

# First global measurement of mid-tropospheric CO<sub>2</sub> from NOAA polar satellites : The tropical zone

A. Chédin, S. Serrar, N.A. Scott, C. Crevoisier, R. Armante

*Laboratoire de Météorologie Dynamique, Institut Pierre-Simon Laplace,  
Ecole Polytechnique, 91128 Palaiseau, France*

## Abstract

Mid-tropospheric mean atmospheric CO<sub>2</sub> concentration is retrieved from the observations of the NOAA series of polar meteorological satellites, using a non-linear regression inference scheme. For the four years of the present analysis (July 1987 – June 1991), monthly means of the CO<sub>2</sub> concentration retrieved over the tropics (20N-20S) from NOAA-10 show very good agreement with what is presently known. Not only the phase of the seasonal variations (location of the peaks) but also their amplitude and their latitudinal evolution match quite well recent *in situ* observations made by properly equipped commercial airliners measuring in an altitude range similar to the one favoured by the satellite observations. Moreover, the annual trend inferred corresponds to the known increase in the concentration of CO<sub>2</sub> as a result of human activities. Also, the impact of El Nino Southern Oscillation (ENSO) events is clearly seen and confirms analyses of *in situ* or aircraft observations and of model simulations. Forty-eight maps of monthly mean mid-tropospheric CO<sub>2</sub> concentration have been produced at a resolution of 15°x15°. A rough estimate of the method-induced standard deviation of these retrievals is of the order of 3.0 ppmv (less than 1%). The coming analysis of the almost 25 years of archive already accumulated by the NOAA platforms should contribute to better an understanding of the carbon cycle.

## Introduction

Knowledge of present carbon sources and sinks, including their spatial distribution and their variability in time is essential for predicting future carbon dioxide atmospheric concentration levels. Because the atmosphere integrates over varying carbon surface sources and sinks, the distribution of CO<sub>2</sub> in the atmosphere and its time evolution can be used to quantify surface fluxes. However, this approach is currently limited by the sparse and uneven distribution of the global flask sampling programs. For example, regional carbon budgets are reconstructed from about 100 points. As a consequence, inferring surface sources and sinks from observed concentrations is still highly problematic (Rayner *et al.* 1999 ; Schimel *et al.* 2000).

Satellite measurements of the distribution of global atmospheric CO<sub>2</sub> would in principle fill this gap in scale (Rayner and O'Brien 2001). Measurements that densely sample the atmosphere, in time and in space, would provide a crucial constraint, allowing uncertainty in transport versus other information (on source and sink characteristics) to be separated and reduced.

Recent studies (Chédin *et al.* 2002a-c) have shown that atmospheric concentration variations (seasonal, annual) of major greenhouse gases (CO<sub>2</sub>, N<sub>2</sub>O, CO) may be retrieved from observations of

the National Oceanic and Atmospheric Administration (NOAA) polar meteorological satellite series, in addition to their main mission of measuring atmospheric temperature and moisture global fields. The method used for these studies was based on the analysis of the differences between the satellite observations and simulations from a radiative transfer model using collocated radiosonde data and fixed gas concentration as the prime input. Its main limit was its dependency upon collocations between satellite observations and radiosonde measurements because of their inability to measure all necessary information (surface temperatures, upper stratospheric temperatures, etc.) and the uneven and, by far, not global distribution of the radiosonde stations.

The method used here, a non-linear regression inverse model based on the Multi-Layer Perceptron (MLP), relies on the only satellite observations, in essence global. It is applied to the platform NOAA-10, providing seasonal cycles and trends for latitude bands of 5° and global monthly maps of mid-tropospheric mean CO<sub>2</sub> concentration, at the spatial resolution of 15° longitude by 15° latitude, for the period July 1987 to June 1991. It may easily be extended to the almost 25 years of archive already accumulated.

