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Opening ceremony

Aviation and Climate: An update

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Aviation emissions contribute to the radiative forcing (RF) of climate. Of importance are emissions of carbon dioxide (CO2), nitrogen oxides (NOx), aerosols and their precursors (soot and sulphate), and increased cloudiness in the form of persistent linear contrails and induced-cirrus cloudiness. Aviation operations have grown strongly over the past years and further growth is expected. This presentation will provide an updated perspective on new research and understanding of the role of aviation in climate and where uncertainties and gaps remain.

Emissions and near field processes

Aircraft engine emissions - European Regulation and Certification

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The purpose of the presentation is to provide an overview of EASA activities in the field of aircraft engine emissions.

We certify civil aeronautical products for a high uniform level of safety and environmental protection in Europe. We are also drafting the requirements and procedures on which the certification is based. We submit these texts to the European Commission when establishing or updating European Regulations. In addition not legally binding material can directly be adopted by EASA.

The European regulatory framework bases the certification for aircraft noise and aircraft engine emissions on the Annex 16 to the ICAO Chicago Convention. For that reason we strongly contribute to the work done within ICAO and SAE International.

The regulated species for the certification of aircraft engines are smoke, HC, CO and NOx. The standard apply to all turbojet and turbofan engines in the case of smoke and only to those with a thrust greater than 26.7kN for the gaseous emissions. The regulatory NOx limits were periodically updated to become more stringent. We are collecting the data from the certification tests in the engine emissions databank.

At the ICAO Committee on Aviation Environmental Protection in February 2016, a new non-volatile particulate matter (nvPM) standard and new CO2 standard for aeroplanes will be proposed for adoption and future implementation in the European Regulation.

We are supporting the research work on establishing the technical requirements for a nvPM measurement method (SAMPLE programme) and the studies on establishing the CO2 certification requirements and regulatory limits. The next EU funded studies relate to engine testing to gather nvPM data for the improvement of the nvPM standard and modelling of cruise nvPM.

Emissions and near field processes

Thrust dependence and engine variability of primary volatile organic compound emissions from commercial aircraft turbine engines

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Non-methane volatile organic compounds (NMVOC) emission indices (EI, pollutant quantity / unit mass of fuel burned) were measured from in-service commercial aircraft turbine engines at the SR Technics engine test facility at Zürich airport, Switzerland. A standardized sampling and measurement system for gaseous and particulate matter emissions is installed there. A single-point sampling probe extracted the exhaust sample at the engine exit plane. The sample was diluted with synthetic air by a factor of 8-10 and drawn via a 25 m long 8 mm I.D. heated line to the instruments. We report more than 100 species with different functional groups, e.g. acids, alcohols, aliphatics, aromatics, carbonyls, measured using a high resolution proton transfer reaction time-of-flight mass spectrometer (HR PTR-TOF) for thrust levels that mimic the standardized landing and takeoff settings (taxi, approach, climb, take-off) as well as cruise thrust that was assumed as 65% take-off thrust. The study focused on the variability of NMVOC emissions with engine thrust and engine type. The NMVOC EI of 1.8 (± 0.7) g / kg fuel at idling (thrust <7 %) decreased to 0.08 (± 0.05) g / kg fuel at take-off (100% rated thrust). The NMVOC EIs were consistently similar across all engine types. The relative contribution (%) of (non-oxidized) hydrocarbons increased with increasing thrust level, while the relative contribution of oxygen containing species such as acids and carbonyls decreased.

Emissions and near field processes

A Volatile Particle Microphysical Simulation Model for the Evolution of Surrogate Organic Emissions in an Aircraft Exhaust Plume

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A microphysics model is presented that numerically simulates the evolution of volatile sulfate and organic particulate matter (PM) in the near-field aircraft plume. Six surrogate organic compounds, pentanoic acid (C5H10O2), naphthalene (C10H8), anthracene (C14H10), pyrene (C16H10), perylene (C20H12), and anthanthrene (C22H12), were selected to represent the range of organics present in the exhaust based on saturation vapor concentration, and their dry mass accommodation coefficients were derived from a correlation to the species water solubility. The 6-species surrogate model was validated against two field measurements, and showed that it can reproduce the experimental results and simulate the evolution of the volatile aircraft emissions both qualitatively and quantitatively. First, through a sector combustor rig test at United Technologies Research Center (UTRC), the model was able to predict the amount of organic and sulfate coatings on the combustion soot particles. It also explained why there is more organic soot coating at higher soot loading condition although the initial vapor concentration of volatile organic species was lower. Second, an Allison T63 turboshaft engine with artificially sulfur-doped fuel was used to investigate the relative compositions among the nucleation/coagulation and soot coating modes. The model reproduced the experimental observation that the nucleation/coagulation mode is dominated by organics and the soot coating mode by sulfates. The model provides an explanation why the nucleation/coagulation mode eventually becomes organics-rich even though the nucleation process is initiated by sulfates. Through this work, the microphysics model demonstrated that it can serve as a working engineering model to simulate the volatile PM emissions from aircraft engines.

Emissions and near field processes

Development of a Certification Method for Aircraft Engine Non-volatile PM Emissions: Results from the North American Reference System Deployment in the Aviation - Particle Regulatory Instrument Demonstration Experiment (A-PRIDE) 4 Campaign

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Accurate inventories of emissions from aviation operations are essential to assess impacts on air quality, health, and climate. A standard methodology for the measurement of non-volatile Particulate Matter (nvPM) number- and mass-based emissions from aircraft engines has been developed. A mobile compliant sampling system, the North American Reference System (NARS) developed, built and operated by Missouri University of Science and Technology (Missouri S&T) will be described with particular attention given to essential design criteria such as sample dilution and line loss. As part of the validation of the NARS for certification measurement validation, it participated along with a fixed compliant system developed and built by Empa, in the Aviation - Particle Regulatory Instrumentation Demonstration Experiment 4 (A-PRIDE 4) campaign at the SR Technics facilities in Zürich, Switzerland in November 2012. The Missouri S&T and Empa systems were compared during a series of dedicated engine tests using a CFM56-5B4/2P engine, and maintenance engine testing using CFM56-7B24/3 and PW4168A engines at a range of engine operating conditions. Overall, these two compliant systems were found to be within 15% of each other, in terms of nvPM number- and

mass-based emission indices. Ancillary instrumentation in both systems was used to determine PM size distributions, effective density, and chemical composition. Particle geometric mean diameter ranged between 20 and 45 nm and geometric standard deviation varied from 1.55 to 1.9 for the three engine types studied. The overall fraction of PM organic content measured in the emissions from the CFM56-5B4/2P engine was ~4%. The mean particle effective density for the CFM56-5B4/2P engine was determined to be 847 kg/m3 ± 7.2 kg/m3.

Emissions and near field processes

In-Situ Measurements of Aircraft Engine Exhaust Measured during the 2013-2014 ACCESS Project

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We present measurements of aerosol microphysical properties measured in-situ behind the CFM56-2-C1 engines of the NASA DC-8 aircraft during the 2014 Alternative Fuel Effects on Contrails and Cruise Emissions (ACCESS) project. Aircraft engine emissions can have a disproportionately large climatic impact since they are emitted high in the troposphere and in remote regions with otherwise low aerosol concentrations. This has motivated numerous past ground-based studies focused on quantifying the emissions indices of non-volatile and semi-volatile aerosol species, however, it is unclear the extent to which emissions on the ground translate to emissions at cruise conditions. In addition, the ability of engine-emitted aerosols to nucleate ice crystals and form linear contrails or contrail cirrus clouds remains poorly understood.

