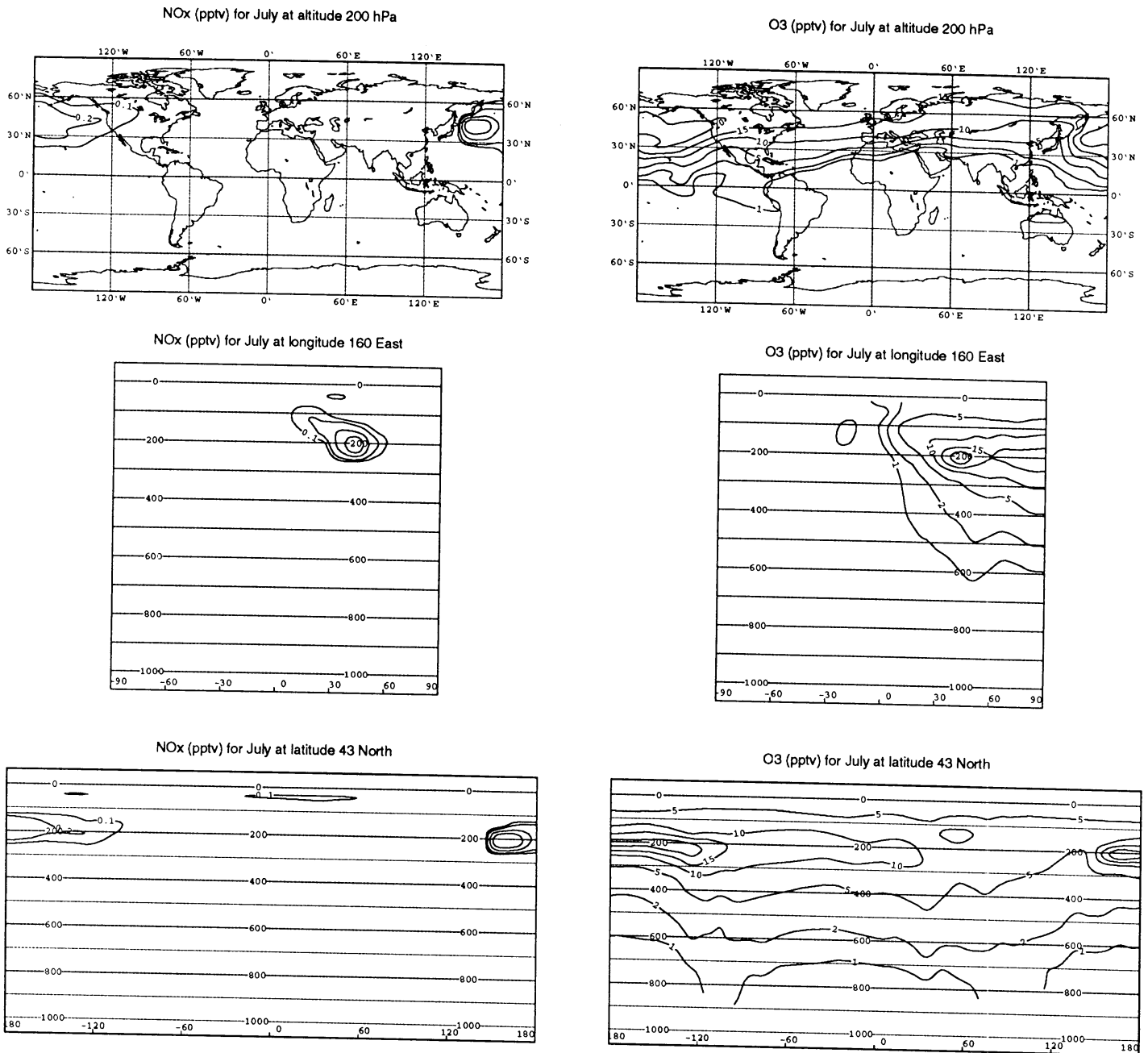
NOx (pptv) for July at altitude 200 hPa

O3 (pptv) for July at altitude 200 hPa

NOx (pptv) for July at longitude 160 East

O3 (pptv) for July at longitude 160 East

NOx (pptv) for July at latitude 43 North

O3 (pptv) for July at latitude 43 North

Figure 2. Same as Fig. 1, but now with additional emissions of 1.81 Gg(NO_2)/yr at 150 East, 43 North and 200 hPa. The isolines are 0.1, 0.2, 0.5, 1 pptv for NO_x and 1, 2, 5, 10, 15, 20 pptv for ozone.

When half of the additional emission was injected only half of the perturbation was obtained. This shows that the perturbation is linear. The difference between the perturbation obtained with the full additional emission and twice the perturbation obtained with the half additional emission is maximally about 0.0004 pptv for NO_x and 0.02 pptv for ozone, i.e. less than about 0.02%.