## Data and method

Details on the data used and on the method are given in *Chédin et al.* (2003a). The approach described in this article was however modified here to prepare processing daytime observations. The modification consists in removing from the predictors of the non-linear regression the HIRS channel 18 measuring at 4.0 μm and potentially contaminated by solar radiation. Results presented here are limited to nighttime observations (around 7.30 pm local time) and to the tropical zone (20N-20S). It is worth pointing out that the tropical zone coincides with the region where the surface flask network is the least efficient and, also, with the region of strong convective vertical mixing which rapidly transmits surface carbon flux variations to that part of the troposphere observed by the satellite.

## Results and comparisons with aircraft observations

Four years of NOAA-10 observations (from July 1987 to June 1991, included) have been processed and interpreted in terms of mid-tropospheric CO<sub>2</sub> concentration.

Results are shown either zonally, for latitude bands of 5°, for the purpose of comparison with existing aircraft observations, or globally, at the resolution of 15° latitude by 15° longitude, chosen in such a way that enough items are present in each grid box to give robust statistics. A grid box with less than 300 items, indicating an area where dense cloudiness dominates, is rejected (see *Chédin et al.* 2003a).

### Global maps of mid-tropospheric CO<sub>2</sub> concentration

Forty-eight maps of monthly mean mid-tropospheric CO<sub>2</sub> concentration (gross average between 4.5-5.0 to 13 km), covering the period from July 1987 to June 1991, have been produced at the spatial resolution of 15°x15° (1°x1° moving average). The choice of this spatial resolution results from a compromise between two requirements of having a relatively dense spatial coverage (increasing the spatial resolution) and obtaining robust statistics (decreasing the spatial resolution). Figure 1 shows maps of CO<sub>2</sub> concentration for April and June 1988 and the corresponding number of items averaged. There is no evidence of a relationship between CO<sub>2</sub> inferred and the number of data averaged. April is the month where CO<sub>2</sub> shows maximum of variability and where CO<sub>2</sub>, accumulated during northern

hemisphere winter, reaches tropical latitudes. One can notice a gradient west-east of CO<sub>2</sub> mean concentration in the northern tropical Pacific in April, and an area of relatively higher CO<sub>2</sub> amount south of India in June. Similar signatures are observed for the same months of the other years considered here. They are likely to be explained by transport mechanisms. Further investigations are necessary to elucidate factors influencing mid-tropospheric CO<sub>2</sub> variations (sources, sinks and transport).

