Chapter 6

Probing the Atmosphere with Research Aircraft—European Aircraft Campaigns

ULRICH SCHUMANN

Why Aircraft Campaigns?

Aircraft are used to investigate the atmosphere and the ground by visual observations and by measurements with instruments onboard the aircraft. They allow for

- Targeted measurement of atmospheric properties above ground with in-situ instruments and with airborne remote sensing instruments along a given flight path *(e.g., from 100 m up to 20 km; looking up and down)*
- Measurements at high temporal/spatial resolution *(order 1 s, 10 m, as often required)*
- Data for process studies *(e.g., cloud formation)*
- Data for validation of models *(e.g., chemical transport models)*
- Test and validation of remote sensing (e.g., GOME, SCIAMACHY, MIPAS, e.g., Heland et al., 2002) .
- Measurements of otherwise not measurable properties *(e.g., tropospheric NO, turbulence, cloud condensation nuclei)*
- Simultaneous measurements of many parameters *(meteorology, air composition, aerosols, cloud physics etc.)*

This lecture is based on experiences gained within several European research projects with research aircraft, such as POLINAT, EULINOX, INCA, and TROCCINOX. The projects dealt with

— POLINAT: Pollution in the North Atlantic tropopause region induced by aircraft and other sources [Schlager et al., 1997, 1999; Schumann et al., 1995, 2000; Ziereis et al., 1999, 2000],

— EULINOX: Lighting induced nitrogen oxides over Europe [Höller et al., 1999; Huntrieser et al., 2002],

— INCA: Impact of different aerosol and trace gas concentrations and atmospheric dynamics on cirrus clouds in the Southern and Northern hemisphere [Ström et al., 2003; Baehr et al., 2003; Minikin et al., 2003; Ovarlez et al., 2002; Ziereis et al., 2004; Gayet et al., 2002, 2004], and

— TROCCINOX: Nitrogen oxides from lightning (besides cirrus and aerosol properties) near deep convective clouds in a tropical continent [Schumann et al., 2004].

Instead of describing the scientific results of these and related projects, this short contribution concentrates on the European research aircraft fleet and the methodological aspect of airborne measurements.

European Research Aircraft

The European fleet for airborne research is, to a large extent, organized within the EU-network EUFAR; see www.eufar.net. Within this network, the European Commission of the European Union provides financial support for transnational access (preferably for young scientists from countries outside the country of the aircraft operator).

The EUFAR fleet composes presently 22 aircraft within 5 categories. Figure 1 lists the aircraft by type and operator together with a small photo. In addition to these research aircraft, in Europe several instrumented airliners are used, in particular several Airbus A340 aircraft within the project MOZAIC (with measurements of H_2O, O_3, CO, NOy; see paper by J.-P. Cammas in this volume), and a Lufthansa A340-600 (previously LTU B767) carrying a container with a large suite of instruments within the project CARIBIC [Brenninkmeijer et al., 1999]. In 1995–1997, a Swiss Air B747 was equipped with a container carrying instruments to measure NO, NO2, O_3 within the project NOXAR [Brunner et al., 2001]. The Swiss project NOXAR was coordinated with the EU-Project POLINAT 2 [Schumann et al., 2000].

In the near future, it is expected to get access to a new research aircraft known under the project acronym HALO. Similar to the project HIAPER in the USA, HALO will be an instrumented Gulfstream G550. The HALO investment is funded by the German Ministry of Research and Education (BMBF) and by German research institutions (MPG, HGF). HALO will be operated by DLR under an open consortium including in addition the German Science Foundation (DFG), the Leibniz Society (WGL), and other institutes. HALO is expected to become operational in 2008.

Compared to other existing European research aircraft, HALO will go "higher, farther, larger:" up to 15.5 km altitude, more than 8000-km range, and up to 3000-kg payload.