The perturbation in NO_x and ozone resulting from an additional emission of 1.81 $Gg(NO_2)$/yr, i.e. 74%, at cruise altitudes over Japan is given in Fig. 2. The perturbations caused by additional emissions over Japan differ from that of the NAFC. The annual global increase due to the additional emissions over Japan are 235 ton (NO_2) for NO_x and 116 kton for ozone. The emissions over Japan cause larger perturbations than the emissions in the NAFC. This is probably the result of the higher background NO_x values in the NAFC which are more saturated.

The perturbations calculated by injecting the additional emissions in the NAFC and over Japan together is almost identical to the sum of the perturbations obtained by injecting these emissions separately. The difference is maximally bout 0.0004 pptv for NO_x and 0.02 pptv for ozone. Hence, it can be concluded that the superposition principle is valid.

The transfer matrices will be used to study the effect of air traffic. The total global amount of additional emissions in this study is not small. Therefore linearity may still be a problem. The results of the model runs with CTMK using the emission scenarios for 2003 and 2015 that have been performed during the first phase of the AERO-project (cf. Wauben *et al.*, 1995a) can be compared with the corresponding results obtained by applying the transfer matrix approach. If this comparison shows that the effects of the total emissions is non-linear, it can as a first order approximation be compensated by scaling the transfer matrices such that they give the correct global contribution.

The calculation with CTMK for using the emission scenarios for 1990, 2003 and 2015 can already be used to check if the total global effect of air traffic is linear. The aircraft NO_x emissions for 2003 and 2015 are, respectively, 1.54 and 2.50 times the emissions of 1990. The total tropospheric amount of NO_x which can be ascribed to aircraft is 1.54 and 2.35 times as large in 2003 and 2015, respectively, compared to the corresponding amounts in 1990 for January, and 1.59 and 2.53 for July. The total tropospheric amount of ozone due to aircraft in 2003 and 2015 are 1.43 and 2.11 times those in 1990 for January, and 1.46 and 2.15 for July. The ratios of the NO_x emissions of aircraft for different years are approximately the same as the corresponding ratios for the total tropospheric amounts of NO_x and ozone that are produced by aircraft. The agreement is better for 2003 compared to 2015, and better for NO_x than for ozone. The linearity on a global scale is therefore best for NO_x in 2003, but it is still reasonable for ozone in 2015.

Reduction of run time

1. Coarser grids

Since many runs of the CTMK-model are required to construct the transfer matrices for NO_x and ozone some effort was put into the development of a reduced version of the CTMK-model. Special attention was given to reduction of the grid, since the chemistry and transport modules in CTMK are optimized already. The previous runs with CTMK were performed with a horizontal grid of 8 by 10 degrees and 15 vertical levels. The results obtained with CTMK by using this grid compared well with observations (Wauben *et al.*, 1995c) as well as with results obtained by other models (AERONOX, 1995). Runs with CTMK performed as part of the AERONOX project also showed that results obtained by using a horizontal grid of 8 by 10 degrees are in agreement with the corresponding results obtained with a horizontal grid of 4 by 5 degrees. Reduction of the horizontal grid to 16 by 20 degrees yielded unrealistic results for both the background concentrations and the perturbation resulting from aircraft emissions. This is illustrated in Fig. 3 which shows that the upward transport of NO_x surface emissions is too small in the coarse model, and the effect of the aircraft emissions is underestimated.
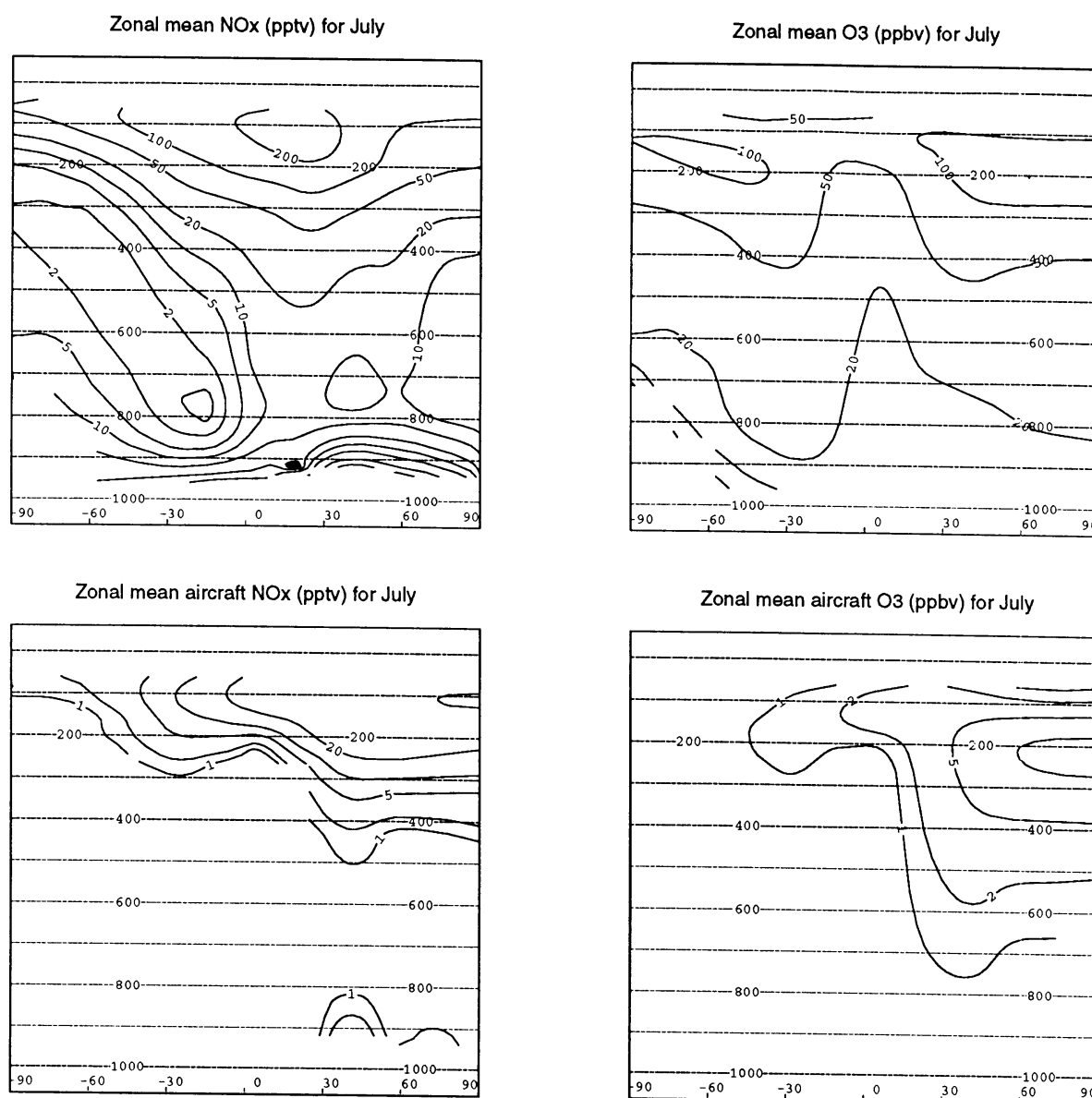
Zonal mean NOx (pptv) for July