To better understand these effects, the ACCESS-I project was conducted in 2013 to quantify aerosol emission indices for a number of petroleum-based and bio-based jet fuels at cruise conditions, while the 2014 ACCESS-II project focused on measuring the contrail microphysics. Three different fuel types are discussed: a low-sulfur JP-8 fuel, a 50:50 blend of JP-8 and a camelina-based HEFA fuel, and the JP-8 fuel doped with sulfur. Emissions were sampled using a large number of aerosol and gas instruments integrated on an HU-25 Falcon jet that was positioned in the DC-8 exhaust plume at approximately 50-500 m distance behind the engines. It was found that the biojet fuel blend substantially decreases the aerosol number and mass emissions indices, while the gas phase emission indices were similar across fuels. The effects of these fuel-induced changes of aerosol emissions on contrail properties will be discussed.

Emissions and near field processes

Chemical characterization of particulate matter aircraft turbine engine exhaust using single particle mass spectrometry

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Background

The emitted particulate matter (PM) from aircraft engines, mainly soot, is of special interest because it alters the Earth's radiation budget by acting as Ice Nucleating Particles and initiate the formation of contrails which could emerge into cirrus clouds. This aerosol-cloud interaction was reported as the most important radiative effect with regard to aviation (1). A recent study (2) shows that a dominant fraction of Ice Residuals collected in cirrus clouds contain metals, which have also been found in aircraft emissions by sampling the exhaust (3). Thus, a thorough chemical and physical characterization thereof is needed to investigate the link between aircraft emissions and atmospheric ice formation.

We present chemical and statistical analysis of fresh aircraft PM exhaust. The emissions were analyzed with respect to the occurrence of metal-containing particles and the mixing state. Furthermore, we try to identify particle sources e.g. engine abrasion, fuel or lubricant oil.

Investigation methods

Single particle mass spectrometry on fresh PM exhaust emitted by a CFM56-7B26/3 was performed using an Aerosol Time-of-Flight Mass Spectrometer (ATOFMS, TSI Model 3800). The unattached engine was operated in a test cell by SR Technics. The particles were sampled directly behind the engine with a probe and passed to the ATOFMS ~30 m downstream.

The ATOFMS measures the chemical composition of single particles by ionizing its constituents. The emerged ions are classified according to their mass-to-charge ratio. The resulting mass spectra are used to identify the chemical components, the mixing state of individual particles and to provide semi-quantitative information on the content of specific particle components.

Results and Discussion

Soot from combustion sources typically contain elemental carbon which is reflected in the mass spectra by a Cn (n = 1, 2, 3, etc.) pattern. This EC pattern was found on a vast majority of the particles analyzed.

A large particle fraction contained additional individual metal species. The most abundant were Cr, Fe, Mo, Na, Ca and Al, but V, Ba, Co, Cu, Ni, Pb, Mg and Si were also present. The metals were internally mixed with the soot particles.

The source-identification of the metal compounds found within the exhaust particles is still ongoing. The presented study will include a comparison between our chemical characterization of single particles with data from chemical bulk analysis of the jet fuel and jet engine lubricant oil performed using inductively coupled mass spectrometry.

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Emissions and near field processes

Sensitivity of aircraft gas turbine non- volatile particulate matter mass and number emissions to fuel aromatic content

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Particulate matter emissions from aircraft gas turbines are a concern for human health, envi-ronmental degradation and climate change. Understanding the effect of aromatics in the fuel on non-volatile particle matter (nvPM) emissions is important for establishing future regulation and for assessing potential emission abatement strategies that intend to change fuel feedstock. This work presents non-volatile PM mass and number emission indices (EIs, mass or number nvPM/ mass fuel) as a function of fuel aromatic content for an aircraft gas turbine source with a modern rich-quench-lean (RQL) combustor run under certification-like conditions in the test cell of SR Technics, Zurich airport.

The nvPM sampling system and system operation corresponded to the recently issued stand-ard (1). The fuel (JET A-1) total aromatics level was changed by a controlled injection of two aromatic solvents into the fuel supply line to the engine. The two aromatic solvents were Solvesso 150 and Solvesso 150ND, of which the first one contained 6% by volume naphtha-lenes. Besides the unmixed fuel that had a total aromatic content of 17.8 % by volume, three fuel blending ratios covering the range up to 23.6% by volume in total aromatic content were tested for each solvent at six static engine thrust points ranging from idle to take-off.

The results show an increase in nvPM mass and number EIs with increasing fuel aromatics content. The most pronounced increase in EI (up to +60% for mass and +50% for number) was found at low engine thrusts, indicating that fuel aromatics have an impact on soot for-mation under this condition. At the engine thrust near take-off, the nvPM EIs increased by 5 – 10% for number and 10 - 20% for mass, indicating a less significant effect of fuel aromatics. A correlation between normalized nvPM EIs and fuel hydrogen mass content was found.

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Emissions and near field processes

Spatial variability of PM and gaseous emissions at the exit plane of an in-service commercial aircraft turbine engine

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To minimize environmental impacts of commercial aviation, the International Civil Aviation Organization (ICAO) has set strict criteria for gaseous emissions and visible smoke from commercial aircraft engines. Because modern aircraft engines generate no visible smoke, this obsolete criterion is about to be replaced by a non-volatile PM (nvPM) number and mass emissions standard. To representatively sample gas turbine exhaust at the exit plane, engine manufacturers use most often multi-orifice sampling probes unique for each engine type. An important question is then if the sample for nvPM measurements is representative, using the same probe as used for gaseous and smoke measurements. We determined how the PM emissions vary at the exit plane of an in-service turbofan engine source burning conventional Jet A-1 fuel. To do so, we deployed a 2D traversing single orifice probe and a standardized nvPM sampling and measurement system in the engine test cell at SR Technics, Zurich airport. The nvPM varied more than gaseous emissions across all engine conditions. All emissions varied most at engine idle (factor of 4 for nvPM mass and number and factor of 2 for gaseous emissions measured at the same radius). Because the traversing probe was further downstream of the engine exit than the certification probe, the bypass flow could have entrained the core flow before sampling and caused asymmetric patterns. The variability decreased with increasing thrust level. At take-off thrust, gaseous emissions were axisymmetric, but the nvPM still varied by a factor of 2 at a constant radius and different angles. This study will help optimize the single point sampling for the given engine, quantify the uncertainty of those measurements, and provide material to assess the appropriateness of the multi-orifice probe used for gaseous certification of the engine.

Emissions and near field processes

The MERMOSE project: characterization of particulates emissions of a commercial aircraft engine: from morphology to chemical composition

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The French national project MERMOSE (characterization of emissions by aircraft engines and sponsored by French Civil Aviation national funds)gathers the capabilities of seven organizations with the aim of better characterizing the commercial aircraft engine emissions and understanding their impact on nucleation in the atmosphere. In this frame, a measurement campaign has been performed on a Snecma/NPO Saturn SaM146-1S17 turbofan. During this work, we established radial and angular profiles of PM properties in the engine hot flow at different engine thrust settings related to the aircraft main operating conditions (idle, climb, take-off, approach and cruise).

