SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Climate Monitoring by Advanced Spaceborne Sounding and Atmospheric Modelling
Computer Project Account:	SPATAC
Start Year - End Year :	2001 – 2011
Principal Investigator(s)	Prof. Gottfried Kirchengast
Affiliation/Address:	Wegener Center for Climate and Global Change (WEGC), and Institute for Geophysics, Astrophysics, and Meteorology/Institute of Physics (IGAM/IP), University of Graz (UniGraz), Graz, Austria
Other Researchers (Name/Affiliation):	Members of the ARSCliSys Research Group of WEGC and IGAM/IP (www.wegcenter.at/arsclisys > *Members*), and Dr. Luis Kornblueh (MPI for Meteorology, Hamburg, DE)

The following should cover the entire project duration.

Summary of project objectives
(10 lines max)

This ECMWF Special Project was undertaken to support a research programme on climate change monitoring and climate modelling, which aims at providing a better understanding of climatic changes in the atmosphere's thermal, moisture, and trace species composition structure, both due to natural and anthropogenic influences. The Special Project, carried out at the WEGC and IGAM/IP of the University of Graz under the lead of Gottfried Kirchengast, was scheduled to last until 2011 so this is the Final Report. The focus was to employ ECMWF data products and computational resources for the benefit of advanced spaceborne atmospheric sounding and atmospheric modelling, including regional climate modelling, with high resolution and accuracy. As a feedback, the project could furnish valuable contributions to the evaluation and improvement of the quality of ECMWF products, especially of the fields of thermodynamic variables.

Summary of problems encountered
(If you encountered any problems of a more technical nature, please describe them here.)

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Experience with the Special Project framework
(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

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Summary of results
(This section should comprise up to 10 pages and can be replaced by a short summary plus an existing scientific report on the project.)

Introduction

At the advanced spaceborne sounding side the primary satellite-borne data sets continuously exploited are occultation data from GPS radio occultation (RO) sensors. RO data provided by GPS/Met, CHAMP, SAC-C, GRACE, and FORMOSAT-3/COSMIC have been processed so far, a test data set from the MetOp-A satellite (GRAS instrument) completes the RO record currently available at the WEGC and IGAM/IP. RO Data from TerraSAR-X, OCEANSAT-2, and TAMDEM-X are expected to be available later in 2011. Furthermore, next-generation occultation techniques combining microwave occultation and infrared-laser occultation between Low Earth Orbit (LEO) satellites for accurate joint profiling of thermodynamic variables, greenhouse gases and wind are explored.
The Special Project aided the atmospheric modelling side of the programme, mostly by enabling seamless access to ECMWF data products, in particular atmospheric analysis and short-range forecast fields from ECMWF's MARS archive. The project also enabled that some pre-processing operations on atmospheric fields and some related data analysis and modelling activities could be performed within the ECMWF computer and storage infrastructure so as to avoid the transfer of large data volumes from ECMWF/Reading to WEGC/UniGraz in cases where this would seem an inefficient work approach. Furthermore, the project provided important computational resources and data from

re-analysis and operational analysis for regional climate modelling.
Primary areas of exploitation of ECMWF data included (i) the use of ECMWF analysis fields (frequently spatially-horizontally averaged to ~T42 resolution) as reference for the quality control and the validation of new satellite data and derived (essentially model-independent) climatologies, (ii) the use of ECMWF short-term forecast fields as background for optimal estimation retrieval to again obtain high-quality monthly or seasonal climatologies of atmospheric variables such as temperature, humidity, and geopotential height of pressure levels from the satellite data, and (iii) the use of ECMWF re-analysis (ERA-40, ERA-Interim) and operational analysis (IFS) for regional climate modelling. Computational (CPU) resources were primarily assigned to regional climate modelling applications. Most of these computational resources have been provided by the Austrian Central Institute for Meteorology and Geodynamics (ZAMG) via the ATAC01 account, in addition to the resources accessible through SPATAC.
Regarding additional use of the processed data obtained, these climatologies and analyses were also compared to climate GCM simulations and projections to assess improvement potentials in GCM physics (e.g., in humidity and cloud modelling) and in GCM forcing input (e.g., in solar forcing). Furthermore, climate change detection studies based on these new data sets were performed.