Instrumentation

Some of the research aircraft are equipped with a specific set of instruments, which can only with large efforts be changed into new configuration. However, many of the research aircraft are equipped with devices (racks, openings, inlets, windows, power supply, data recording system, etc.) that allow for equipment

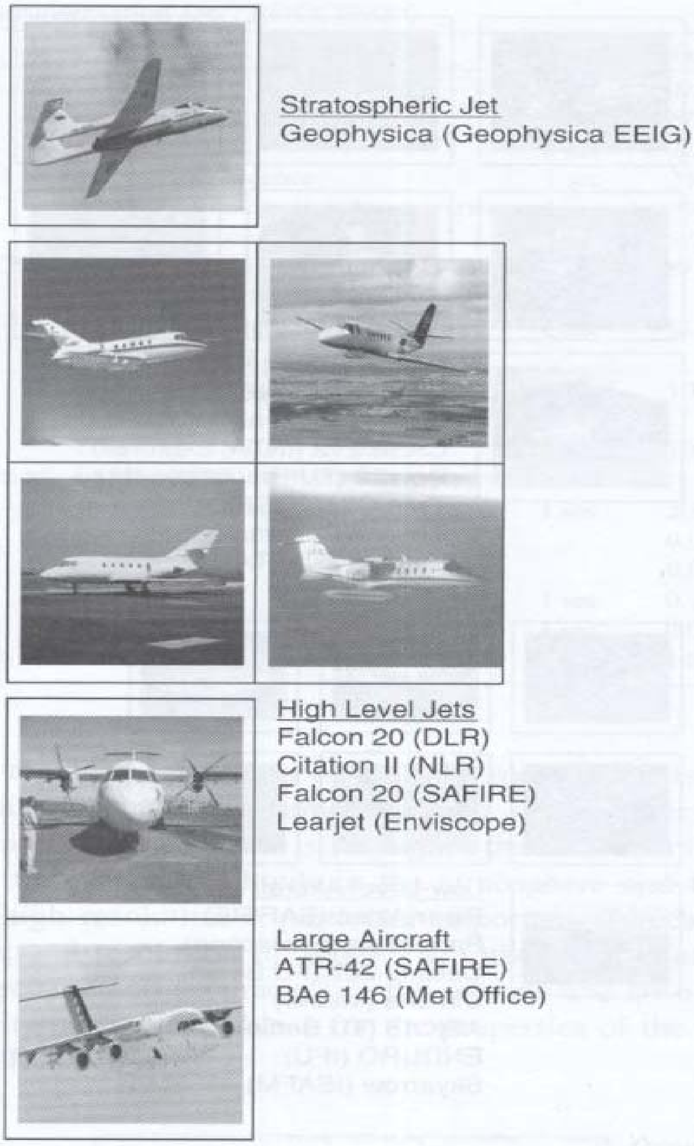

FIGURE 1. The EUFAR fleet.

with variable sets of instruments. For example, the Falcon research aircraft of DLR was equipped with instruments as listed in Table 1, during the field campaign of the project TROCCINOX in Jan–March 2004.

In particular, DLR has developed instruments to be flow on the Falcon for trace gas measurement systems [Schlager et al., 1997], particle instrumentation [Schumann et al., 2002; Minikin et al., 2003], Lidar instruments [Ehret et al., 1999, 2000; Fix et al., 2002] (available for O_3, H_2O, wind profiles), and standard instruments (position, speed, temperature, humidity, wind etc.) [Schumann et al., 1995]. The trace gas measurement system is available to measure many of the components important for photochemical reactions in the troposphere.

FIGURE 1. (*Continued*)

In addition to the particle instrumentation listed in Table 1, an extended set of instruments was available within the project INCA, to cover the whole size range from a few nanometers to millimeters; see Figure 2.

During TROCCINOX, the Lidar was flown looking upwards to measure Lidar backscattering—at wavelengths 532 and 1064 nm—and H_2O by differential absorption with two wavelengths near 935 nm, in the altitude range up to 16 km; see Figure 3 for an example.