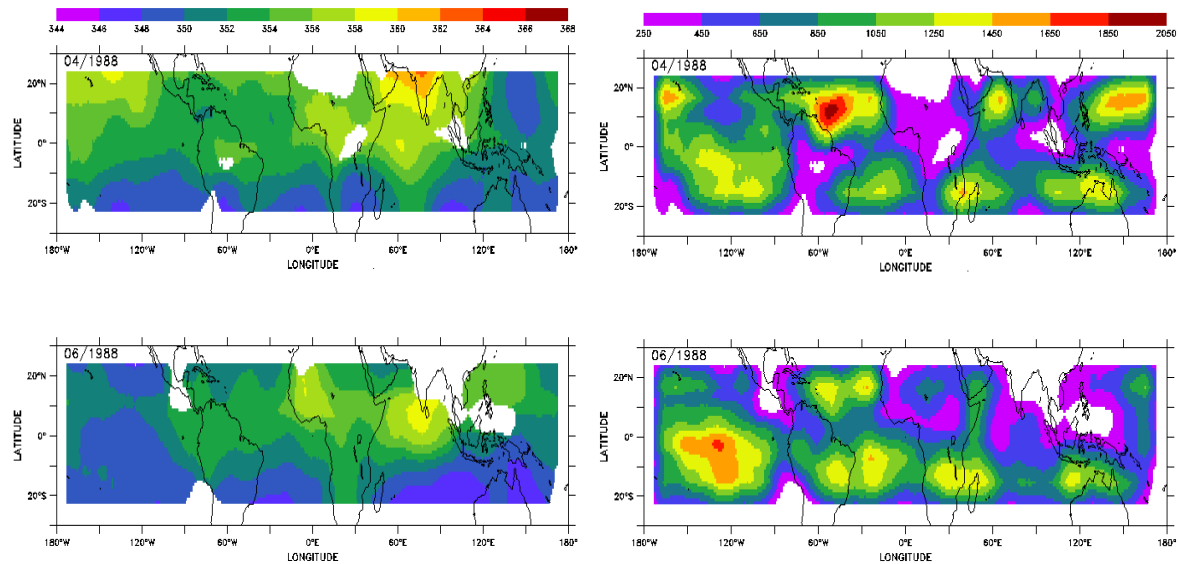


Figure 1 Left: CO<sub>2</sub> monthly mean concentration maps as retrieved from NOAA-10 for 04/88 at the top and 06/88 at the bottom, Right: The corresponding number of items averaged.

Figure 2 shows the time variation of inferred CO<sub>2</sub> mean standard deviation over the tropics. There is evidence of a seasonal variation with maxima in spring (values between 4 and 5 ppm) and minima in summer, early fall (about 3 ppm). These standard deviations may tentatively be seen as resulting from the combination of the standard deviation of the method ( $\sigma_M$ ) itself and of the standard deviation of the natural variability ( $\sigma_V$ ) of CO<sub>2</sub> (15°x15°, one month). Doing so,  $\sigma_M$  comes to about 3.0 ppmv (less than 1%) and  $\sigma_V$  comes to 1 ppmv in July-September and to less than 3 ppmv in February-April. Such numbers look reasonable. However, this result is more an appreciation of the internal consistency of the method than an estimation of its accuracy.

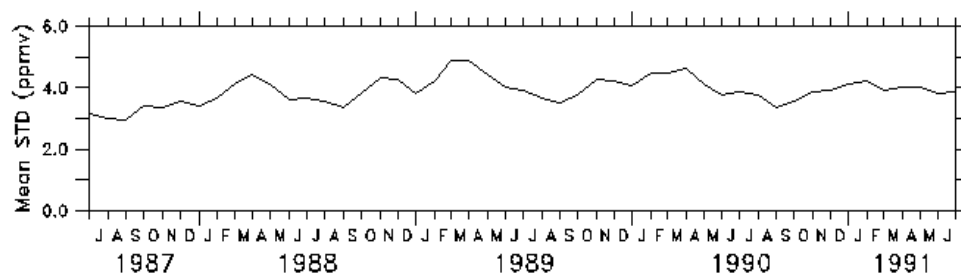


Figure 2: Time variation of mean standard deviation of the inferred CO<sub>2</sub> over the tropics

### Seasonal cycle and trend (zonal means)

Our knowledge of the distribution of CO<sub>2</sub> in the mid to high troposphere is quite limited at present. However, two studies (*Matsueda et al. 2002* ; *Nakazawa et al. 1991*) cover relatively long periods of time and relatively wide domains of latitude. *Matsueda et al. (2002)*, hereafter referred to as “MII”, report on *in situ* observations made twice a week from commercial airliners. These measurements go from April 1993 to April 1999 and were made within the altitude range 9-13 km and extend in latitude from 30N to 30S, between Japan and Australia. In 1984 and 1985, similar observations made between Tokyo and Anchorage, and between Tokyo and Sydney, were analysed by *Nakazawa et al. (1991)*. Figure 8 of MII shows the mean observed seasonal cycle for 12 latitude bands of 5° each, between 30N and 30S. It may be directly compared to our Figure 3 which displays similar cycles, retrieved from NOAA-10 between 20N and 20S. The agreement is relatively good for what concerns both the amplitudes and the phases of the cycles: rapid decay of the amplitude from 20N to the Equator and delay of phase. Similarly, both sources of data show a more complex Southern Hemisphere seasonality, also pointed out by *Nakazawa et al. (1991)*, with two concentration peaks: around June-July and November-December for the aircraft observations, and around May and November for the satellite retrievals. This one-month lag may be explained by the fact that the altitude ranges observed are different: from 9 to 13 km for *in situ* observations and from 4.5-5.0 to about 13 km for NOAA-10 (*Nakazawa et al, 1991-1992*). Figure 3 also shows peak-to-peak amplitudes of the average seasonal CO<sub>2</sub> cycles slightly larger than those shown on Fig. 8 of MII, in agreement with the above references.