Zonal mean O3 (ppbv) for July

Zonal mean aircraft NOx (pptv) for July

Zonal mean aircraft O3 (ppbv) for July

Figure 3. Zonal means of the background concentrations (top) and the perturbation resulting from the aircraft NO_x emissions (bottom) for NO_x (left) and ozone (right) obtained with coarse CTMK-model.

2. Perpetual month mode

Another way to reduce computer time is to run CTMK in a perpetual month mode. Instead of running CTMK for a year, some months to initialize the model and at least another 6 months including January and July to include the seasonal cycle, CTMK is run for a number of identical months. This yields realistic results for the background concentrations of NO_x and ozone. Figure 4 shows the zonal mean aircraft perturbations obtained with a perpetual July run of CTMK. The aircraft perturbation of the first month is lower than that of the following months since the emissions build up in the atmosphere. The build up of NO_x, with a chemical life time of about 10 days, is stabilized in the second month, except for the NO_x in the lower stratosphere. Ozone, however, with a chemical life time in the order of months keeps increasing. After 6 months of integration the ozone perturbations caused by aircraft NO_x emissions obtained with the perpetual CTMK run are smaller than the corresponding results obtained with the annual CTMK run.

NOx (pptv) for July after 1 month

O3 (ppbv) for July after 1 month

NOx (pptv) for July after 3 months

O3 (ppbv) for July after 3 months

NOx (pptv) for July after 5 months
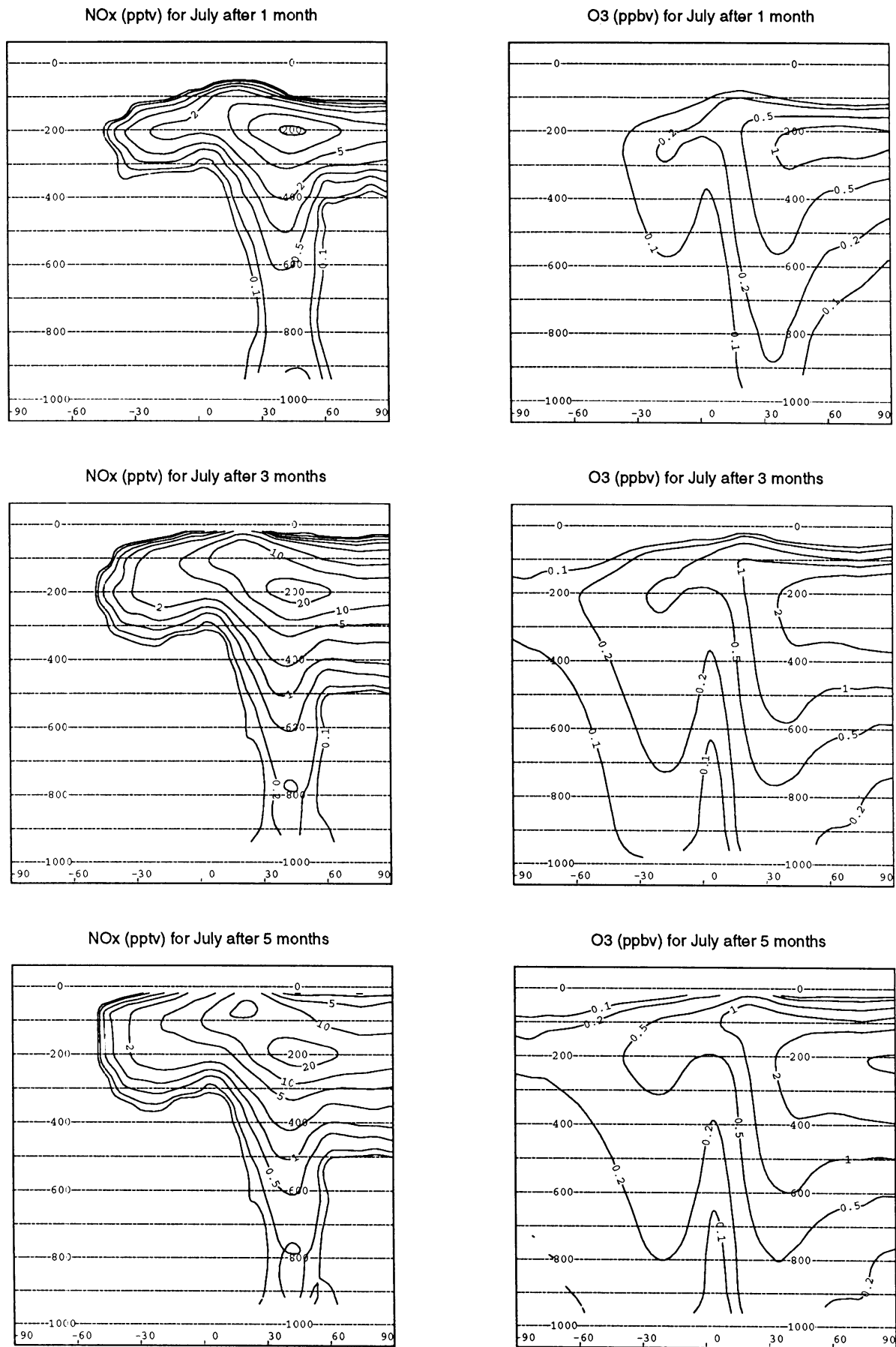
O3 (ppbv) for July after 5 months

Figure 4. Zonal mean perturbation of NO_x (left in pptv) and ozone (right in ppbv) due to air traffic for the 1990 emissions. The perturbations have been obtained after 1 (top), 3 (middle) and 5 (bottom) months of perpetual July.

3. Parallel runs

Another option is to reduce the number of CTMK runs that are used for the construction of the transfer matrices. If emissions in each individual grid are considered a total number of 36*24*15=12960 runs with CTMK would be required. However, in view of the available computer resources only a limited number of runs (less than about 50) is possible. The number of runs can be reduced by considering only subsonic aircraft (i.e. in the lower 9 levels of CTMK), by not taking aircraft emissions in certain regions into account which at present, and possibly in the near future, have a negligible effect (such as above the Antarctic or in the lower