During transit from Germany to Brazil and back, the Lidar was looking downward to measure aerosol and H_2O profiles from 11 km downward to the ground within the troposphere. In other projects, the Lidar systems were flown to measure O_3 and wind profiles.

TABLE 1. Falcon Instrumentation for TROCCINOX

Species/Parameter	Technique	Δt	Precision/Accuracy
Aerosol Profile	DIAL	5 sec	1/5%
Remote H_2O Profile	DIAL upward or downward	1 min	5/10%
Ozone	UV absorption	5 sec	1/5%
NO	Chemiluminescence	1 sec	3%/10%
NO_y	Chemiluminescence + Au converter	1 sec	5%/15%
CO	VUV fluorescence	5 sec	1/3 nmol/mol
Condensation nuclei (CN)	Condensation particle size analyzer (lower cutoff 4, 9, 13 nm)	1 sec	5/10%
Nonvolatile CN	CN counter with heated inlet (lower cutoff 13 and 50 nm)	1 sec	5/10%
Aerosol absorption coefficient	PSAP (particle soot absorption photometer)	30 sec (BL)	10/20%
Aerosol and cloud element size distribution	PCASP-100X (0.2–1.0 μm) FSSP-300/300 (0.3–20/5–100 μm)	20–60 sec	10/20%
Position, wind	INS, GPS, 5-hole probe	1 sec	200 m (horiz.) 0.05/1 m/s (h) 0.05/0.3 m/s (v)
Temperature	Rosemount	1 sec	0.1/0.5 K
Humidity	Lyman-alpha	1 sec	0.01/0.3 g/m^3
NO_2 photolysis, $J(NO_2)$	Filter radiometer	1 sec	1 E-4/5 E-4

The spatial and temporal resolution of airborne measurements is usually far higher than what can be achieved by remote sensing -on the other hand, the coverage reached by satellite instruments is far higher than for aircraft. For properties influenced by turbulence or clouds in the atmosphere and for short lived chemical species, high resolution is particular important. Typically the instruments reach a temporal resolution of about 1 s. Other important properties of instruments are precision and accuracy, i.e., the relative and absolute resolution of the measured parameter. See Table 1 for the properties of the Falcon instrumentation during TROCCINOX.

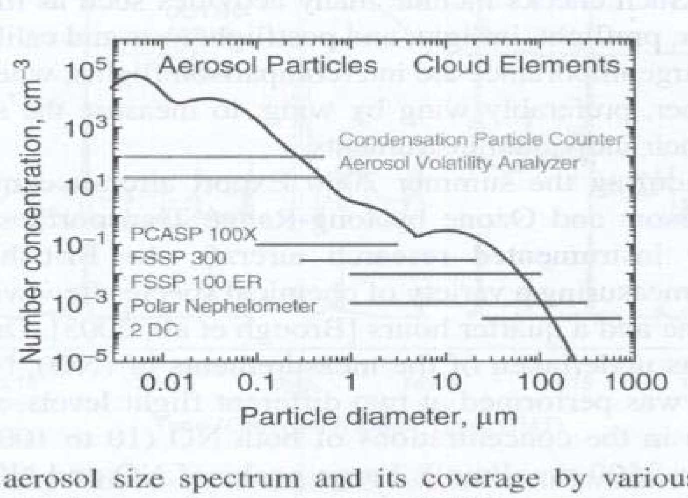

FIGURE 2. Typical aerosol size spectrum and its coverage by various instruments. [A. Petzold, A, Minikin, DLR, pers. Communication, 2003.]