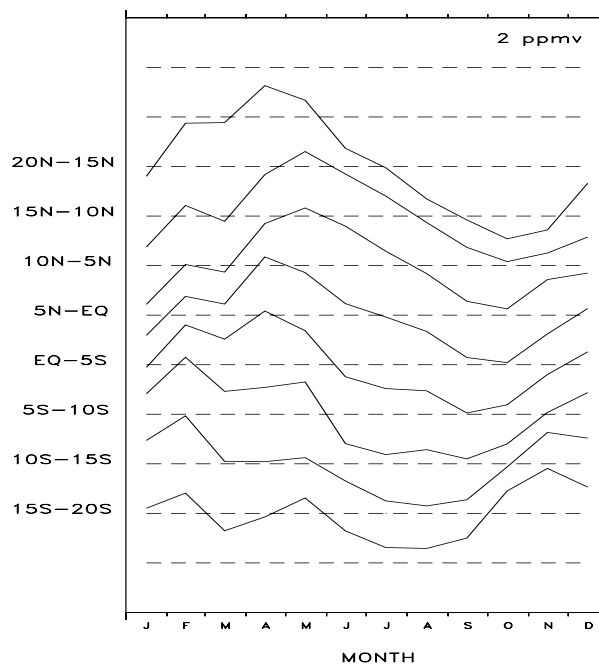


Figure 3: The mean seasonal cycle for 8 latitude bands between 20N and 20S as retrieved from NOAA-10 (July 1987-June 1991) ; mean altitude range covered ~4.5-5.0 to 13 km . Ordinate division length is 2 ppmv.

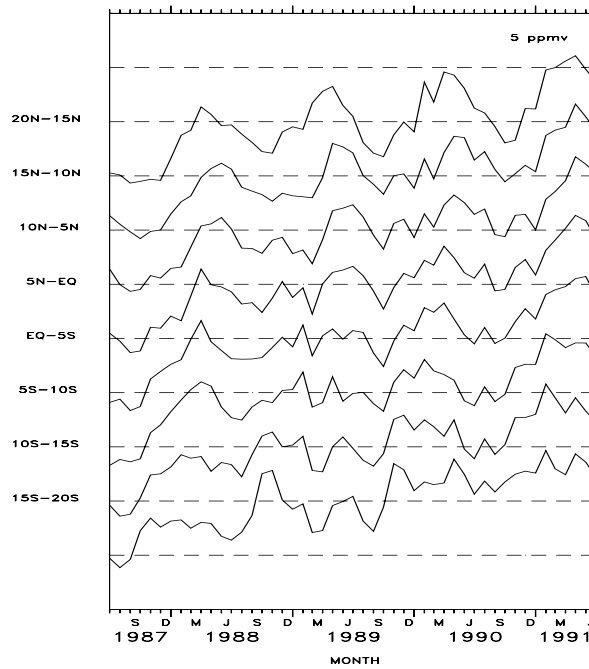


Figure 4: Time variation (monthly means) of the CO<sub>2</sub> concentration for 8 latitude bands between 20N and 20S as retrieved from NOAA-10 for the period July 1987 to June 1991. Ordinate division length is 5 ppmv.