The experimental set-up was composed of a sampling probe, two undiluted lines and a diluted line. Exhaust samples were collected, on quartz fiber filters, transmission electron microscopy (TEM) grids and silicon windows to perform analyses of elemental/organic carbon ratio (EC/OC), morphology (TEM), elemental composition (EDX) and chemical composition by Fourier Transform Infra-Red spectroscopy (FTIR), respectively. Additional measurements have been done, so that the soot particles size distribution could be precisely determined by means of a Differential Mobility Sizer (DMS500). Finally, two Scanning Mobility Particles Sizers, a Nano-particle Surface Area Monitor (NSAM), a Multi Angle Absorption Photometer (MAAP), a Pegasor Particle Sensor as well as two Condensation Particle Counters (CPC) were used to provide measurements of the particles size distribution, number and surface area density and mass concentration.

The first results show that the mode electrical mobility diameter of the particles ranges from 17 nm to 55 nm and is sensitive to the thrust. The sampled particles showed a complex morphology and were composed of nanoparticles of about 15 nm in diameter. They were mainly composed of carbon (with traces of O, S and Ca) and their EC/OC ratio showed an increase as a function of the maximum thrust from 20/80 for 30% to 87/13 for 100%.

Emissions and near field processes

NASA Alternative-Fuel Effects on Contrails and Cruise Emissions (ACCESS) Flight Experiments

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Although the emission performance of gas-turbine engines burning renewable aviation fuels have been thoroughly documented in recent ground-based studies, there is still great uncertainty regarding how the fuels effect aircraft exhaust composition and contrail formation at cruise altitudes. To fill this information gap, the NASA Aeronautics Research Mission Directorate sponsored the ACCESS flight series to make detailed measurements of trace gases, aerosols and ice particles in the near-field behind the NASA DC-8 aircraft as it burned either standard petroleum-based fuel of varying sulfur content or a 50:50 blend of standard fuel and a hydro-treated esters and fatty acid (HEFA) jet fuel produced from camelina plant oil. ACCESS 1, conducted in spring 2013 near Palmdale CA, focused on refining flight plans and sampling techniques and used the instrumented NASA Langley HU-25 aircraft to document DC-8 emissions and contrails on five separate flights of ~2 hour duration. ACCESS 2, conducted from Palmdale in May 2014, engaged partners from the Deutsches Zentrum für Luft- und Raumfahrt (DLR) and National Research Council-Canada to provide additional scientific expertise and sampling aircraft (Falcon 20 and CT-133, respectively) with more extensive trace gas, particle, or air motion measurement capability. Eight, muliti-aircraft research flights of 2 to 4 hour duration were conducted to document the emissions and contrail properties of the DC-8 as it 1) burned low sulfur Jet A, high sulfur Jet A or low sulfur Jet A/HEFA blend, 2) flew at altitudes between 6 and 11 km, and 3) operated its engines at three different fuel flow rates. This presentation further describes the ACCESS flight experiments, examines fuel type and thrust setting impacts on engine emissions, and compares cruise-altitude observations with similar data acquired in ground tests.

Emissions and near field processes

MEASUREMENT OF AIRCRAFT ENGINE EMISSIONS INSIDE THE AIRPORT AREA

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Deterioration of air quality near the busiest airport and adverse consequences for public health is crucial problem, especially in relation to the breach of limit and target values for many air pollutants, mainly nitrogen oxides and particulate matter. Analysis of inventory emission results at major European airports highlighted, that aircraft is the dominant source of air pollution in most cases under consideration.

Aircraft is a special source of air pollution due to some features. The most important feature of the source of emission is a presence of exhaust gases jet, which contains significant momentum and thermal buoyancy and in accordance may transport contaminant on rather large distances and the rise the plume centerline over the height of engine installation and over the ground surface appropriately. The value of such a distance is defined by engine power setting and installation parameters, mode of an airplane movement, meteorological parameters.

Of course aircraft is a moving source of pollution and with varied emission factor during the LTO and ground running procedures. In addition, despite designed LTO cycles, operational procedures of aircraft are sometimes not well adapted to engine settings (thrust) and standard time operation (TIM), which are specified under ICAO engine emission certification procedure.

This study was devoted to determination of nitrogen oxides (NOx) emissions from passenger aircraft at International Boryspol airport (Kiev) under real operation conditions (when aircraft is taxing, accelerating on the runway and take-offs) with aim to provide input data (emission index and maximum concentration) for improvement and validation tasks of complex model PolEmiCa. Experimental investigation was focused on measurement NOx, CO2, O3 in jet and plume modes to detect maximum instantaneous concentration from each aircraft engine and take into account process of transform and dilution of air contaminants by exhaust gases jet near the ground.

Combined approach of modeling and measurement methods provides a more accurate representation of aircraft emission contribution to total air pollution (local pollution) in airport area.

Emissions and near field processes

Estimating Gaseous Emission Production of an Entire Flight of Commercial Aircraft Based on Emission Measurements and Actual Flight Data Records

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In this study, engine emission measurement results and actual flight data records are used to obtain an emission production profile of a gate-to-gate flight activity. The platform and powerplant are selected as B737-800 and CFM56-7B26, while the emissions measured are carbon monoxide (CO) and nitrogen oxides (NOx (NO2+NO)). The emissions are measured during a test matrix between idle and the highest power of an engine in a test-cell environment. Establishing empirical relationships between the engine power and the amount of certain regular emissions species, emissions are not only identified for the LTO envelope, but also for the climb, descent and cruise flights which take place at above 3000 ft, the theoretical mixing height altitude.

According to the analyses, the total CO emission of 52 minutes flight is found to be 14 kg, whereas 37% of this is produced during the LTO activity, below 3000 ft of altitude. The total NOx emissions during the LTO activity constitutes 21% of the NOx emissions of the entire flight. In addition, since the CO emissions are strong functions of fuel flow at low power settings, in actual world operation conditions, the CO emissions during a taxi run can be considerably different from the standard values, due to variation in engine power based on a number of factors (i.e., ambient air temperature, bleed air utilization or engine state).

Emissions and near field processes

Procedures to apply NOx correlation methods to engine concepts with staged, lean combustor technology

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Reduction of NOx Emissions has been an important goal in combustor technology development for many years. RQL technology has been able to control NOx emissions even with increasing cycle pressure and temperature which are needed to improve engine efficiency and reduce CO2 emissions. To be able to provide input data for local air quality as well as atmospheric and climate modelling, correlation methods have been developed, which allow for estimating the emissions of the global fleet on the basis of publically available data only. Only recently new engine types with advanced low NOx combustion technology have been certified and similar types from other manufacturers are expected to follow. These engines make use of lean combustion technology and usually feature some sort of fuel staging to provide the combustion stability required for aircraft engines. As a result, standard application procedures of correlation methods cannot be applied for modelling emissions of these types of engines. Therefore new, alternative procedures have been developed and analyzed, which take into account the specific properties and parameters that influence NOx production in staged, lean-burn combustion systems.

Miscellaneous

TEAM_Play for Europe

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TEAM_Play -Tool Suite for Environmental and Economic Aviation Modelling for Policy Analysis- offers a range of European capabilities for the modelling of aviation noise, local air quality, greenhouse gas emissions, climate response, technology and economic impacts, and respective interdependencies. These useful capabilities for historic, current and future year impact assessments are combined in a unique single tool suite, and thus to be operated in a common environment. The further use of a single input data source (i.e., data warehouse and exchange platform) is an enabler for consistent and more accurate aviation economic and environmental trade-off studies and policy impact assessments.

The collaborative project TEAM_Play, co-funded by the European Commission (EC) as part of the 7th Research Framework Programme (FP7) of the European Union (EU), ended in 2013. Progress on aviation environmental modelling and capability management in Europe has been slow since, or concentrated within specific activities (ICAO CAEP, Clean Sky, SESAR). In order to collaboratively move on, and supporting and strengthening the European position in the international policy arena, the European aviation environmental modelling strategy needs further implementation and momentum.