Work during the Project

As quality control and inter-comparison background within our radio occultation processing and analysis system for GPS radio occultation data, ECMWF analysis and short-term forecast fields were continuously used at large-scale resolution (T42L60 until end January 2006, T42L91 since February 2006). For this purpose, global fields of temperature and humidity (and related basic parameters such as surface pressure and orography) were extracted for every single day, four time layers a day, from the MARS archive. Since mid 2001 this has been done for the processing and validation of CHAMP RO profiles. Meanwhile ECMWF fields have also been used in the processing of RO data from GPS/MET, SAC-C, FORMOSAT-3/ COSMIC, GRACE, and MetOp-A. This work also provided valuable feedback on the (steadily increasing) ECMWF analysis data quality regarding (absolute) accuracy, since the GPS RO data served as essentially independent reference state. With the aid of these RO data we have also carried out a climate signal detection study. A study on atmospheric tides in the free atmosphere was performed comparing amplitudes and phase of diurnal and semi-diurnal tides from FORMOSAT-3/COSMIC data and ECMWF short-term forecast data.

Global ECMWF analysis fields at T799L91 resolution have been used for simulation studies and fields at T511L91 resolution to generate realistically simulated occultation observables employing high-precision ray tracing. These simulated data have been used to analyse the sensitivity of occultation data to horizontal variability within the atmosphere. ECMWF data were particularly valuable for end-to-end performance analyses of the LEO-to-LEO crosslink occultation concept ACCURATE, proposed in the framework of the European Space Agency (ESA). ACCURATE was undergoing various scientific studies and pre-developments in this context (ESA studies and studies in the Austrian Space Applications Programme ASAP). In these cases, where the novel combined microwave and infrared-laser occultation concept (conceived at WEGC) was investigated, also additional state variables like ozone and wind fields, as well as cloud liquid and ice water content fields, were utilized.

Regarding regional climate modelling, the ECMWF high performance computing facility has been used to conduct numerous highly resolved (10 km, ~3 km, and ~1 km grid spacing) short-term simulations (covering multiple time scales up to 3 years) with two non-hydrostatic models, the PSU/NCAR model MM5 and the COSMO model in CLimate Mode (CCLM) of the German Weather Service (DWD). The driving lateral boundary conditions (LBCs) have been derived from the re-analysis dataset ERA-40 and from ECMWF's operational deterministic analysis and forecast system (IFS). These simulations embedded in sensitivity studies focussed on, (1) exploiting of downscaling errors for model development, and (2) deriving well-balanced model setup (domain setting, parameterisations, nesting strategy) for regional climate modelling applications (see below).

These short-term simulations (periods November 2002 to December 2003, June / July 2007, December / January 2007 / 2008, January 1998 to December 2000) were driven by 3-hourly lateral boundary conditions from the IFS (T511L91, T799L91) and ERA-40 (T106), respectively. The IFS-driven simulations contributed to the three-year project "Non-hydrostatic climate modelling – NHCM-1", funded by the Austrian Science Fund (FWF), and enabled a systematic exploitation of error ranges of state-of-the-art regional climate models (RCMs) – CCLM, WRF, and MM5 – operated in the Alpine region. Some of these simulations were also part of the international model-inter-comparison study on convection-resolving scale, the "Local Climate Model Intercomparison Project" (LocMIP) contributed to also by the Max-Planck Institute for Meteorology (MPI-M), Hamburg, Germany, and the Lehrstuhl für Umweltmeteorologie, BTU Cottbus, Germany.
The ERA-40 driven simulations were conducted within the framework of two Austrian regional climate modelling projects, "Research for Climate Protection – Model Run Evaluation (reclip:more)" (funded by the Austrian Government) and "Entwicklung eines Basisdatensatzes regionalisierter Klimaszenarien (reclip:century)" (funded by the Austrian Climate Research Programme) and focused on the definition of suitable model configurations for regional climate modelling applications.
In addition to these sensitivity studies long-term climate simulations (30 km / 10 km grid spacing with MM5 and 50 km / 10 km with CCLM) driven by global ECHAM5 climate simulations (periods 1981 to 1990 and 2041 to 2050, emission scenario IS92a; periods 1955 to 2050, SRES scenario A1B) were conducted within the framework of reclip:more and reclip:century, respectively. The computational resources of these climate simulations have been provided by ZAMG via the ATAC01 account.
ERA-Interim data had been used for first test simulations with CCLM and WRF in the South-Asian region at another high-performance-facility, the Juelich Supercomputing Centre (JSC).