levels above oceans), by lumping individual cells together (e.g. 3 longitude and 2 latitude cells taken together), by calculating the perturbation resulting from additional emissions in several cells with one CTMK run (since the perturbation of ozone extends almost over the entire hemisphere only one cell in the northern and one in the southern hemisphere could be considered together). The assumption that the perturbation resulting from emissions in individual cells is identical (but shifted) for some cells also reduces the number of runs. This assumption can be made and validated while the runs for the construction of the transfer matrix are performed. These runs should be started for cells in different regions which might be typical for other cells as well. These regions could be the polar regions, mid-latitudes and tropical region, and the surface, lower-middle-upper troposphere and lower stratosphere. The transfer matrices for these typical regions can be used for generating a global perturbation which can be validated against a CTMK run. When the agreement is satisfactory the choice of the typical regions is correct. Otherwise more regions need to be considered. Note that the perturbations of aircraft emissions in the NAFC and over Japan (same latitude and altitude, but different longitude) are different (cf. Figs. 1 and 2). This longitudinal variation also needs to be considered in the typical region approach.

The details of the runs that will be performed during the third phase of the AERO-project will be decided in close cooperation with the RLD and Resource Analysis. The envisaged accuracy as well as the limited number of runs will thereby be taken into account. First several runs can be performed with additional emissions in individual cells, e.g 2 cellls at different longitudes ($0°$ and $180°$ which are mainly over continents and land, respectively), 3 at different latitudes (in the polar, mid-latitudinal and (sub)tropical region) and at 3 vertical levels (surface, free troposphere and at cruise altitudes). Emissions in one cell in the northern hemisphere can be considered in combination with emissions in one cell in the southern hemisphere. The typical region approach can then be applied in order to see if the transfer matrices constructed from these 18 runs give reasonable results compared to the CTMK runs for the 2003 and 2015 emissions scenarios. If not, more runs with CTMK can be considered with emissions in those areas where the largest descrepancies are found.

