1 TROPOSAT: the project and the scientific highlights

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1.1 Introduction

The successful launch in early 2002 of the SCIAMACHY instrument (SCanning ImAging spectroMeter for Atmospheric CHartographY) on the ESA ENVISAT satellite opened the second phase of a substantial European effort to study trace substances and pollutants in the troposphere with measurements from space. It was also the culmination of ideas, first mooted fifteen years ago by a team led by two of the coordinators of TROPOSAT, *John Burrows and Ulrich Platt*, which found their first expression in 1995 with the launch of GOME (Global Ozone Monitoring Experiment) on the ESA ERS-2 (Earth Research Satellite 2).

The results already obtained from GOME, and the preliminary ones from SCIAMACHY and MIPAS (also launched on ENVISAT), more than justify the enormous effort made by so many people to bring the overall project to fruition. The results give a hitherto unobtainable picture of the chemical state of the atmosphere on global and regional scales. The continuing flow of results, and the hoped-for development of a geostationary platform for tropospheric chemical studies, is likely to influence significantly the way science is carried out in tropospheric chemistry and, in the long run, provide a reliable system for monitoring pollutants on regional scales, as well as monitoring the state of the atmosphere on a long term basis.

The EUROTRAC-2 subproject, TROPOSAT, was set up in 2000 with the realisation that those engaged in developing the satellite data products and those using them required a common forum to ensure that the available data would be fully and correctly used. It was also evident that the results would directly affect the community engaged in tropospheric chemistry and that the community needed to be shown how to make best use of them.

More than 40 groups attended the first workshop in Heidelberg in April 2000 and most of them, together with those who joined subsequently, are still active contributors to TROPOSAT.

The present chapter outlines the scientific highlights of TROPOSAT and presents some lessons learned, together with some suggestions for the future. The whole shows how successful TROPOSAT has been, despite the short time it has been running. It also indicates the need for a follow-up project to ensure that full use is made of the plethora of data now becoming available on the concentration fields of chemical trace substances in the troposphere.

1.2 The aims of TROPOSAT

The aims of TROPOSAT were to explore and encourage the use of satellite data to determine two- and three-dimensional distributions and time series of trace gases and other parameters in the troposphere, and so facilitate future research and environmental monitoring on regional and global scales, in particular through:

- the development of algorithms for the retrieval of tropospheric species and parameters;
- the use of satellite data for understanding atmospheric processes;
- the synergistic use of different instrumentation and platforms for tropospheric measurements; and
- the development of validation strategies for tropospheric satellite data products.

Four task groups were set up to tackle these topics. In addition TROPOSAT decided to emphasise the following underpinning activities: the development of appropriate data assimilation techniques combining satellite measurements with modelling, and the specification of the requirements for future satellite instruments for tropospheric work.

As will be seen from the following section and chapters, the aims have been amply fulfilled. However much work remains to be done and it will be necessary to continue the project so as to ensure that the increasing amount of data is fully utilised by the community for whom it is intended.

1.3 Some TROPOSAT scientific highlights and activities

A rich variety of results have been obtained by the principal investigators working in TROPOSAT. This section includes a few of the highlights; more complete information can be found in the overviews in chapter 2 and in the contributions from the principal investigators in chapters 3 to 6.

1.3.1 Global and regional distributions of trace gases and pollutants

The results from GOME have already provided global and/or regional distributions of O_3, NO_2, SO_2, BrO, formaldehyde and aerosols, and many of these are publicly available. Appendix 1 gives a current list of sources for such data. The new ENVISAT data will shortly be on line two. Some idea of the resolution available from SCIAMACHY can be seen in Fig. 1.3.1.

1.3.2 Data retrieval

The inherent difficulty with tropospheric satellite measurements to date is the retrieval of the tropospheric absorption from reflected earthshine, which is measured in a downward-looking (nadir) configuration from about 800 km through the stratosphere. Some trace gases of interest in the troposphere (*e.g.* O_3, NO_2) are also abundant in the stratosphere, and so interfere with the observation of the troposphere, while others (like SO_2 or HCHO) are not, so current retrieval methods tend to be species specific.