The SPATAC project resources supported the finishing of one Habilitation Thesis (with a second one becoming finished in summer 2011) and twelve PhD Theses as well as of numerous MSc Theses.

Selected Results

In *Foelsche et al*. (2011b) we could demonstrate that ECMWF analysis fields are excellently suited to compute (and remove) the errors due to spatio-temporal undersampling in climatologies based on radio occultation data.
With the aid of high-resolution ECMWF analysis fields (T799L91) we have quantified the random and systematic errors due to the geometry – and specifically obliquity – of RO profiles (*Foelsche et al.*, 2011a). These errors are reduced by up to a factor of two when the measurement geometry is properly taken into account. These results convinced the responsible persons at ECMWF to take the measurement geometry into account when assimilating RO profiles.
In *Gobiet et al*. (2005), *Borsche et al*. (2007) and *Foelsche et al*. (2008a) we discovered weaknesses in ECMWF analyses in the tropical tropopause region, over Antarctica and occasionally over the Arctic (Figure 1). The former disappeared with the implementations of a new ECMWF analysis scheme, the latter with the assimilation of RO data at ECMWF (*Foelsche et al*., 2009b).

Regarding next-generation occultation observing systems based on the microwave and infrared-laser occultation method between Low Earth Orbit satellites (LMIO method; *Kirchengast and Schweitzer*, 2011) we benefitted from high-resolution ECMWF analysis fields (including liquid and ice water cloud fields; Figure 2) in an end-to-end performance analysis for LEO-LEO microwave occultation (*Schweitzer et al.*, 2011) and a range of other studies (e.g., *Kirchengast and Hoeg*, 2004; *Kirchengast et al.*, 2004b; *Kirchengast et al.*, 2005; *Gorbunov and Kirchengast*, 2005, 2007; *Schweitzer et al.*, 2010; *Kirchengast and Schweitzer et al.*, 2010).
Beyond single studies the whole process of preparing a complete satellite mission concept based on the LMIO method (*Kirchengast et al.*, 2010) benefitted in many relevant assessments from ECMWF data products acquired under the Special Project SPATAC.