In this context, the proposed presentation addresses TEAM_Play for Europe.

Miscellaneous

Research strategies for developing alternative fuels in aviation

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The aviation community in Europe aspires to develop an economic future that is sustainable in terms of fuel supply and with regards to climate impact. In support of this objective, sustainable alternative fuel pathways have begun to emerge as a promising option to augment and diversify fuel supplies whilst simultaneously reducing its environmental impact and emissions. It is this vision that is set out within the Biofuel Flightpath 2020 and EU aviation policy [1]. Research in this domain involves several different specialisms from fuel composition, chemical kinetics, combustion and propulsion, through to atmospheric chemistry and climate research. As a consequence, research is often disconnected across Europe and an integrated overview on how to best develop alternative fuels in aviation is often missing.

In this contribution we discuss a structure to traverse this gap: As a first objective we present a synopsis of state-of-the-art research covering key disciplines crucial for advancing the use of alternative fuels in aviation. As a second objective we present key open questions, and sketch pathways on how to overcome these challenges and advance research in this domain. In this context we introduce the idea of a network whose strengths reside in the breadth of competences from which it draws, supported by durable commercial involvement from across Europe, and cutting edge information exchange on new approaches, latest methods and recent findings in this emerging field. Concepts are introduced on how to best balance individual project requirements with cross cutting activities to preclude disconnected research definitions and promote integrated and efficient knowledge transfer. The paper will discuss identified research needs, visions for prospective research, and some of the strategic issues to be addressed in designing sustainable alternative fuel pathways into the future.

[1] “The Roadmap to a Single European Transport Area” White paper, EC 2011. Available at http://ec.europa.eu/transport/themes/strategies/2011_white_paper_en.htm

Miscellaneous

Limiting aviation's full climate impact by market-based measures - Main results of the research project AviClim

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Aviation contributes to climate change by both long-lived CO2 and short-lived non-CO2 effects, such as NOX or contrail cirrus: According to Lee et al. (2009), aircraft-induced CO2 contributed 1.6% to the total anthropogenic radiative forcing in the year 2005. If both CO2 and non-CO2 effects are considered, aviation contributed 4.9% to the total radiative forcing in 2005.

The interdisciplinary research project AviClim has explored the feasibility for including aviation's full climate impact in international protocols for climate protection and has investigated the economic impacts. This presentation provides main results of this research project.

In AviClim four reduction scenarios have been designed which differ concerning the level of international support for climate protecting measures. These scenarios have been combined alternatively with an emissions trading scheme on CO2 and non-CO2 species, a climate tax and a NOX emission charge combined with operational measures (such as climate-optimized flight paths). Also, two different metrics for quantifying aviation's full climate impact have been assumed alternatively: Average Temperature Response 'atr 20' and 'atr 50'. The Average Temperature Response 'atr' is the mean change in near surface temperature averaged over 20 and 50 years, respectively.

The results indicate that the choice of the metric has a great influence on both the economic and the environmental effects of the market-based measure analysed. All in all, a global emissions trading scheme for both CO2 and non-CO2 emissions would be the best solution. Costs and impacts on competition could be minimized and effects on employment are moderate. At the same time, environmental benefits are significant.

Eco-efficiency in aviation: From design to routing options for climate mitigation

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Examples on options for climate mitigation in aviation are given based on project results from CATS, AHEAD, REACT4C, WeCare, etc. The talk addresses questions such as: How can we adapt the design of an aircraft or the daily routing to reduce the climate impact from aviation? What kinds of concepts are discussed? How can we deal with uncertainties in atmospheric science and how can we compare costs and climate impact reduction?

Mitigation of aviation's climate impact

Assessment of non-volatile PM emissions from a turbojet engine with Synthesized Aromatic Kerosene derived jet fuel blends at simulated altitudes

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The aviation industry’s desire to augment and diversify fuel supplies coupled with the potential for environmental benefits is driving research and development of alternative jet fuels for aviation. ASTM International has certified a new specification for synthetically produced jet fuels, D7566, which allows blending of Hydrotreated Esters and Fatty Acid (HEFA) and other Synthetic Paraffinic Kerosene (SPK) fuels with conventional jet fuel. Virent and Shell have developed an alternative jet fuel product that uses bio-derived sugars as the feedstock. This fuel – Hydrodeoxygenated - Synthesized Aromatic Kerosene (HDO-SAK) is intended for use as a blend component to form semi-synthetic or fully-synthetic jet fuels. In this study, SAK-derived jet fuel blends of varying composition, designed to match the aromatic content of the equivalent conventional jet fuel, were combusted in a Microturbo TRS-18 turbojet engine in an altitude chamber at the National Research Council Canada facility in December 2014. The non-volatile particulate matter (nvPM) number- and mass-based emissions were assessed at different engine operating conditions and different simulated altitudes using a standardized system. Results comparing a SAK-HEFA blend with aromatic contents of 17% and 9% with the equivalent aromatic content Jet A fuel will be presented. Correlation of nvPM emissions with fuel properties will also be discussed.

The Implications of Intermediate Stop Operations on Aviation Emissions and Climate

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Among the various transport modes aviation’s transport impact on climate change deserves special attention. Due to typical flight altitudes in the upper troposphere and above the effect of aircraft engine emissions like carbon dioxide, water vapour, nitrogen oxides and aerosols on radiative forcing agents is substantial. The projected duplication of aircraft movements in the next 15 years will lead to an increase of aviation’s transport impact on climate and requires immediate mitigation options. Besides technological measures also new operational strategies are widely discussed; one of these concepts which has been subject of several studies in the past is Intermediate Stop Operations (ISO). It is based on the idea to reduce the stage length of flights by performing one or more intermediate landings during a mission. Due to shorter flight distances the amount of fuel burnt over the mission can be reduced, as the amount of fuel necessary to transport a certain percentage of the fuel for a long distance can be omitted. Besides fuel cost saving implications, many previous studies anticipate a strong reduction of the environmental impact compared to direct flight operations. So far, none of them has actually quantified this impact in a realistic scenario. While for the amount of emitted species which are produced proportional to fuel burn, a reduction is straightforward, this is not the case for other species. Moreover, the geographic location and altitude of the emissions have to be taken into account for a sound climate impact assessment.

The paper presents results of the ecological analysis of the ISO concept for today’s worldwide aircraft fleet, including its influence on global emissions distributions as well as the transport impact on climate change. A method is described that comprises of different models for a realistic traffic simulation taking into account operational constraints and ambient conditions, like e.g. wind, the calculation of engine emissions and the integration of a linear climate response model.

Climate impact assessment of routing strategies: Interactive air traffic in a climate model

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Aviation contributes considerably to climate change e.g. via emissions of CO2, NOx, water vapour and particles, which affect climate agents such as contrail-cirrus, ozone, methane, and carbon dioxide. Mobility becomes more and more important to society and hence air transportation is expected to grow significantly over the next decades. Mitigating the climate impact from aviation is required to cope with the increasing impact of aviation on climate. Currently, a number of studies suggest avoiding climate sensitive regions by re-routing (lateral and vertically). These mitigation options have a great potential in reducing the climate impact, since most of the climate impact arises from non-CO2 effects, which are shortlived and vary regionally. However, currently no assessment platform exists, with which different mitigation options can be assessed. Here we introduce a climate-chemistry model to which an air traffic model is coupled, enabling the assessment of re-routing strategies as well as technological options. A modeling strategy is presented, how re-routing strategies can be tested and may lead to recommendations for air traffic control.