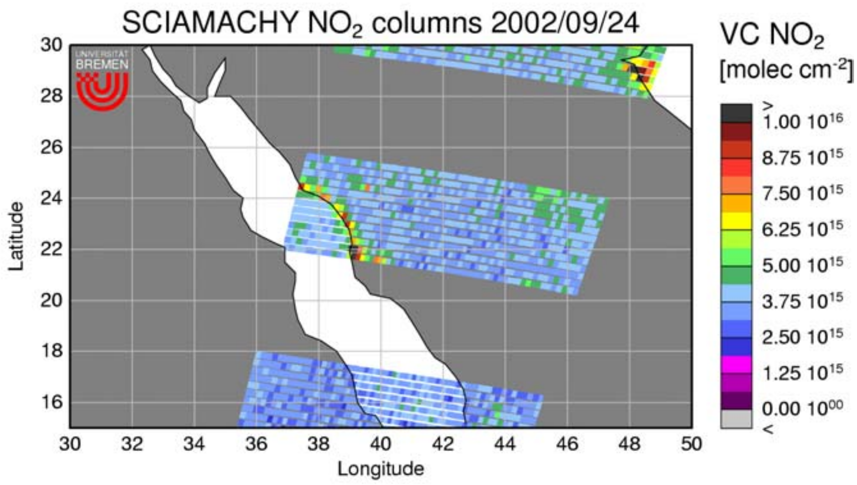

Fig. 1.3.1. NO_2 total columns derived from measurements of the new SCIAMACHY instrument on ENVISAT in September 2002. Pollution from individual cities such as Jeddah, Mecca, Medina and Kuwait City can clearly be identified in the otherwise clean region (Richter 2003)

The principal investigators in TROPOSAT task group 1 have largely devised, and extensively developed, all the present methods for retrieving tropospheric information from the satellite data stream. Among these are the Tropospheric Excess Method in which signals from known NO_2–free tropospheric regions are compared with those from polluted tropospheric regions to give the NO_2 in the boundary layer; the difference between "on-" and "off-cloud" signals can give concentrations at levels depending on the cloud height; and advantage can be taken of the differences in the spectroscopic features and temperature dependences to obtain profiles of ozone in the troposphere.

The task of retrieving the tropospheric contribution will be simplified by the new instruments on ENVISAT, which are capable of making measurements looking at the horizon (limb) as well as nadir observations. Comparison of these will yield tropospheric trace gas concentrations directly without resorting to any other assumptions or, favourable conditions. However further retrieval algorithms are required to make the best use of the data.

The development of algorithms is a difficult task and, until now, most of data available is the product of detailed skilled work on individual data sets. But, as experience grows, automation can be expected. Algorithms have been developed or improved for O_3, NO_2, BrO, SO_2 and HCHO, with particular contributions to the problems posed by cloudy pixels. Several groups have concentrated on algorithms for determining aerosols in the troposphere, with specific work being done on the effects of volcanic eruptions on the aerosol load, the transport of Saharan dust and the effect of complex terrain on the aerosol distribution.

1.3.3 Neural networks

One novel development concerned with determining tropospheric concentration profiles is that of Kaifel, Müller and coworkers, who have developed a neural network ozone retrieval system, NNORSY, to determine profiles of O_3 from GOME data. The network is trained with thousands of profiles obtained from sonde measurements and then, from the data for each pixel, yields the ozone profile in the atmosphere. These are still early days with much work to be done on both normal and neural retrieval; but here we appear to have a glimpse of the future, with trained neural networks rapidly yielding concentration profiles and free from many of the assumptions which are necessarily present in normal retrievals.