Two sensitivity studies

Two possible measures to reduce the atmospheric effects of aircraft have been investigated. The total amount of NO_x emitted by aircraft was not changed in both these cases, but the time of emissions and the location of the emissions was changed. In the first case considered aircraft NO_x emissions were supposed to occur during night time only (cf. Fig. 5). This resulted in a small decrease of the perturbation by air traffic compared to the case when the emissions occur day and night. Only a small change of the perturbation could be expected in view of the chemical life time of about 5-10 days for NO_x and in the order of a month for ozone. The second case assumes that all aircraft NO_x emissions occur one layer lower. These emissions reduced the perturbation by air traffic drastically. The emissions at cruise altitudes now occurred at about 250 hPa instead of at 200 hPa and hence were more often in the troposphere rather than in the stratosphere. This reduced the effect of aircraft NO_x emissions considerably.

NOx (pptv) for July standard case

O3 (ppbv) for July standard case

NOx (pptv) for July night time

O3 (ppbv) for July night time

NOx (pptv) for July layer lower

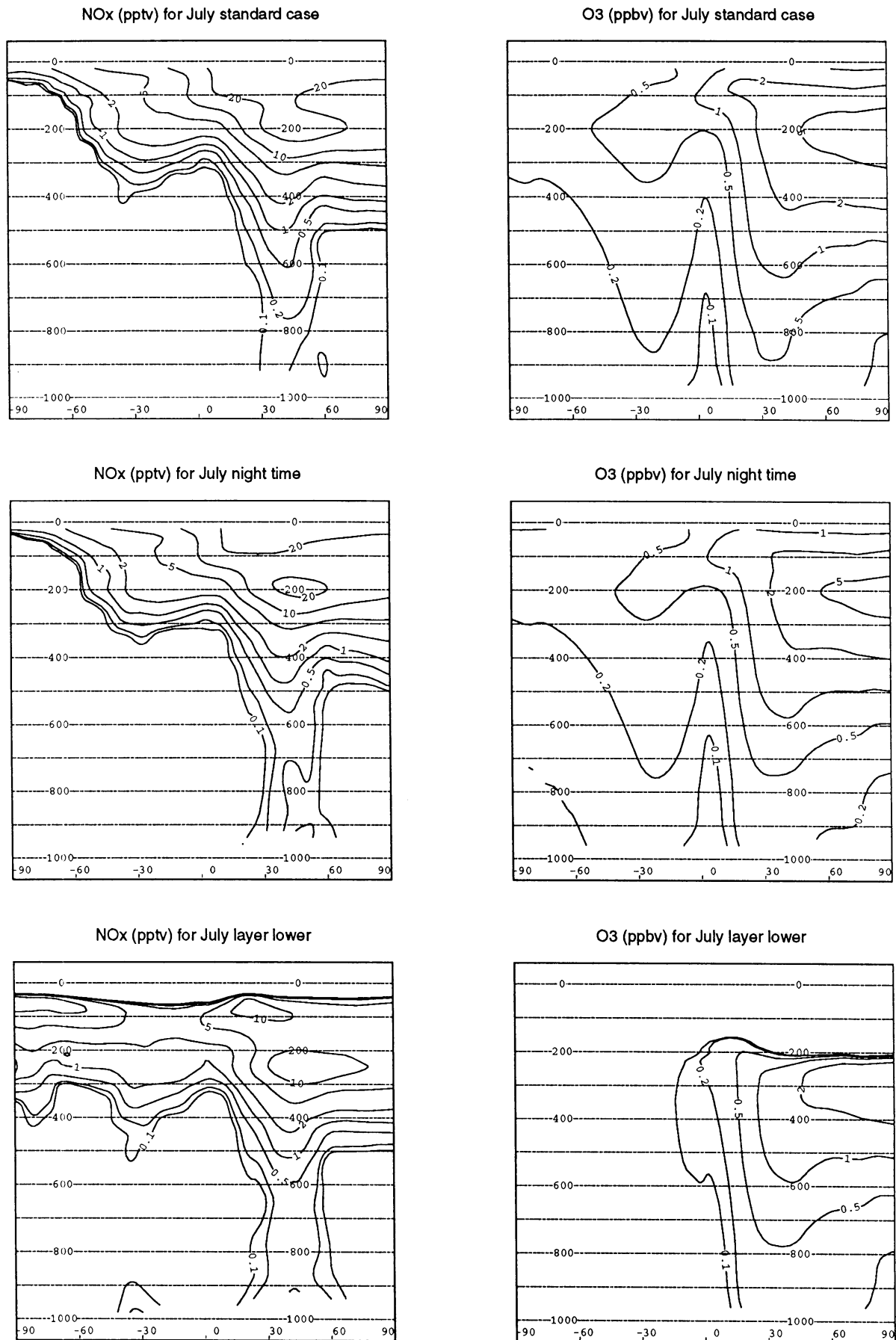O3 (ppbv) for July layer lower

Figure 5. Zonal mean perturbation of NO_x (left in pptv) and ozone (right in ppbv) due to air traffic for the 1990 emissions. The perturbations have been obtained with the original aircraft emissions (top), with emissions only during night time (middle) and with aircraft emissions one layer lower (bottom).