### Growth rates

Further analysis of the data of Figure 4 was carried out following a procedure similar to *Matsueda and Inoue* (1996) or to *Duglokencky et al.* (1994) (details are given in *Chédin et al.* (2003a)). Figure 5 summarizes the results of this analysis for the northern tropics (0N-20N; Figure 5a) and for the southern tropics (0S-20S; Figure 5b). The derivative of the long term trend (the dashed line) gives the growth rate.

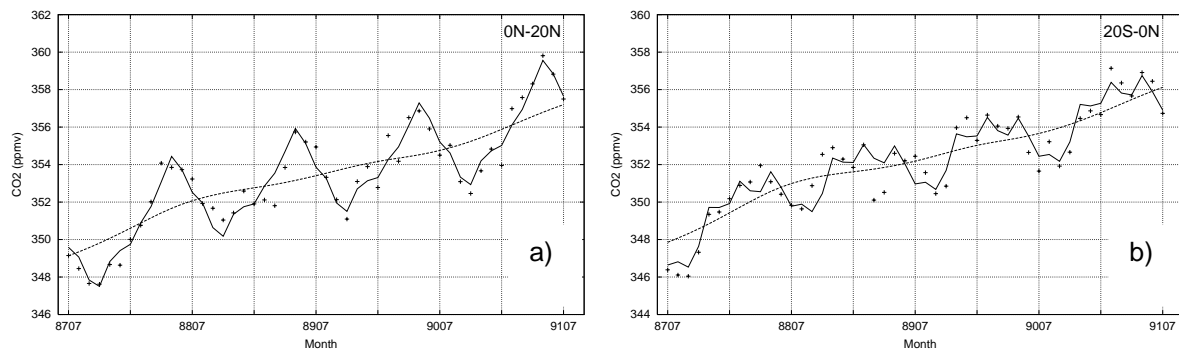
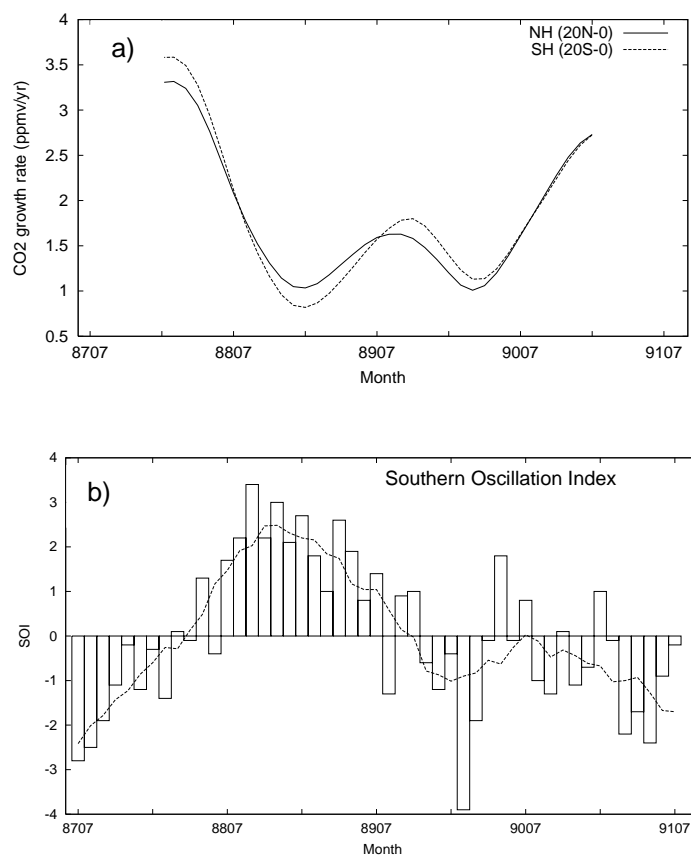


Figure 5: Time variations of CO<sub>2</sub> concentration for the northern tropics (0N-20N; left) and the southern tropics (0S-20S; right) . The crosses represent the individual (monthly mean) data. The dashed line represents the long term trend, and the solid line represents the sum of the trend and the four harmonics used for the fit