Characteristic weather patterns over the North Atlantic and their effect on air traffic climate impact and route optimization

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The climate impact of non-CO2 aviation emissions depends on emission location and time and thereby on the prevailing weather situation. Different weather patterns may or may not support formation and persistence of contrails and contrail cirrus or may result in different lifetimes of emitted NOx or H2O, or aviation exhaust gases may experience weak or strong ozone formation. Hence, an emission at a certain location or time may result in a larger climate impact than the same emission at another location or time. This dependency can be used for the optimization of air traffic routes. Emissions are then preferably released at locations with small climate impact, avoiding climate sensitive regions. This climate impact mitigation option was investigated within the EU project REACT4C (Reducing emissions from aviation by changing trajectories for the benefit of climate). For this purpose a modelling chain was established including several steps. First, the fate of emissions and their radiative impact is calculated for a multitude of emission locations and times by means of the chemistry-climate model EMAC, including parameterisations calculating the contribution of emissions to the atmospheric composition and the formation of contrails. This yields a four dimensional data set of climate-cost-functions (CCF), describing the global mean climate impact of a specific aviation emission as a function of location and time. The CCFs can then be used to quantify climate impact and optimize aircraft trajectories with respect to minimum climate impact. As the climate impact of non-CO2 emissions depends on the weather situation, we calculated the CCFs for a set of characteristic weather patterns for the North Atlantic for winter and summer. Here, we concentrate on the comparison of the CCFs for different weather patterns and seasons. We analyse the differences and show their influence to the optimization of routes exemplarily for the North Atlantic region.

Mitigation of aviation's climate impact

Climate-optimized trajectories in the North Atlantic and mitigation potential

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Mitigation of aviation climate impact is one strategic goal spelled out for a durable development of air traffic. Operational measures to identify climate-optimal aircraft trajectories by air traffic management (ATM) are one option to reduce climate impact. We present estimates of seasonal mitigation potential from a comprehensive approach for climate-optimized flight planning applied for a case study the North Atlantic Flight corridor (NAFC) performed within the collaborative project REACT4C (Reducing Emissions from Aviation by Changing Trajectories for the benefit of Climate) funded under the European FP7 programme.

Ultimate goal of climate-optimized flight planning is to identify maximum mitigation gain (in climate impact) for a specific investment, hence minimal marginal mitigation costs. Total climate impact of aviation emissions is considered here in terms of CO2 and non-CO2 aviation emissions, which both need to be addressed when aiming to minimize climate impact, as their climate impacts are in the same order of magnitude. For this purpose those flights are selected which offer the highest mitigation potential taking into account five typical weather patterns in NAFC, and traffic samples in eastbound and westbound both direction. Using a concept of 4-dimensional climate cost functions integrated into a simulation system for operational planning (SAAM), we identified climate-optimal trajectories, by generating Pareto fronts from marginal costs of a mitigation routing option versus reduction of climate impact. Quantitative estimates of mitigation potentials in individual weather patterns will be presented together with an estimate overall mitigation potential by applying a system approach and generating the overall Pareto front. Applying such system approach has the potential to reduce considerably required investment for a given climate impact mitigation target.

FAA research and poster session

A Brief Overview of FAA Research on Aviation Emissions and Their Environmental Impacts

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At present, aviation is a small contributor to overall emissions that impacts climate change, air quality and public health. However, given the projected growth for air transportation, aviation emissions are expected to increase both in absolute and relative terms (particularly given that background emissions from other major sources are expected to decrease in future) unless emissions reduction measures are implemented. A combination of advances in aircraft technologies and alternative jet fuels along with operational procedures offers a great potential to reduce aviation emissions. The US Federal Aviation Administration is pursuing all these emissions reduction approaches simultaneously to allow environmentally unconstrained growth in air transportation. This presentation will briefly describe currently ongoing research activities on aviation emissions and their environmental impacts as relate to current and future aviation operations under baseline and mitigation scenarios.

Impact on air quality and climate

The impact of shipping on air pollution in North Sea coastal areas - situation today and in the future

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Ships emit large amounts of nitrogen oxides and sulphur oxides into the coastal atmosphere. Europes three biggest ports are located at the North Sea coast. Therefore this region is particularly affected by air pollution from ships. These pollutants undergo chemical transformation in the atmosphere, they are transported into other areas and finally deposited. Thereby, they contribute to acidification and eutrophication. The share of ships in the total deposition will very likely increase in the future, because ship traffic will increase and emission redcution technologies are not yet implemented in this sector.

Emissions from ships in the North Sea were calculated for the year 2011 based on AIS position data and ship characteristics data. Future shipping emissions were simulated for three scenarios for 2030. These emissions were used together with land based emissions to calculate the impact of shipping to concentrations of air pollutants and deposition of nitrogen and sulfur by means of the chemistry transport model system CMAQ. Meteorological fields were taken from the mesoscale model COSMO-CLM.

The contribution of shipping to the concentrations of the gaseous pollutants NO2, SO2 was found to be in the order of 20-30% of the total concentrations of these substances in North Sea coastal areas. The aerosol bound pollutants NO3- and SO42- had a lower share, around 15-20% of the total, but were more widespread. Aerosol concentrations were mainly enhanced in summer. The contribution of shipping emissions to the deposition of oxidised nitrogen reached more than 40% in summer in the English Channel and its surrounding areas. The scenarios for 2030 revealed that this share will increase further if no additional emission reduction measures will be taken.

Impact on air quality and climate

Sensitivity Analysis Approaches for Assessing Air Quality Impacts of Airport Emissions

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Emissions from commercial aircraft have known to contribute to air pollution, specifically ozone and fine particulate matter (PM2.5), both of which have adverse health impacts. The aviation sector contributes a growing proportion of these pollutants to the atmosphere, in the presence of decreasing emissions from other source sectors. Recent studies have quantified the overall burden to air pollution due to the aviation sector both under current and future emissions scenarios, and have highlighted the growing importance of PM2.5 due to aviation activity at downwind distance from airports. However, to assess the individual contributions from each airport, it can be computationally expensive to calculate the proportion of PM2.5 attribution from each airport using finite difference (brute force) or regression-based methods. Using the Community Air Quality Model (CMAQ) instrumented with the Decoupled Direct Method in Three Dimensions (DDM-3D) – an advanced sensitivity analysis approach, we are able to calculate sensitivity coefficients for precursor emissions from individual airports in the domain.

We will present the design of experiments and preliminary results from a modeling study conducted in the U.S., where sensitivity coefficients for six precursor species (to PM2.5) were computed for each of 66 airports in the U.S. This group of airports accounts for about 61% of total flights and 77% of total aviation jet fuel consumed annually in the U.S. National Air Space (NAS). The O3 and PM2.5 sensitivity coefficients derived can be used to quantify the air quality impacts of air pollution burden from each individual airport due to landing and takeoff (LTO) activity in the U.S., as well as characterize the spatio-temporal patterns in aviation-attributable O3 and PM2.5. Future scenarios that take into account changes in policy such as differential growth in aviation activity across multiple airports, and changing population characteristics can be accurately evaluated with this new information.