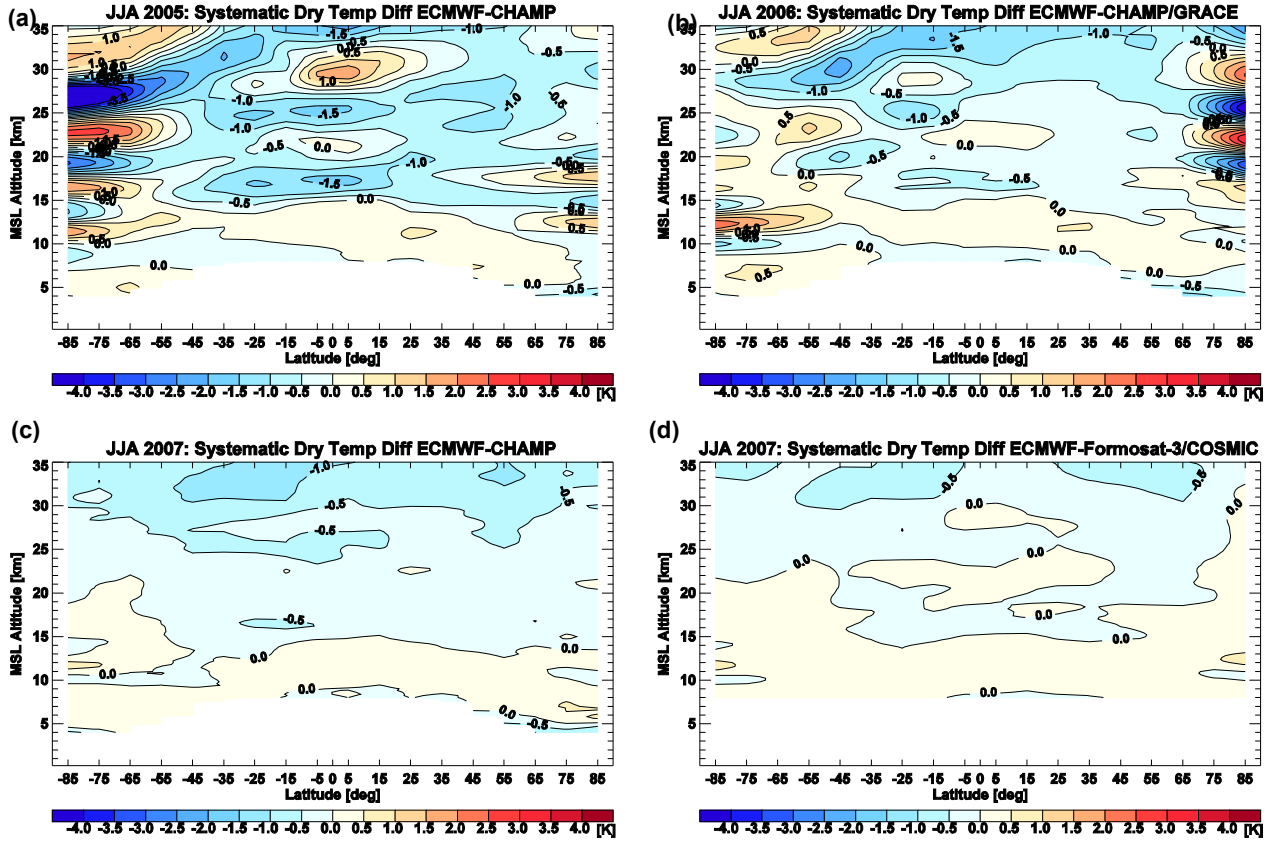

Figure 1: Systematic differences between Radio Occultation dry temperature climatologies and ECMWF analyses for northern summer seasons June-July-August (JJA): 2005 (a) and 2006 (b) based on CHAMP and CHAMP + GRACE data, respectively; JJA 2007 based on CHAMP data (c) and JJA 2007 based on F3C data (d). From *Foelsche et al*. (2009b).