Figure 6a shows the mean growth rates for the northern (0-20N) and the southern (0-20S) tropics and emphasizes the previously observed patterns, and, at the same time, draws attention to the relationship between the rate of rise of CO<sub>2</sub> and the ENSO (*Bacastow 1976 ; Keeling et al. 1995 ; Feely et al. 1999 ; Jones et al. 2001*). Figure 6b shows the southern oscillation index (SOI) monthly means from NOAA/ National Centers for Environmental Prediction (NCEP) website ([www.cpc.ncep.noaa.gov/products/](http://www.cpc.ncep.noaa.gov/products/)), for the time period considered. The dashed line is the 7-month running mean as in MII. The correlation between the CO<sub>2</sub> growth rate and the SOI is obvious and very similar to the correlation observed by MII, although the time period is different. La Nina events clearly correspond to a decrease of the growth rate and the contrary for El Nino events. Figure 6c, similar to Figure 5 of MII, shows the relationship between the CO<sub>2</sub> monthly mean growth rates and the SOI, the solid line being for the northern tropics and the dashed line for the southern tropics. Each cross represents one month and the time sequence starts from the upper left crosses, the first month being here January 1988. The relationship appears most significant when the SOI values are not too close to zero, which is not surprising, and appears mostly noisy when it is the case. The upper part of the sequence corresponds to the decrease of the growth rate, itself associated with the decline of the 1986-1987 El Nino and the development of the 1988-1989 La Nina, and the lower part to the overall increase of the growth rate, consequence of the decline of the La Nina event and of the arriving El Nino of 1991. The relationship observed by MII presents numerous similarities (see their Figure 5), with almost the same slope. The differences, in particular the bi-modal behavior seen on Figure 6c, contrary to Fig. 5 of MII, may probably be attributed to the differences between the two time periods studied. Altogether, the conclusions obtained here almost completely agree with those of MII.



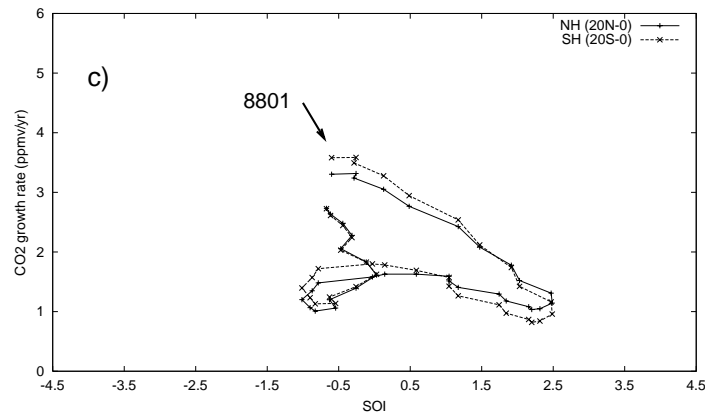


Figure 6 : (a) : time variation of the CO<sub>2</sub> growth rate for the northern tropics (0N-20N), solid line, and for the southern tropics (0S-20S), dashed line, as retrieved from NOAA-10 ; (b) : time variation of the Southern Oscillation Index (SOI) and its 7-month running mean, dashed line ; (c) : relationship between the CO<sub>2</sub> growth rate and the SOI for the northern tropics, plusses, and for the southern tropics, crosses.