1.3.4 Validation of models

Task group 2 brought into TROPOSAT a number of atmospheric modellers and other investigators interested in actually using the concentration fields and profiles produced from satellite data to compare and verify their model calculations, particularly on global scales. There was encouragingly free exchange of data and experience between the research groups who produced the data (mainly in group 1) and those in group 2 using it. The results are all heartening in the agreement between satellite and model although, necessarily, the differences highlight inadequacies, which may be in the models or perhaps in the data retrieval. One model under development concentrates on the details of the formation of aerosols and is looking forward to comparison with satellite data.

1.3.5 Environmental case studies

The use of data to explore both natural and anthropogenic phenomena, which show the potential of satellite data for studying the environment, include:

- studies of forest fires in Canada and Siberia together with the transport of the plumes between continents;
- the long-range transport of tropospheric NO_2 from power stations in the high veldt of South Africa to Australia;
- the estimation of NO_2 global source strengths using GOME data combined with other satellite information on lightning flashes and night-time surface light emissions;
- the source of NO_2 over the Indian subcontinent;
- the aerosol and SO_2 produced by volcanic eruptions;
- the transport of Saharan sand over the Atlantic Ocean and Mediterranean Sea; and
- the export of pollution from Europe into the northern hemisphere.

1.3.6 Synergism and global observation

Many of the studies mentioned use not only satellite concentration data but also data from ground stations, sondes, aircraft and other satellites. The "synergy" obtained by combining data from various sources will surely be the norm in the future and, for this reason, task group 3 was set up to encourage such work. It is not an easy task since the data from various sources is so different, in both temporal and spatial coverage.

Two major sources of data for the upper troposphere are the long term programmes, CARIBIC: and MOZAIC:, in which instrument packages are flown regularly on long-distance passenger or freight aircraft. These provide concentrations along the popular inter-continental flight routes, and are to be used with data from SCIAMACHY to obtain information on water vapour and other trace species.

One long standing problem that now can be tackled is how much NO_2 is produced by lightning. Data from two satellites has been combined to examine large tropical storms, and estimates can now be made which will improve our NO_2 budgets as well as our understanding. Such estimates could only previously be guessed at.

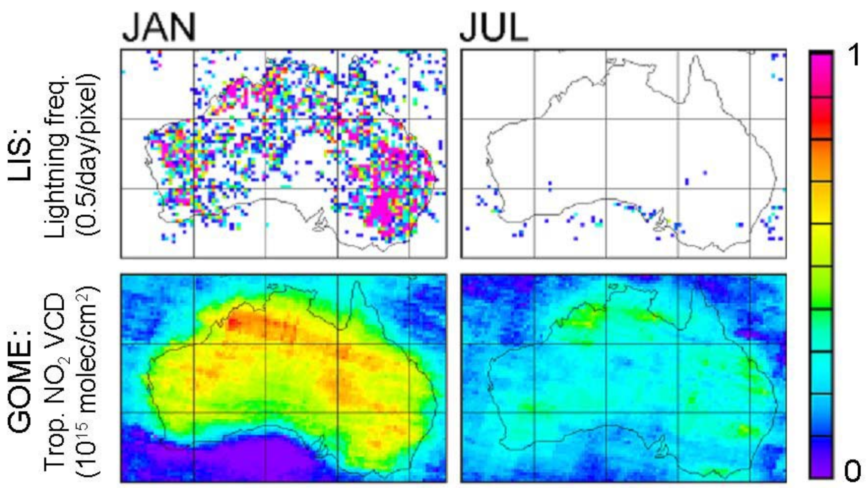

Fig. 1.3.2. Monthly means of the lightning frequency (from LIS) and tropospheric NO2 vertical column density (from GOME) over Australia for selected months in 1999. High NO2 values are only seen for strong lightning activity (S. Beirle, University of Heidelberg)

Since TROPOSAT task group 3 started work, an international initiative has been taken by a number of global organisations to form IGOS, International Global Observation Strategy. The atmospheric part is IGACO, International Global Atmospheric Chemistry Observations. The IGACO planning group intends to foster the formation of an integrated system which will include satellites, ground-based stations, aircraft and ships, supported by comprehensive modelling to provide a continuous picture of the state of the atmosphere, the environmental situation of which can be assessed on a regular basis. IGACO is just what the PIs of task group 3 had in mind at the start. Their brief assessment below gives an indication of the likely difficulties that will be encountered in setting up an observation system. The coordinators of TROPOSAT together with Hennie Kelder serve on the planning group for IGACO.