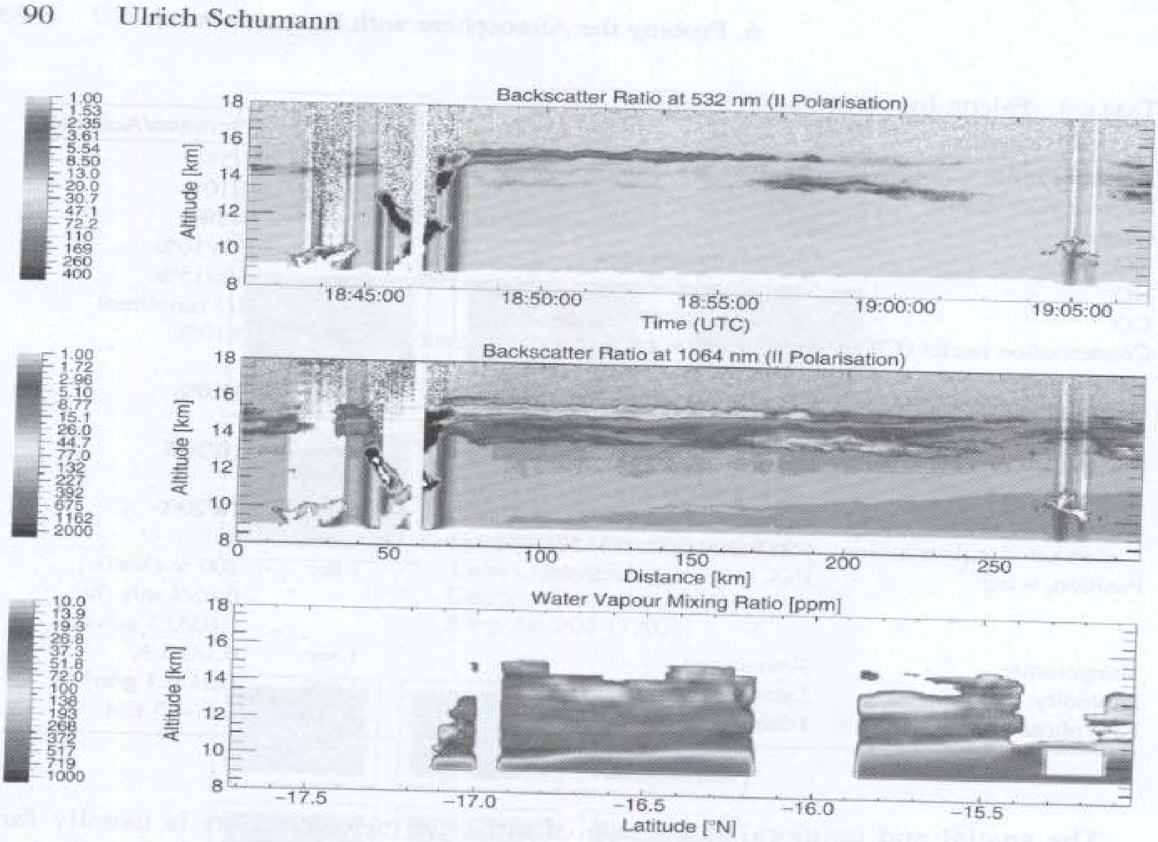

FIGURE 3. Observations of backscatter and water vapor near the anvil of a tropical thunderstorm during TROCCINOX [G. Ehret, A. Fix, H. Flentje, M. Wirth, personal communication, 2004].

Quality Checks

An important task in performing airborne measurements are quality checks of the instrumentation. Such checks include many activities such as model analysis and laboratory studies, preflight, inflight, and postflight tests and calibrations. One specific activity of large importance are intercomparison flights, where two aircraft fly close to each other, preferably wing by wing, to measure the same atmospheric parameter with their individual instruments.