Impact on air quality and climate

The global impact of the transport sector on atmospheric aerosol and climate in the Representative Concentration Pathways

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Using the EMAC global climate-chemistry model coupled to the aerosol module MADE, we simulate the impact of land transport, shipping and aviation emissions on global atmospheric aerosol and climate in 2030. Future emissions of short-lived gas and aerosol species follow the four Representative Concentration Pathways (RCPs) designed in support of the IPCC AR5. We compare the resulting 2030 transport-induced aerosol concentrations to the ones obtained for the year 2000 in a previous study with the same model configuration. The simulations suggest that black carbon and aerosol nitrate are the most relevant pollutants from land transport in 2000 and 2030 and their impacts are characterized by very strong regional variations during this time period. Europe and North America experience a decrease in the land-transport-induced particle pollution, although in these regions this sector remains a major source of surface-level pollution in 2030 under all RCPs. In Southeast Asia, however, a significant increase is simulated, but in this region the surface-level pollution is still controlled by other sources than land transport. Shipping-induced air pollution is mostly due to aerosol sulfate and nitrate, which show opposite trends towards 2030. Sulfate is strongly reduced as a consequence of sulfur reduction policies in ship fuels in force since 2010, while nitrate tends to increase due to the excess of ammonia following the reduction in ammonium sulfate. The continuous growth in air traffic in the future leads to increasing impacts in all scenarios, affecting black carbon and sulfate concentrations in the northern mid-latitudes at cruise level with some effects also close to the surface. The aerosol-induced climate impact of the transport sectors is dominated by aerosol-cloud effects and, with the exception of aviation, is projected to decrease between 2000 and 2030, nevertheless still contributing a significant radiative forcing to Earth’s radiation budget.

Impact on air quality and climate

REACT4C: Radiative forcing from aircraft emissions of NOx: role of H2O and O3 stratospheric changes

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A climate-chemistry model (ULAQ) and a 2D chemistry-transport model (MMU) have been used in the EU FP7 project REACT4C to quantify the tropospheric and stratospheric response to NOx emissions from global aviation. The ULAQ radiative transfer model is also used to quantify the different components of the associated radiative forcing (RF). The tropospheric NOx enhancement produces a short-term O3 increase with a positive RF (+11.44 mW/m2). This is largely compensated by the CH4 decrease due to the OH enhancement (-10.25 mW/m2). The latter is a long-term response that needs to be calculated using a surface CH4 flux boundary condition (FBC). In turn, it induces a long-term response of tropospheric ozone because less HO2 and CH3O2 become available for O3 production (-4.37 mW/m2), with respect to a reference case where a constant CH4 surface mixing ratio boundary condition (MBC) is used. The decreased amount of methane induces a long-term response of stratospheric H2O (-1.54 mW/m2). The latter finally perturbs HOx and NOx in the stratosphere, with a more efficient NOx cycle for mid-stratospheric O3 depletion and less ozone production in the lowermost stratosphere. This produces a long-term ozone loss with a negative RF (-1.31 mW/m2) with respect to the CH4 MBC case. According to the ULAQ model, aviation NOx emissions for the year 2006 produced a small net cooling effect in the atmosphere, with RF of -0.35 mW/m2 and column ozone changes of +0.32 DU in the troposphere and -0.053 DU in the stratosphere. A marginally reduced NOx impact is calculated when the tropospheric NOx balance also takes into account the changes in sulphate aerosol surface area density produced by aircraft plume production of ultrafine sulphuric acid aerosols. In this case the net short- and long-term RF from NOx emissions is calculated to be +0.13 mW/m2.

Impact on air quality and climate

Global and regional climate impacts of aviation and on-road transport

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Transportation emits a broad range of species characterized by varying timescales, spatial distributions, and chemical and physical impacts. This result in the potential for significant geographical variations in the impact on atmosphere and climate, and the emission location can be important. Moreover, increased knowledge of such spatial variations is important for the design and evaluation of mitigation strategies for the sector.

Using the chemistry-transport model OsloCTM3, we investigate the impact on atmospheric composition and radiative forcing (RF) of aerosols and ozone from aviation and on-road transport emissions in six different source regions. While RF is a commonly used indicator for quantifying and comparing impacts, there is an increasing need to also quantify the temperature impacts. Currently, our ability to quantify spatial distributions of temperature responses is limited by the capabilities of global climate models. As an alternative, we use the recently developed Regional Temperature change Potential (RTP) to estimate the temperature response across four broad latitude bands to the pattern of RF. The RTP does not provide the small-scale temperature change estimates ultimately required, but provide additional insight into the spatial pattern beyond that available from traditional metrics using global-mean values. Finally, using the Community Earth System model (CESM), we perform a first evaluation of the application of the RTP in the case of aviation.

Our results show a significant variability in the efficiency with which emission in different regions affect the atmospheric composition and RF. Furthermore, we explore the relationship between patterns of RF and temperature response, in particular the strong sensitivity of Arctic surface temperature response to remotely exerted RF and the impact of accounting for the vertical sensitivity in the forcing-temperature relation.

Impact on air quality and climate

Quantifying the climate impact of emissions from land-based transport in Germany

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Although climate change is a global problem, specific mitigation measures are frequently applied on regional or national scales only. This is the case in particular for land-based transport which is largely characterized by localized systems with independent infrastructures and local organization. The climate perturbations caused by such localized emission sources are small compared to those resulting from global emissions. As a consequence, they can be smaller than the statistical significance level in global three-dimensional chemistry-climate model simulations, hampering the evaluation of the climate benefit of the mitigation strategies. For these reasons we developed a new methodology to quantify the climatic impact of localized land-based transport emissions.

The method is based on a combination of simulations performed with i) a global chemistry-climate model system to quantify ozone changes and their radiative impact, ii) a newly developed simplified aerosol-climate model which enables to simulate the climate forcing of aerosol perturbations, and iii) an existing simplified climate-model to simulate the concentration changes of long-lived greenhouse gases (CO2 and CH4) and the resulting radiative and climatic impacts. For demonstration purposes, the method has been applied to the results of a transport and emission modelling suite which was designed to quantify the present-day and possible future transport activities in Germany as well as the resulting emissions of climatically relevant species. The study was carried out within the German project VEU (transport development and environment) which has the objective to analyse the German transport system and its environmental impacts. The resulting model framework enables an evaluation of mitigation strategies by modelling the full cause-effect chain ranging from transport demand, over transport activity and emissions, to the resulting climate effects. We present the methodology and show results from first applications.

Impact on clouds

Detecting Contrail Cirrus – First results of the HALO mission ML-CIRRUS

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Despite recent progress, contrail cirrus still provide a major source of uncertainty to current estimates of the climate impact from aviation. In particular, the prediction and the characterization of contrail cirrus within their natural environment are prone to substantial ambiguities.

Here, we present new results on contrail cirrus detected during the ML-CIRRUS mission on mid-latitude cirrus clouds with the German atmospheric science community aircraft HALO. The first in-situ cloud mission with the HALO aircraft combined a suite of state-of-the-art cloud instruments in wing stations with a novel aerosol, trace gas and radiation instrumentation and a differential absorption LIDAR inside the cabin. In addition, the Contrail and Cirrus Model CoCiP was specifically developed to predict and investigate effects of aircraft induced cloudiness.

In March and April 2014, the HALO research aircraft performed 16 flights (88 flight hours) in mid-latitude cirrus clouds and contrail cirrus at longitudes from 15°W to 15°E and latitudes from 36° to 58°N. Cirrus clouds with an ice water content < 0.5 mg m-3 were encountered up to 14 km altitude over a wide range of temperatures down to 204 K. As the relative humidity is a crucial parameter for contrail formation and persistence, we investigate the accuracy of the water vapor observations on HALO. We specifically focus on 4 flights which were designed to detect and characterize contrails and contrail cirrus above Europe and in the northern Atlantic flight corridor. We estimate the age of the contrail cirrus using information on dilution of the engine's nitrogen oxide emissions. Interestingly, we find significant differences in the microphysical properties of contrail cirrus compared to the surrounding natural cirrus up to 10 hours contrail age. In addition, new data on the size distribution and composition of contrail cirrus residuals are presented.