Recent improvements of CTMK

The CTMK model is continuously being improved. The model version used for the first and second phase of the AERO project has a fixed ozone flux from the stratosphere into the troposphere (cf. Wauben *et al.*, 1995a). However, test calculations showed that prescribing ozone concentrations at 50 hPa with climatological values yielded higher ozone concentrations in the upper troposphere which were more in agreement with observations. Furthermore a stratospheric source of NO_x is taken into account which accounts for photolysis of N_2O. The effect of these changes is an increase of the NO_x and ozone background, especially at cruise altitudes. Therefore, the relative contribution of aircraft NO_x emissions to NO_x and ozone decreases, but the absolute contribution is almost the same.

In the third phase of the AERO-project first results of stratospheric effects due to subsonic air traffic will be given. For that purpose CTMK will be extended with levels in the stratosphere. Presently a new CTMK version with more stratospheric layers is under development in cooperation with the Max-Planck Institute fuer Meteorology in Hamburg. An orientation into gasphase photochemistry for the stratosphere has also been performed.

Conclusions

The results of the preparatory work for APDI can be summarized as follows:

- The transfer matrices for the perturbation of atmospheric concentrations of NO_x and ozone due to additional aircraft NO_x emissions in individual grid cells are linear and the superposition principle is valid for emission levels between 1990 and 2003.

- Our calculations have shown that the construction of the transfer matrices must be performed with CTMK using a horizontal resolution of 8 by 10 degrees.

- Perpetual January and July runs do not give a reduction of the computer time required for each run.

- The number of runs can be reduced by lumping individual grid cells (averaging the effect of the individual cells) in combination with the typical region approach and calculating the perturbation of a cell in the northern and southern hemisphere with one run.

- Emitting an equal amount of NO_x only during night time resulted in a small decrease of the perturbation by air traffic compared to the case when the emissions occur day and night.

- Releasing all aircraft NO_x emissions one layer lower reduced the perturbation by air traffic considerably.

Calculations for direct and indirect environmental impact

Changes in atmospheric composition due to aircraft emissions are calculated in the APDI module. The environmental impacts resulting from these changes determine whether action should be undertaken to reduce the emissions that caused these impacts. The contribution of aircraft emissions to two environmental impacts have been investigated at KNMI for the second phase of the AERO-project:

(i) Changes in atmospheric constituents may alter the radiation budget of the Earth. The resulting climate effects are studied by using the concept of radiative forcing, i.e. the net change in radiation at the tropopause.

(ii) Changes in ozone influence the amount of damaging ultraviolet radiation (DUV) that reaches the surface.