For example, during the summer 2000 Export aircraft campaign (European eXport of Precursors and Ozone by long-Range Transport), see Figure 4, two comprehensively instrumented research aircraft, the British C-130 and the German Falcon, measuring a variety of chemical species flew wing tip to wing tip for a period of one and a quarter hours [Brough et al., 2003]. During this interval a comparison was undertaken of the measurements of (NO), NO_y, CO, and O_3. The comparison was performed at two different flight levels, which provided a 10-fold variation in the concentrations of both NO (10 to 1000 pmol/mol) and NO_y (200 to over 2500 pmol/mol). Large peaks of NO and NO_y observed from the *Falcon 20*, which were at first thought to be from the exhaust of the *C-130*,

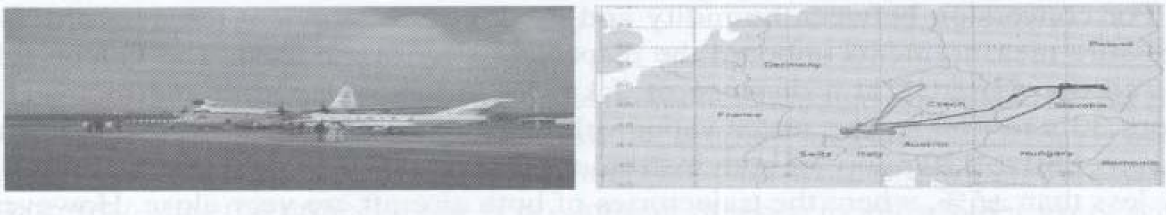

FIGURE 4. Left. The MRF *C-130* and the DLR *Falcon 20* during EXPORT. Right: Flight paths of the *Falcon* (light gray) and the *C-130* (dark gray) [Brough et al., 2003].

were also detected on the 4-channel $NO_{x,y}$ instrument aboard the *C-130*. See Figure 5, for example. These peaks were a good indication that both aircraft were in the same air mass and that the *Falcon 20* was not in the exhaust plume of the *C-130*. Correlations and statistical analysis are presented between the instruments used on the two separate aircraft platforms. These were found to be in good agreement, giving a high degree of correlation for the ambient air studied. Any deviations from the correlations are accounted for in the estimated inaccuracies of the instruments. These results help to establish that the instruments aboard the separate aircraft are reliably able to measure the corresponding chemical species in the range of conditions sampled.

An intercomparison of airborne in-situ water vapor measurements by two European research projects (MOZAIC and POLINAT) was performed from aboard the respective Airbus (MOZAIC) and Falcon (POLINAT) aircraft [Helten et al., 1999]. The intercomparison took place southwest of Ireland on September 24, 1997, at 239 hPa flight level. MOZAIC uses individually calibrated capacitive humidity sensors for the humidity measurement. POLINAT employs a cryogenic frost-point hygrometer developed for such measurements [Ovarlez et al., 2003].

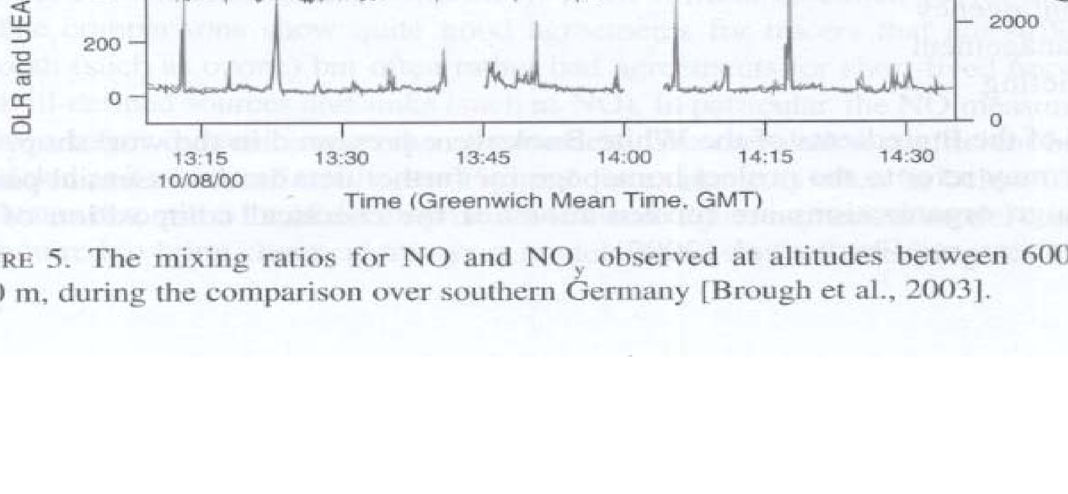

FIGURE 5. The mixing ratios for NO and NO_y observed at altitudes between 6000 and 8000 m, during the comparison over southern Germany [Brough et al., 2003].