## Conclusion and perspectives

Recent studies (*Chédin et al.* 2002a-c) have shown that signatures of the atmospheric concentration variations of major greenhouse gases and, in particular, CO<sub>2</sub>, may be detected from the observations made by the NOAA polar meteorological satellites, in addition to the main signatures of atmospheric temperature, moisture, surface or cloud characteristics. The CO<sub>2</sub> signatures, which essentially come from the mid to high troposphere, are weak and not easy to interpret in terms of global fields of CO<sub>2</sub> concentration. The method developed in this article, a non linear regression inference scheme based on the Multi-Layer Perceptron (MLP), has proven its ability to retrieve important features of the distribution of CO<sub>2</sub> and of its time evolution. The period covered goes from July 1987 to June 1991 and the observations are from NOAA-10. The area analyzed has been, in a first step, restricted to the tropics (20N-20S) where the lower variability of the atmospheric temperature helps de-correlating its variations from those of CO<sub>2</sub>. In almost complete agreement with accurate, mid to high tropospheric *in situ* measurements made by properly equipped commercial aircrafts over a long period of time (see MII), satellite retrievals are able to:

- describe the CO<sub>2</sub> seasonal cycle and its evolution in latitude ;
- describe the time variation of the CO<sub>2</sub> concentration as a function of latitude ;
- quantify the mean rate of rise of CO<sub>2</sub> over the 4-year period (a value of 1.75 ppmv/year is found) and describe the time evolution of the CO<sub>2</sub> growth rate as a function of latitude ;
- confirm the strong correlation between the growth rate and the Southern Oscillation Index (SOI) during a time period marked by the declining 1986-1987 El Nino, the strong 1988-1989 La Nina, and the coming 1991 El Nino ;
- produce monthly mean global maps of mid-tropospheric CO<sub>2</sub> concentration at a resolution of 15° by 15°. Within each such grid-boxes, the standard deviation of the sample of CO<sub>2</sub> retrievals, after having

deduced an estimate of the part attributed to the natural variability of CO<sub>2</sub> over one month, is of the order of 3.0 ppmv, less than 1%.

The main limit of the method developed here is the dependence of the retrievals on the capability of the forward radiative transfer model, used to create the MLP training data set, to accurately match the satellite observations. Any such model has biases that are air mass, and possibly latitude, dependent. Removal of these biases goes through the use of large sets of collocated radiosonde (to feed the forward model) and satellite observations. Problems arise when latitude bands are not enough covered by such “matchups”. To refine our knowledge of the forward radiative transfer model systematic biases, great efforts are presently being made to augment the number of collocations using the European Center for Medium Range Weather Forecasting (ECMWF) ERA-40 archive.

The planned analysis of the almost 25 years of archive already accumulated by the NOAA polar platforms should certainly contribute to a better understanding of the carbon cycle through the interpretation of these retrievals in terms of surface carbon fluxes via a carbon flux inversion model, coupling *in situ* and space observations.

These results also strengthen our hope to greatly improve our knowledge of the global distribution of a variety of radiatively active gases with the coming second generation vertical sounders like AIRS or IASI, both characterized by a much higher spectral resolution allowing a more sophisticated retrieval scheme than the one developed here for the present TOVS channels (Chédin *et al.* 2003b) and a still better handling of the cloud detection. The first simulations obtained with a similar retrieval method presented in this paper are extremely encouraging (Crevoisier *et al.*, this issue).