Radiative forcing

Aircraft emissions introduce many pollutants in the atmosphere that contribute directly or indirectly to radiative forcing. First estimates for the radiative forcing of different components were given by Fortuin *et al.* (1995). These results were obtained by using literature estimates for the increase of the various components due to aircraft emissions and pertain to northern mid-latitudes. For the second phase of the AERO-project the ozone perturbation as calculated by CTMK is used in KRCM (KNMI Radiative Convective Model) in combination with the actual temperature and humidity profiles (see Wauben *et al.*, 1995b). The resulting radiative forcing is given in Fig. 6. The altitude of the tropopause, where the radiative forcing is specified, is calculated from the temperature profile. The surface albedo is taken from a global data set. The maximum radiative forcing is located at northern mid-latitudes and agrees with the estimates given by Fortuin *et al.* (1995). Note that these maxima do not occur at the location of the maximum ozone perturbation, but are shifted to regions with higher radiation levels (i.e. higher solar elevation or higher surface temperature) since a perturbation gives a larger change in radiation if more radiation is present. Especially the long wave radiation contributes to the radiative forcing.
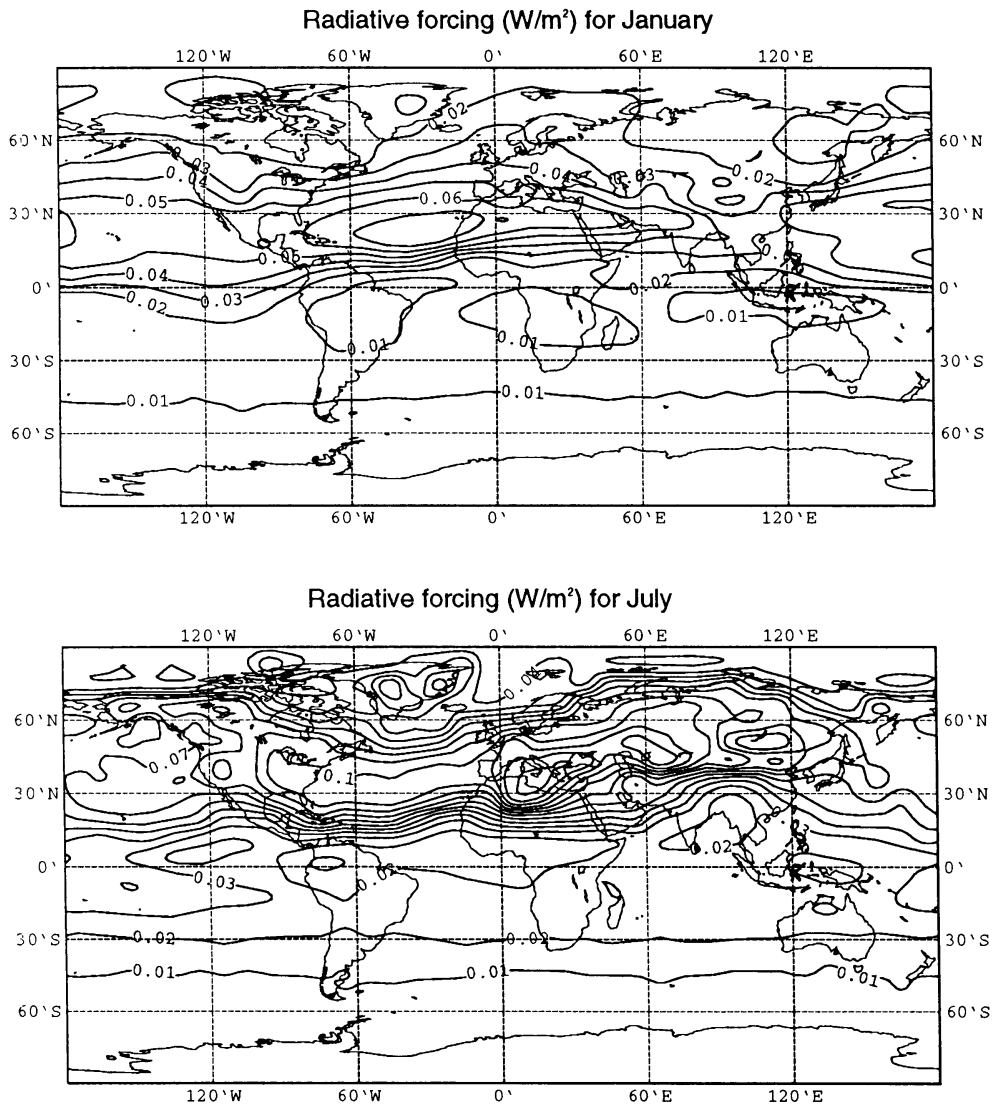

Figure 6. Radiative forcing in W/m^2 due to ozone changes from air traffic for January (top) and July (bottom).

For the calculation of the radiative forcing in ENVI we propose to use a sensitivity curve that gives the radiative forcing as a function of the changes in ozone at each vertical level (cf. Fortuin *et al.*, 1995 and Fig. 7). Note that the sensitivity of radiative forcing to ozone changes strongly just below the tropopause and that there are large differences between summer and winter. Also note that increasing ozone in the troposphere and lower stratosphere gives positive radiative forcing (warming) whereas increasing ozone in the upper stratosphere gives a negative radiative forcing (cooling).
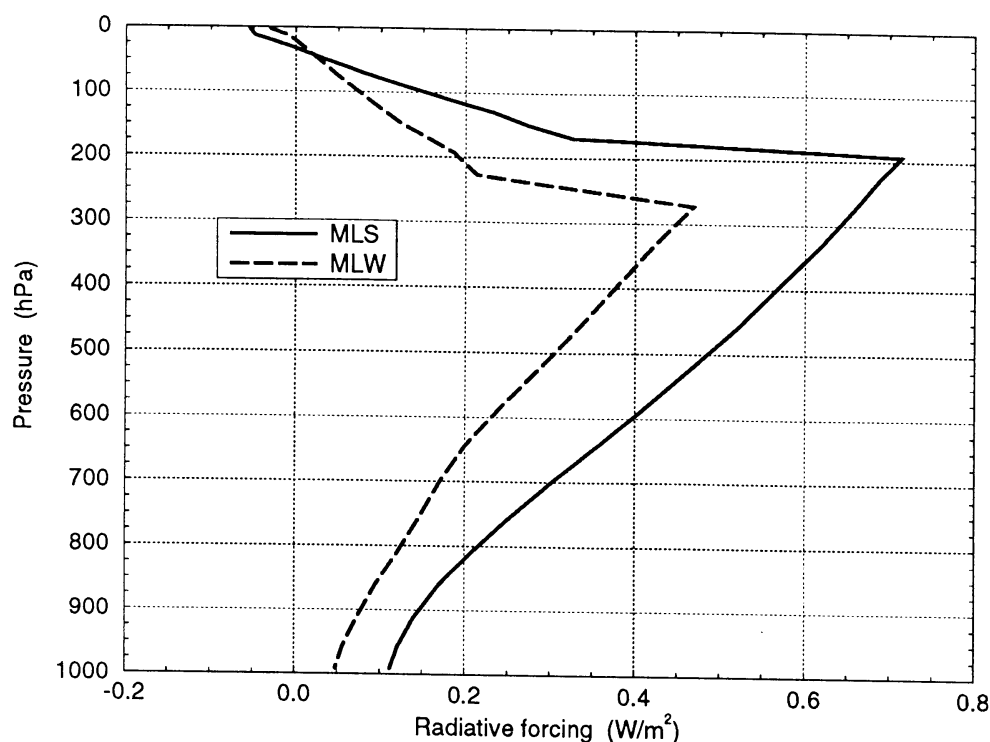

Figure 7. Radiative forcing in W/m^2 resulting from a 10 DU (Dobson Units) increase in ozone at each vertical level for mid-latitude summer and mid-latitude winter.