1.3.7 Data validation

Validation of satellite data is essential if the results are to have any meaning, so task group 4 was set up to bring together those involved. In fact validation activities are by definition synergistic so members of task group 3 are also involved. Comparison of data for ozone from several satellites, GOME, TOMS and TOVS, shows some systematic discrepancies between them.

A lot of effort has gone into setting up ground-based FTIR instruments to use for satellite validation. The instrument on the Jungfraujoch (Switzerland) has a long record of profile measurements in the upper troposphere which are used in climatology. To that is now added FTIR spectrometers and other instruments on the Zugspitz, Germany, at Harestua in southern Norway and in Bremen, Germany. All will provide validation data for SCIAMACHY.

There are also validation activities using research aircraft such as the DLR Falcon: and also, courageously, a micro-light aircraft. Aircraft allow measurements to be undertaken within a particular pixel, if this is desired.

1.3.8 Data assimilation

Data assimilation was designated as an underpinning activity at the start of TROPOSAT. Several of the modelling groups in TROPOSAT use data assimilation to integrate experimental results into the model framework in order to improve model performance. As is pointed out below, data assimilation offers perhaps the only way, in the long run, to bring together experimental observations from a variety of sources in order to generate a reliable comprehensive picture of the state of the atmosphere at any given time.

1.3.9 Geostationary satellites: the future?

The major activity in the underpinning activity, future instrumentation, was the formulation of a proposal for a geostationary satellite, GeoTROPE. The satellites used at the moment are sun-synchronous low earth orbit (LEO). They typically provide a measurement of a particular area on the earth's surface every three days, and can do no better than global coverage in one day. The timescales of chemical and physical processing in the troposphere is such that a better resolution is required, which could be provided with a geosynchronous satellite, orbiting at about 36000 km above the equator. Despite the increased distance, the time integration advantage over an LEO satellite, would yield a chemical picture of one third of the earth every half hour. A team, led by one of the co-ordinators and comprising many of the TROPOSAT principal investigators, prepared and submitted a proposal to ESA in 2001. Unfortunately, despite the overwhelming scientific case, and the potential of the satellite for environmental monitoring, the proposal, although highly praised was not selected for a Phase A study. However discussions are continuing and it is to be hoped that the case for a geostationary satellite to study chemical weather will soon be accepted.

1.4 Policy-relevant results

The availability of satellite data for the troposphere will ultimately be the preferred method for those responsible for environmental policy development in Europe. Satellite data will be used by the authorities to monitor pollutant concentrations on a regional scale in order to verify the compliance with the control measures. Also, since the development of legislation to control pollutants must be based on sound science encapsulated in reliable chemical transport models, satellite-derived tropospheric data will be invaluable for the thorough validation of such models.

A nice example of the possibilities offered by satellite-derived data is provided by Fig. 1.4.1, which shows the NO_2 concentrations over Europe in the summer and winter of 1999. The high concentrations generally seen over north-western Europe and in the Po valley are consistent with the model results and projections obtained by David Simpson from EMEP (The Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe). These are just the regions where the NO_2 concentrations are high enough to titrate out much of the ozone formed in the boundary layer, and furthermore they are regions where a substantial *reduction* of NO_2 may actually lead to an *increase* in the photochemically produced ozone.