Further progress in contrail cirrus research can be achieved by comparing characteristic contrail cirrus properties derived from in-situ instruments to remote sensing data from the onboard LIDAR and the MSG satellite and to results from the CoCiP model.

Impact on clouds

Cirrus Properties from Commercial Aircraft Measurements and Implications for Flight Operations

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Measurements of cloud ice crystal size distributions have been made by the Backscatter Cloud Probes (BCP) mounted on five commercial airliners flying international routes that cross five of the six continents. Bulk cloud parameters were derived from the measurements. As of 31st of December, 2014, a total of 4399 flights have accumulated data from 665 hours in 19,000 cirrus clouds larger than 5 kilometers in length. The BCP measures the equivalent optical diameter (EOD) of individual crystals 5-75 μm from which size distributions are accumulated and recorded every four seconds. The ongoing development of the cirrus cloud property database registers the total crystal number and ice mass concentration, ice crystal effective and median volume diameters and extinction coefficients derived from the size distribution. This information is accompanied by the environmental temperature, pressure, aircraft position, date and time of each sample. The seasonal variations of the cirrus cloud properties measured from 2012 to 2014 are determined for six geographic regions in the tropics and extra-tropics. Number concentrations range from a few per liter for thin cirrus to several hundreds of thousands for heavy cirrus. Temperatures range from 205 – 250 K and effective radii from 12-20 μm.

A comparison of the regional and seasonal number and mass size distributions, and the bulk microphysical properties derived from them, demonstrate that cirrus properties cannot be easily parameterized by temperature or by latitude. The seasonal changes in the size distributions from the extra-tropical Atlantic and Eurasian air routes are distinctly different, showing shifts from monomodal to bi-modal spectra out of phase with one another. This phase difference can be linked to the timing of deep convection and cold fronts that lead to the cirrus formation. Likewise, the size spectra of cirrus over the Tropical Atlantic and Eastern Brazil differ from each other although they were measured in adjoining regions. The cirrus crystalss in the maritime continental tropical region over Malaysia form tri-modal spectra that are not found in any of the other regions measured by the IAGOS aircraft.

Frequent measurements of ice crystal concentrations greater than 1x105 L-1, often accompanied by anomalously warm temperature and erratic airspeed readings, suggest that aircraft often experience conditions that affect aircraft sensors. This new instrument, if used operationally, has the potential of providing real-time and valuable information to assist in flight operations

Impact on clouds

Spatial Simulation of Contrail Formation in the Near-Field of a Commercial Aircraft

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Contrails may contribute a large-share of the radiative forcing due to aviation. In this context, investigation of contrails formation in the near field of an aircraft may be helpful to provide strategies in order to reduce their impact. In this study, we perform three-dimensional RANS simulations of contrails produced by commercial aircrafts in cruise conditions. A realistic geometry (here a Boeing 737) is taken into account including engine core and bypass flows which allows several possible parametrical studies and avoids using parameterizations for the description of the plume's dilution. The objective is to simulate the early development of contrails in the near-field's plume whose dilution is obtained by a spatial simulation of the dynamical flow around the aircraft. A coupling is carried out with a microphysical model implemented in the CFD code CEDRE to simulate particle growth using an Eulerian approach. The implemented microphysics model is capable of simulating water condensation onto soot particles, taking into account their activation by adsorption of sulfuric species and scavenging of volatile particles. Their concentrations are obtained with the simulation of the chemical evolution within the bulk plume.

Results show that the chemical and mixing processes in the bulk plume are in good agreement with studies from literature. We have also investigated the formation of a contrail in the near-wake of the aircraft for two values of ambient relative-humidity. This parameter plays a significant role in contrail local properties. Increased relative humidity led to an increase of the fraction of particles under supersaturated condition and condensation rate. This resulted in higher mean particles radius and, as a consequence, in higher optical depth, making contrails more distinct. Particle-size distribution shifted toward larger particles due to an increase in available vapor.

Impact on clouds

Numerical Modeling of natural cirrus and contrail-cirrus. How different are they?

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High-resolution numerical simulations of contrail-contrails and natural cirrus are presented. The anelastic LES-model EULAG coupled with a Lagrangian ice microphysics module (Sölch & Kärcher, 2010) was employed for this purpose.

Millions of ice crystals are tracked and their trajectories and size/humidity history can be analyzed. The Lagrangian approach allows for a precise numerical implementation of various processes like aggregation, sedimentation and sublimation since these processes act on individual ice crystals. Moreover, ice from various sources can be easily discriminated in our model.

We find that characteristics of the lifecycles strongly depend on the synoptic scenario. Weak, but enduring updraughts allow for the longest life times of contrail-cirrus. For cirrus clouds, the updraft speed during their formation is most crucial.

Despite their different formation mechanisms (contrails are generated locally and have much higher ice crystal number concentrations than natural cirrus) we could not single out robust microphysical criteria which could help to distinguish safely between both cloud types in observations (in-situ and remote).

Impact on clouds

A numerical study of contrail-to-cirrus transition using 3D large-eddy simulations

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Contrails and contrail-cirrus are the most uncertain contributors to aviation radiative forcing. This motivated the renewed interest in contrail research, and the extensive modeling, computational and experimental efforts made in this area over the last two decades. Most of published computational studies focused on characterizing the contrail dynamics, microphysics and radiative properties using different modeling approaches at various scales.

The present study analyzes the contrail-to-cirrus transition in the diffusion phase, a problem that has been investigated to a much lesser extent compared to the jet and vortex phases. The spatial scales considered here range from meters up to 10 km atmospheric scales; the timescales range from 5 minutes up to 1 hour contrail age. We employ fully 3D large-eddy simulations coupled to a radiative transfer module and to a forcing scheme that mimics the atmospheric motions at scales larger than the computational box in order to sustain coherent turbulent fluctuations at the resolved scales. We focus on the interaction between contrail dynamics and radiative transfer and its role in determining the contrail 3D structure and consequently its radiative forcing. We tested different ambient turbulence levels and different radiative conditions corresponding to specific ideal situations: infrared radiation (night conditions); infrared+solar radiation (day conditions); and radiative transfer switched off. We finally propose some guidelines for contrail parameterization into global models.

Impact on clouds

Angular dependence of individual condensation trails on the extinction of solar radiation

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Persistent condensation trails are condensed water vapor, emitted by aircrafts flying in

a cold and ice-supersaturated environment, which are cooling and

heating the atmosphere by scattering solar radiation and absorbing terrestrial radiation,

respectively.

The influence of condensation trails on the Earth-atmosphere energy balance has mostly been approximated on a global scale by treating those as plane parallel layers with constant properties. Individual condensation trails and solar angles have been analyzed using a course spatial grid. In this work, a continuous model is developed to estimate the solar scattering and absorption properties and their dependence on the aircraft performance. The initial microphysical properties of realistic condensation trails are calculated using a flight performance model yielding precise information about fuel flow and emission of water vapor and heat. The evolution of the microphysical properties during the diffusion regime is calculated with a Gaussian plume model. Likewise, the ice particle number density within the condensation trail is defined by a two-dimensional Gaussian distribution function. The radiation field around the aircraft induced ice cloud is calculated with the radiative transfer library libRadtran using a discrete ordinate radiative transfer solver for solar radiation.