UV radiation

Many factors control the amount of UV radiation that reaches the surface (cf. Kuik and Kelder, 1994). A complex radiative transfer model is needed in order to account for all these factors such as the solar elevation, the ozone column, the aerosol (small particles) loading of the atmosphere, clouds, the surface pressure and the surface reflectance. Such a model requires too much computer time and besides the characteristics of aerosol and the effects of clouds are not well known. Therefore we propose to use an empirical relation for ENVI that gives the amount of DUV radiation reaching the surface in terms of an analytical expression involving the ozone column and the solar elevation. This DUV is obtained by multiplying the spectral UV radiation with the sensitivity of the human skin to sun burn and integrated over wavelength (cf. Kuik and Kelder, 1995). The relation is illustrated in Fig. 8 which gives the DUV irradiance reaching the surface as a function of local time. The effect of variations in the ozone column is also indicated. The observed DUV curve is found to agree reasonably well with the corresponding empirical curve.
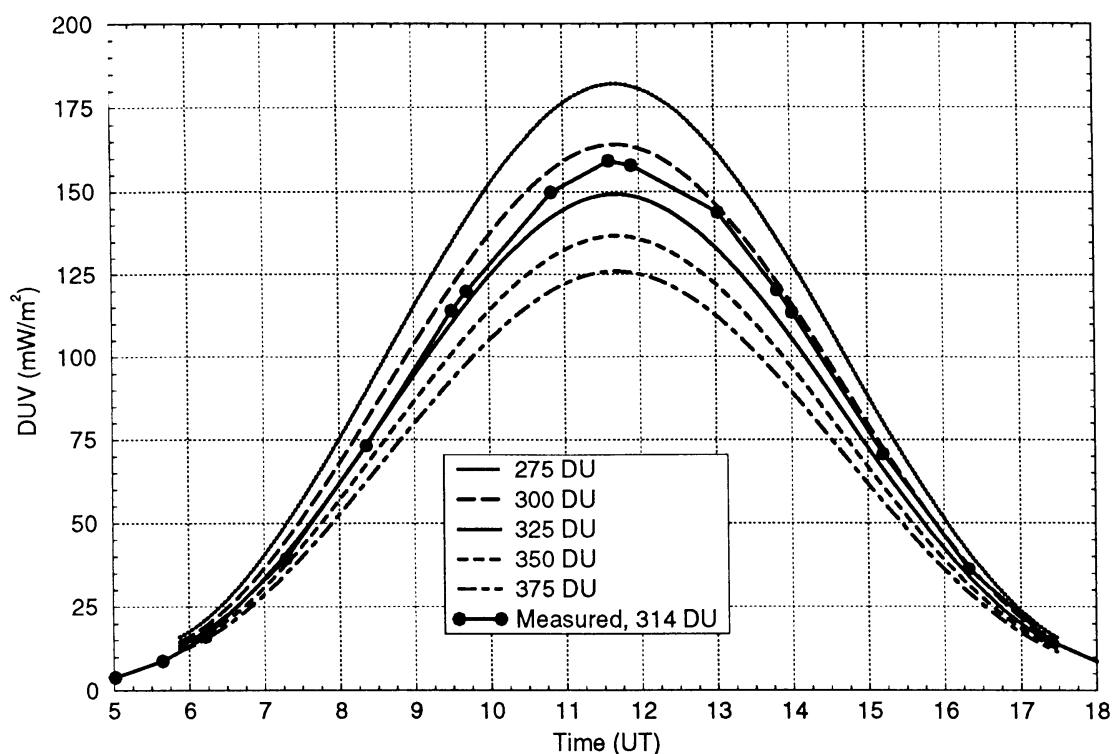
Figure 8. Computed and measured diurnal variation of DUV for various total ozone columns.

Conclusions

The results of the preparatory work for ENVI can be summarized as follows:

● Sensitivity curves for radiative forcing can be used to assess the climatic impact of e.g. ozone changes resulting from air traffic. These sensitivity curves need to be constructed for each column in the global grid and both for January and July.

● The effect of ozone changes on the amount of damaging UV radiation reaching the surface can be assessed with an empirical relation that has been developed at KNMI.

Outlook

During the third phase of the AERO-project the transfer matrices for APDI and the parametrizations for ENVI will be constructed and implemented in AIMS.
In cooperation with LUW and RIVM-LLO within the framework of the AIRFORCE project the CTMK model will be validated and extended to include the stratosphere.

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