## References

- Bacastow, R. B., Modulation of atmospheric carbon dioxide by the Southern Oscillation, *Nature*, 261, 116-118, 1976.
- Chédin, A., S. Serrar, R. Armante, N. A. Scott, and A. Hollingsworth, Signatures of annual and seasonal variations of CO<sub>2</sub> and other greenhouse gases from NOAA/TOVS observations and model simulations, *J. Climate*, 15, 95-116, 2002a.
- Chédin, A., S. Serrar, A. Hollingsworth, R. Armante, and N.A. Scott, Detecting annual and seasonal variations of CO<sub>2</sub>, CO and N<sub>2</sub>O from a multi-year collocated satellite-radiosonde data-set using the new Rapid Radiance Reconstruction Network (3R-N) model, *In Press in J. Quant. Spectrosc. Radiat. Transfer*, 2002b.
- Chédin, A., A. Hollingsworth, N.A. Scott, S. Serrar, C. Crevoisier, and R. Armante, Annual and seasonal variations of atmospheric CO<sub>2</sub>, N<sub>2</sub>O and CO concentrations retrieved from NOAA/TOVS satellite observations, *Geophys. Res. Letters*, 29, 110-1/4, 2002c.
- Chédin, A., S. Serrar, N. A. Scott, C. Crevoisier, R. Armante, First global measurement of midtropospheric CO<sub>2</sub> from NOAA polar satellites: Tropical zone, *J. Geophys. Res.*, 108(D18), 4581, doi:10.1029/2003JD003439, 2003a.
- Chédin, A., R. Saunders, A. Hollingsworth, N. A. Scott, M. Matricardi, J. Etcheto, C. Clerbaux, R. Armante, and C. Crevoisier, The feasibility of monitoring CO<sub>2</sub> from high-resolution sounders, *J. Geophys. Res.*, 108(D2), 4064, doi:10.1029/2001JD001443, 2003b.

- Duglokencky, E. J., K. A. Masarie, P. M. Lang, P. P. Tans, L. P. Steel, and E. G. Nisbet, A dramatic decrease in the growth of atmospheric methane in the northern hemisphere during 1992, *Geophys. Res. Letters*, 21, 45-48, 1994.
- Feely R. A., R. Wanninkhof, T. Takahashi, and P. Tans, Influence of El Nino on the equatorial Pacific contribution to atmospheric CO<sub>2</sub> accumulation, *Nature*, 398, 597-601, 1999.
- GLOBALVIEW-CO<sub>2</sub>, Cooperative Atmospheric Data Integration Project- Carbon dioxide. CD-ROM, NOAA/CMDL, Boulder, Colorado. [Also available on Internet via anonymous FTP to <ftp.cmdl.noaa.gov>, Path: ccg/co2/GLOBALVIEW], 1999.
- Jones, C. D., M. Collins, P. M. Cox, and S. A. Spall, The carbon cycle response to ENSO : a coupled climate-carbon cycle model study, *J. Climate*, 14, 4113-4129, 2001.
- Keeling, C. D., T. P. Whorf, M. Wahlen, and J. van der Plicht, Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980, *Nature*, 375, 666-670, 1995.
- Matsueda, H., and H. Inoue, Measurements of atmospheric CO<sub>2</sub> and CH<sub>4</sub> using a commercial airliner from 1993 to 1994, *Atm. Environ.*, 30,1647-1655, 1996.
- Matsueda, H., H. Y. Inoue, and M. Ishii, Aircraft observation of carbon dioxide at 8-13 km altitude over the western Pacific from 1993 to 1999, *Tellus*, 54B, 1-21,2002.
- Nakazawa, T., K. Miyashita, S. Aoki, and M. Tanaka, Temporal and spatial variations of upper tropospheric and lower stratospheric carbon dioxide, *Tellus*, 43B, 106-117, 1991.
- Nakawaza, T., S. Murayama, K. Miyashita, S. Aoki, and M. Tanaka, Longitudinally different variations of lower tropospheric carbon dioxide concentrations over the North Pacific ocean, *Tellus*, 44B, 161-172,1992.
- Rayner, P. J., I. G. Enting, R. J. Francey, and R. Langenfels, Reconstructing the recent carbon cycle from atmospheric CO<sub>2</sub>, d13C and O<sub>2</sub>/N<sub>2</sub> observations, *Tellus*, B51, 213-232, 1999.
- Rayner, P. J., and D. M. O'Brien, The utility of remotely sensed CO<sub>2</sub> concentration data in surface source inversions, *Geophys. Res. Lett.*, 28, 175-178, 2001.
- Schimel, D. S., J. Mellilo, H. Tian, and A. D. McGuire, Contribution of increasing CO<sub>2</sub> and climate to carbon storage by ecosystems in the United States, *Science*, 287, 2004-2006, 2000.