For conversion between humidity and mixing ratio, ambient temperature and pressure measurements onboard the respective aircraft are used. The Falcon followed the AIRBUS at a distance of 7 km to 35 km with a time-lag increasing from 30 s to 160 s. The water vapor volume mixing ratio measurements in the range of 80 to 120 ppmv of both instruments are in excellent agreement, differing by less than ±5%, where the trajectories of both aircraft are very close. However, the relative humidity (RH) calculated from POLINAT frost-point measurements and the Falcon -PT500 temperature sensor is up to 15% higher relative to the RH of MOZAIC. The agreement improved to within 5% when using the temperature measurement of the PT100 sensor instead of the temperature measurement of the PT500 sensor for RH determination of POLINAT.

Campaign Planning

An important part of any airborne campaign is the campaign planning. This topic is usually not reported in the scientific literature. It simply belongs to the tasks of any such experiment. Nevertheless, it is important to recognize that this task usually takes months before the experiment, and its quality is one of the main reason for project success or failure. The "White Book" by Rob MacKenzie et al. (written as part of the TROCCINOX project), includes the following tasks:

Pre-Campaign Phase: Instrument preparation and upgrading, model development, tools development for flight planning, and logistics and operational planning, aircraft preparation.

Campaign Phase: Calibration of the instruments, campaign performance, data analysis

Interpretation Phase: Modeling of the observed scenarios using state-of-the-art models and hypotheses tests by intercomparison with the data sets.

The results of the Pre-Campaign Planning are documented in a document called "White Book". Its content includes

— Key scientific questions
— Campaign methodology: Site selection, observational platforms, alternate airports, flight objectives, instrumentation
— Flight templates
— Timelines
— Contingency
— Management
— Briefing

Some of the ingredients of the White Book were presented in the workshop. The reader may refer to the project homepage for further details. An essential part of campaign organizations are recalculations of the chemical composition of the atmosphere, see Flatoy et al. [2000].

Databases

Usually, the results of the data of a measurement campaign are collected in a project specific database, which includes all the original measurements for access by all project partners. Usually, the data banks are pass-word-controlled until at least one year after the project ends. It is common practice to allow other users access on the condition that the results are published in agreement with the experimenters, including co-authorship were reasonable.

The databases can usually be found via the homepages of the specific projects in the internet, e.g., http://www.pa.op.dlr.de/polinat/,../inca/,../eulinox/,./troccinox/, etc.

Comparison to Models

Collection of data from various projects for a class of measurements is required if one wants to compare various chemical transport models or other models to the measured results available. Some well-known examples of such data collection activities are described by Emmons et al. [2000]. The "classical" approach for evaluating a model in such studies was to aggregate the observations over specific domains, altitude ranges, and time periods, and then to compare statistical quantities such as mean or median values and standard deviations for these aggregates with corresponding model data.

However, the model fields were usually not sampled at exactly the same times and positions as the measurements but rather averages over entire time periods (e.g., monthly means) and domains (e.g., over a range of grid cells) were calculated because such quantities can easily be derived from standard model output. A more direct approach was used, e.g., by Brunner et al. [2003], compares each measured data point with its temporally and spatially interpolated model counterpart. Such a "point-by-point" analysis requires us to simulate exactly the same time periods when the measurements were obtained.