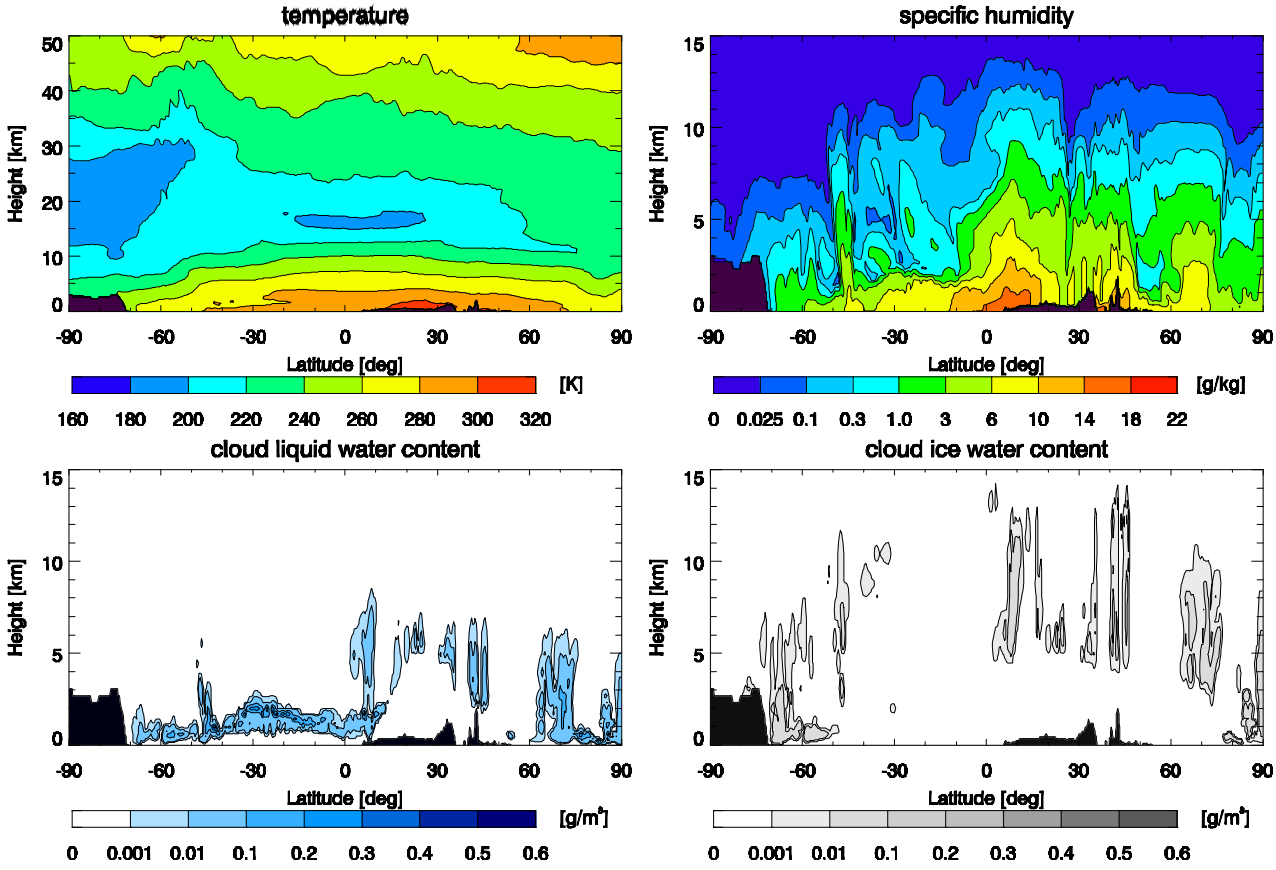

Figure 2: Latitude-vs-height cross sections of temperature (top left), specific humidity (top right), liquid water density (bottom left), and ice water density (bottom right) at 0° longitude through the ECMWF analysis used in the simulations (T511L91, 15 July 2006, 12 UTC), indicating the atmospheric variability covered. From *Schweitzer et al*. (2011).

Concerning regional climate modelling the knowledge of the error range of RCMs is of utmost interest for further model development and for the development of error correction and statistical downscaling methods in order to provide applicable user-tailored climate change scenarios to the climate change impact community. Furthermore, if the error range is empirically explored by means of sensitivity experiments, well-balanced model configurations can be found for specific regional climate modelling applications. In order to explore the error ranges in the Greater Alpine Region of four well-known RCMs (CCLM, REMO, WRF, and MM5), 62 short-term simulations (simulation period 1999; horizontal resolution 10 km grid spacing) driven by ERA-40 have been conducted and analysed during the project NHCM-1 (see above). From model/observation comparisons the model range of monthly biases averaged over the Greater Alpine Region of mean sea level pressure/air temperature/precipitation (see Figure 3) are smaller than/equal to/larger than the natural variability, respectively. Hence, precipitation in complex terrain is one of the most difficult variables to be captured by modern RCMs.