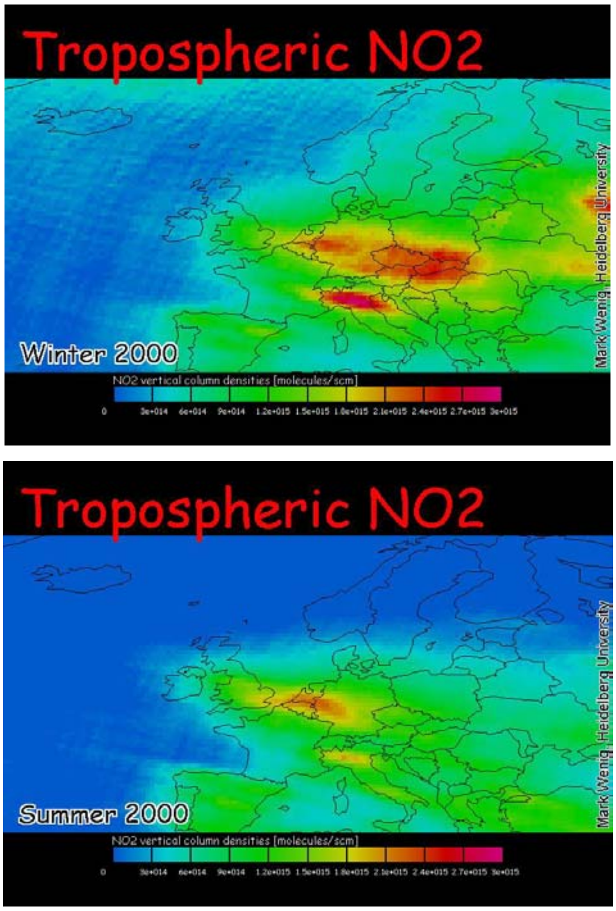

Fig. 1.4.1. Seasonal variation of tropospheric NO_2 vertical column over Europe derived from GOME measurements (Wenig, University of Heidelberg, 2001)

Several of the studies already mentioned in sections 1.3.4 and 1.3.5 also illustrate the potential of tropospheric satellite measurements for use in environmental management. These include the observation of inter-continental plumes containing NO_2, SO_2 and aerosol from forest fires, volcanoes and high-lying South African power plants; identification and quantification of sources of pollutant emissions on global and continental scales, the transport of sand from the Sahara over the neighbouring seas and lands, and the export of pollution from Europe into the northern hemisphere.

Here, a recent development involving members of TROPOSAT is the EC project EVERGREEN (EnVisat for Environmental Regulation of GREEN house gases) which is bringing together European expertise on calibration/validation, retrieval algorithm development, data assimilation and inverse modelling. In addition to the scientific members, the user community is represented by climate and environmental government organisations and a major coal industry.

The Kyoto agreement requires the long term monitoring of the troposphere to try to identify changes which are due to man's activities. SCIAMACHY and MIPAS (which will measure some 30 environmentally important species in the stratosphere and from 6 km upwards in the troposphere), will offer a first opportunity to investigate the accuracy required for space-based monitoring of greenhouse gases targeted by the Kyoto Protocol for emission control. Clearly satellites, once they have been launched and the instrumentation and data products validated, offer a definitive way to achieve reliable and long term monitoring on global and regional scales.

Finally, should the global observation system envisaged by IGACO be set up, satellite measurements of tropospheric constituents will be vital to its success.

1.5 Future perspectives and opportunities

1.5.1 Atmospheric chemistry

What opportunities do these still newly available satellite data offer to atmospheric chemists? A simple scrutiny of the concentration maps on global and regional scales should provide confirmation of, or provoke questions about, what was previously not observable. The data will provide a direct comparison with the output from chemical transport models (CTM) on global and regional scales and will be used for realistic validation and sensitivity work to improve substantially the accuracy and reliability of CTMs. Satellite measurements should also be useful in providing real boundary conditions for operational models. In addition source strengths of trace gases can be derived. For field campaigns, a knowledge of the actual concentrations of appropriate species in the vicinity of the campaign area will be available. In short, satellite data will soon be an essential adjunct to the major activities in atmospheric chemistry in the future.