Within the TRADEOFF project [Brunner et al., 2003], an extensive database including all major research aircraft and commercial airliner measurements between 1995 and 1998 as well as ozone soundings were established. The database is constructed to support direct comparison between model results and measurements. Moreover, quantitative methods were applied to judge model performance including the calculation of average concentration biases and the visualization of correlations and RMS errors in the form of so-called Taylor diagrams.

The comparisons show quite good agreements for tracers that are sufficiently smooth (such as ozone) but often rather bad agreements for short-lived trace gases with ill-defined sources and sinks (such as NO). In particular, the NO measurements show a larger dynamic range than the models. The correlation coefficient between modeled and measured results, see Figure 6 for example, is often far below 0.5. This indicates that still a lot of development work and higher numerical model resolution is required to bring chemical transport models into a state of satisfying accuracy.

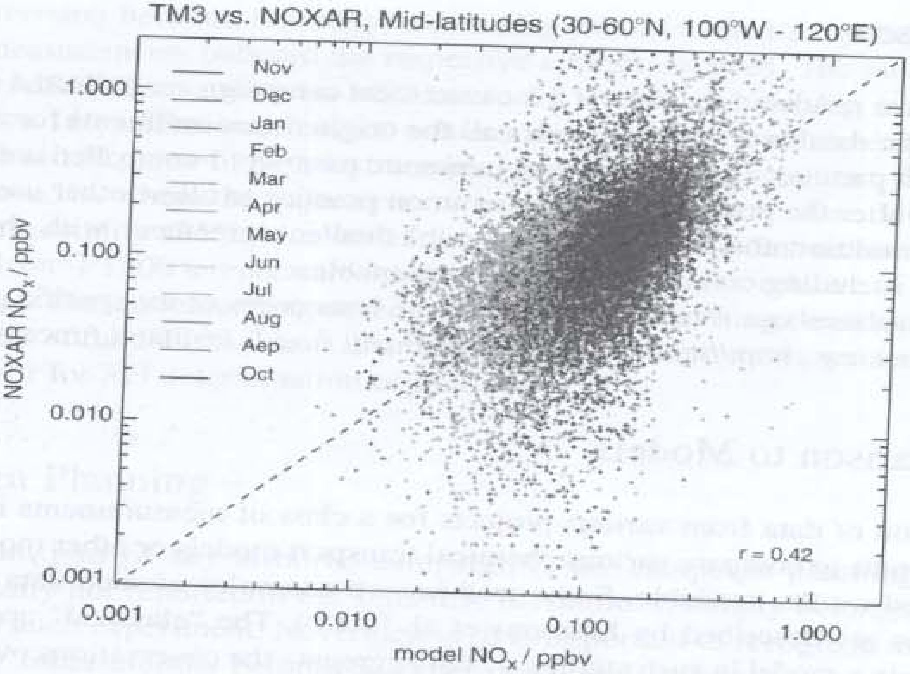

FIGURE 6. Scatter plot of model results versus NOXAR NO [Brunner et al., 2003].

Conclusions

Research aircraft form an essential component of the atmospheric (and Earth observation) research infrastructure. Usage of aircraft requires skills, as indicated in this lecture, not only with respect to the underlying science, but also with respect to aviation, instrumentation, campaign management, and data evaluation.

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CETEMPS-Dipartimento di Fisica
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via vetoio
67010 Coppito (AQ), Italy
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Piero Di Carlo
CETEMPS-Dipartimento di Fisica
Università degli Studi di L'Aquila
via vetoio
67010 Coppito (AQ), Italy
piero.dicarlo@aquila.infn.it

William H. Brune
Department of Meteorology
Penn State University
505 Walker Building
University Park, PA 16802, USA
brune@meteo.psu.edu

Mark Schoeberl
Earth Sciences Directorate
Mail Code 900
NASA Goddard Space Flight Center
Greenbelt, MD 20771, USA
mark.r.schoeberl@nasa.gov

Andreas Wahner
Forschungszentrum Jülich GmbH
ICG-II: Troposphäre
D-52425 Jülich
Germany
A. wahner@fz-juelich.de

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