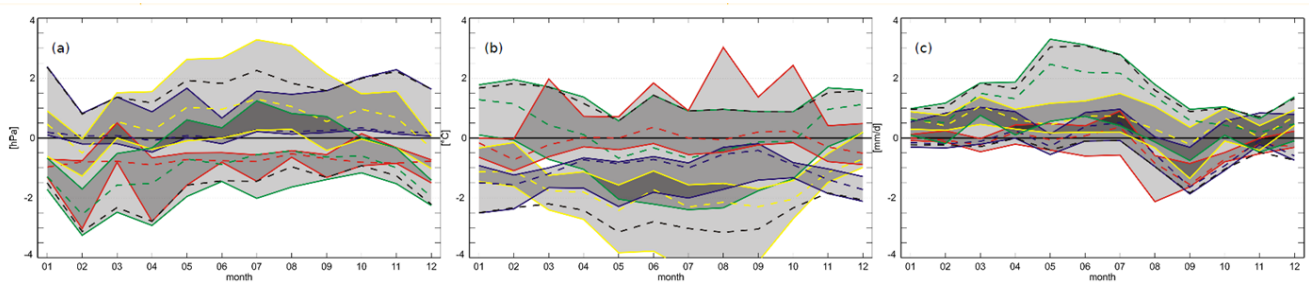

Figure 3: Annual cycles of biases (averaged over the Greater Alpine Region) of 62 short-term simulations (period: 1999; grid spacing 10 km) driven by ERA-40. (a) Mean sea level pressure (evaluated against ERA-40), (b) 2m air temperature (evaluated against E-OBS, http://eca.knmi.nl/), and (c) total precipitation amount (evaluated against an observation dataset from ETHZ). Colours correspond to the four models: CCLM (blue), REMO (red), yellow (MM5), and WRF (green). Coloured dashed lines show the median bias of each model, solid lines the 2.5 and 97.5 percentiles. Grey shades annotate the 2-sigma interval. The darker the shade, the more ensemble members share the same bias. From *Suklitsch et al.* (2010).

List of publications/reports from the project with complete references

Selected list of publications where the underlying work benefited from SPATAC (i.e., where ECMWF data products and/or computational resources aided the work):

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Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

The primary areas of exploitation of ECMWF products and the usage of ECMWF CPU resources will continue via the ECMWF access of ZAMG. Since ZAMG closely cooperates with WEGC, requesting for a further ECMWF special project is set aside.

WEGC usage of ECMWF resources will include: (i) the use of analysis fields to provide a reference for quality control and validation of a constantly increasing number of new satellite data (with focus on occultation data), (ii) the use of monthly mean fields as inter-validation datasets for observed climatologies, (iii) the use of short-term forecast fields and associated analysis/forecast error fields as basis for optimal estimation retrieval using advanced sounding data, (iv) the use of analysis and forecast fields and associated error fields for supporting end-to-end performance analysis and demonstration studies related to next-generation microwave and infrared-laser occultation observing systems, and (v) the use of re-analysis and operational analysis and forecast fields to prepare lateral boundary conditions for regional and local-scale climate models operated at very high resolution (10 km to 1 km scale).

Regarding the computational resources, ECMWF CPU resources (accessible by ATAC01) will be used (i) for simulations of a large ensemble of radio occultation data based on outputs from 25 years of ECHAM5 GCM runs within a climate observing system simulation experiment, (ii) for long-term regional climate simulations (period 1961 to 2100) preparing the next generation of highly resolved (10 km grid spacing) climate scenarios for the Alpine region, and (iii) for further high-resolution simulations within the follow-up project of NHCM-1 (see above).

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