1.5.2 Environmental policy development

For those engaged in environmental policy development, satellites used together with CTMs will provide a method to monitor pollutant concentrations on a continuous basis, allow the firm identification of pollutant sources, and in tracing the transport of pollutants in the atmosphere both globally and regionally. In addition, satellite data will be an essential component for any global observation system such as that envisaged by IGACO.

1.5.3 Integrated use of data from several satellite instruments

Probably the biggest challenge within the field is to integrate the data from several sensors, such as aerosol and cloud data from MERIS and trace gas information from SCIAMACHY and MIPAS, to obtain more useful data products. If such a synergistic use is to be implemented at the retrieval level, and not only in the final products, it will necessitate new approaches and much interaction between the algorithm communities. TROPOSAT task group 1 is already at work on starting this process, and much progress is expected in the future.

1.5.4 Synthesis and integration of data from many sources

An important lesson learned by task group 3 is that the synergistic use of different data sets is a continuous process of developing retrievals, validation and integration. It is imperative to explore the required strategies to bring together data produced with different techniques to obtain an overall picture of the atmosphere. Such strategies will be an essential step in the construction of an “Integrated Observation System” for the observation and monitoring of the troposphere and its future changes. The crucial importance of such an approach has been recently pointed out by the IPCC-2001 report. Initiatives in this field are pioneering work and a large challenge for the scientific community in the coming years.

1.5.5 The necessity for a geostationary satellite

The most pressing requirement for the future is the early acceptance of a project to launch a geostationary satellite capable of measuring tropospheric concentrations of pollutants and trace species. The integrated observation system desired by the international community and required for environmental policy development, needs the daily time-resolved data from such a satellite to combine with the information from low earth orbit satellites, ground-based and *in-situ* sensors, in order to obtain a continuous picture of the atmosphere. Considering the lead time required to launch such a satellite, such a project should be initiated now.

1.5.6 Conclusions

It is evident from this report that, though much has been achieved, even more remains to be done to realise the full potential for the data becoming available. The formation of TROPOSAT and its clear success has shown that a group devoted to producing and exploiting the data, and to bringing together "producers" and "users" is necessary, and every effort will be made to continue the project, if not under the good auspices of EUROTRAC-2, then perhaps with the help of the EU, or ESA itself.

1.6 TROPOSAT organisational activities

Seven well-attended workshops were held by the TROPOSAT community, at which current work was reported and discussed, joint work arranged and future plans made.

University of Heidelberg	April 2000
ESA Symposium, Göteborg	November 2000
ESRIN, Frascati	April 2001
University of Leicester	November 2001
EUROTRAC-2 Symposium, Garmisch-Partenkirchen	March 2002
KNMI, Utrecht	November 2002
ESRIN, Frascati,	May 2003

The workshops were really the crux of TROPOSAT since they brought together not only groups engaged in similar activities but also those engaged in complementary work such as the producers and users of tropospheric data.

A project description was produced at the start of the project, and annual reports, to which all participants contributed, produced for 2000 and 2001. In addition, a number of articles were written by the TROPOSAT coordinators and steering group to explain the work of the project, and presentations about TROPOSAT were made at several major conferences. These were, of course, in addition to the publications produced by many of the principal investigators in the refereed literature. A web page was set up at the beginning to provide information about TROPOSAT and encourage the use of the data becoming available by a wider community.

1.7 Further information

TROPOSAT web page: http://troposat.iup.uni-heidelberg.de

TROPOSAT: The use and usability of satellite data for tropospheric research; subproject description, EUROTRAC-2 ISS, München, pp.106.

TROPOSAT: Annual Report, 2000, EUROTRAC-2 ISS, München, pp.138.

TROPOSAT: Annual Report, 2001, EUROTRAC-2 ISS, München, pp.200.

http://www.springer.com/978-3-540-40873-4

Sounding the Troposphere from Space
A New Era for Atmospheric Chemistry
Borrell, P.; Borrell, P.M.; Burrows, J.P.; Platt, U. (Eds.)
2004, XXIX, 446 p., Hardcover
ISBN: 978-3-540-40873-4