Radiative extinction due to the condensation trail is calculated utilizing a Monte Carlo simulation. This radiative extinction model is calibrated and tested for a wide range of realistic parameter settings. Radiative extinction strongly depends on the irradiation angle and on the geographical orientation of the condensation trail both determining the distance photons travel through the condensation trail. Furthermore, strong forward scattering, defined by the particle shape and wavelength cause a reduced cooling effect at noon, when the main part of solar radiation is irradiating perpendicular to the condensation trail axis. The extinction increases with growing particle radius. The particle number density and condensation trail cross-section have a minor impact on radiative extinction.

Impact on clouds

Synergetic study of the evolution of a contrail cluster

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During the ML-Cirrus campaign in-situ measurements were carried out in aircraft induced cirrus clouds. On the 10th of April 2014, a cirrus cloud was probed that could not be forecast by models. Thanks to the temporal resolution of the SEVIRI instrument on board of the MSG satellites, we are able to identify the original contrail cluster that produced it. We show the temporal evolution of the optical depth and particle size of the cluster that lead to said cloud and eventually compare the results with the optical depth and particle size derived from the HALO measurements. The satellite retrievals allow us to analyse the evolution of optical depth and particle size of natural cirrus clouds in the vicinity as well. The potential of the different satellite retrievals is shown and a comparison between different methods is carried out.

Electro mobility: Technological options and contribution to reduction of emissions

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Electric mobility is based on a wide range of technological option: battery vehicles, fuel cell vehicles, hybrid concepts, electric bicycles, and not to forget, trains and maybe- in future- more electric airplanes. A short technical draft on these options is given in this speech, followed by the analysis of typical daily driving ranges. In the next step electric vehicles are compared with conventional combustion vehicles, with respect to primary energy consumption, cumulated energy, emission of co2 and other relevant climate and ambient gases. In the end the potential of emission reduction of electric vehicles is estimated and discussed.

Impact on clouds

Properties of Linear Contrails Detected in 2012 Northern Hemisphere MODIS Imagery

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Observation of linear contrail cirrus coverage and retrieval of their optical properties are valuable data for validating atmospheric climate models that represent contrail formation explicitly. These data can reduce our uncertainty of the regional effects of contrail-generated cirrus on global radiative forcing, and thus improve our estimation of the impact of commercial aviation on climate change. We continue our work to create a multi-year climatology of the physical properties of linear contrails from multi-spectral satellite observations.

We use an automated contrail detection algorithm (CDA) to determine the coverage of linear persistent contrails over the Northern Hemisphere during 2012. The contrail detection algorithm is a modified form of the Mannstein et al. (1999) method, and uses several channels from thermal infrared MODIS data to reduce the occurrence of false positive detections. A set of contrail masks of varying sensitivity is produced to define the potential range of uncertainty in contrail coverage estimated by the CDA. Global aircraft emissions waypoint data provided by FAA allow comparison of detected contrails with commercial aircraft flight tracks. A pixel-level product based on the advected flight tracks defined by the waypoint data and U-V wind component profiles from the NASA GMAO GEOS-4 reanalysis has been developed to assign a confidence of contrail detection for the contrail mask. To account for possible contrail cirrus missed by the CDA, a post-processing method based on the assumption that pixels adjacent to detected linear contrails will have radiative signatures similar to those of the detected contrails is applied to the Northern Hemisphere data.

Results from several months of MODIS observations during 2012 will be presented, representing a near-global climatology of contrail coverage. Linear contrail coverage will be compared with coverage estimates determined previously from 2006 MODIS data. In addition, examples of output (including optical depth, particle size, and radiative forcing) from a multi-spectral cloud property retrieval method will be presented.

Impact on clouds

Radiative Forcing Due to Linear Contrails Detected in 2006 and 2012 Northern Hemisphere MODIS Imagery

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Contrail effects on climate result from the hydrological and radiative changes induced by their presence in the atmosphere. Linear contrails can be detected in satellite data and it is possible to retrieve their optical and radiative properties (contrail temperature Tcon, optical depth, COD; contrail particle effective radius, CRE) using several different techniques. These properties can then be used to compute the radiative forcing (CRF) due to contrails in a radiative transfer model (RTM) if the surrounding background (clouds, surface, and atmosphere) conditions are known. The results of an automated contrail detection algorithm applied to Terra and Aqua MODerate-resolution Imaging Spectroradiometer (MODIS) are used to determine which pixels correspond to contrails over the Northern Hemisphere during 2012. Cloud properties are also retrieved globally from the MODIS data, and together with the radiative properties of the surface and atmospheric profiles of temperature and humidity from NASA GMAO GEOS-5 reanalyses are used to compute the upwelling longwave and shortwave fluxes for each pixel with the Fu-Liou RTM. The contrail pixels are overlaid on this background and COD, Re, and Tcon are determined in the same fashion used by Bedka et al. (2013). These properties are then added to the background to compute fluxes including the contrails above the background as in Spangenberg et al. (2013).

Results from several months of MODIS observations during 2012 will be presented, representing a near-global climatology of contrail coverage. Linear contrail properties and CRF will be compared with similar estimates determined previously from 2006 MODIS data.

Impact on clouds

Contrail-cirrus predictions compared to observations

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Modelled contrail-cirrus properties are compared with cirrus and contrail properties observed during the Mid-Latitude Cirrus Experiment (ML-CIRRUS) in March/April 2014.

During ML-CIRRUS (see Voigt et al., EGU, 2015), 13 scientific mission-flights have been performed with the High Altitude and Long Range research aircraft HALO in March/April 2014 over Europe and the North Atlantic, partly in high-density air-traffic regions. HALO carried in-situ instruments for meteorology, gases, aerosols and cloud properties, and lidar, and other instruments. Model simulations are performed with the Contrail Cirrus Prediction model (CoCiP). CoCiP simulates a large ensemble of contrails as a function of given air-traffic and meteorology (Schumann, GMD, 2012). Measurement-data and model results are collected (partly preliminary)in the HALO data-bank.

The model results depend strongly on the quality of the input data. Here we use high-quality ECMWF forecast or analysis data and suitable traffic data. Measurements and simulations do not agree uniformly. For example, the relative humidity in an aged cirrus field is less well represented than in a cloud-free ice-supersaturated region. In high-density traffic regions hundreds of overlapping contrails form so that we compare contrail ensembles.

This paper shows that contrail-cirrus is, to some degree, predictable on time scales of several days. A metric to measure the accuracy of the predictions is difficult to specify and depends on the information that is retrieved from such predictions. Here we assess the agreement in terms of contrail-cirrus cover observable with METEOSAT, and with NOx concentration, ice water content, and ice crystal size and number concentration, measured with HALO.

The authors gratefully acknowledge contributions from the whole ML-CIRRUS team.

Impact on clouds

The effect of climate change on the potential for contrail formation.

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Ice-supersaturation (ISS) in the upper-troposphere and lower stratosphere is important for the formation of cirrus cloud and long-lived contrails. We analyse projected changes to 250 hPa ISS distribution and frequency over the twenty-first century using data from the RCP8.5 simulations of a selection of models from the 5th Coupled Model Intercomparison Project, which fed into the Fifth Assessment Report (2013) of the Intergovernmental Panel on Climate Change. The models show a global-mean annual-mean decrease in ISS frequency of 4% by the end of the twenty-first century, relative to the present-day period 1979–2005. Changes are analysed in further detail for three sub-regions where air traffic is already high and increasing (Northern Hemisphere mid-latitudes) or expected to increase (tropics and Northern Hemisphere polar regions). The largest change is seen in the tropics, where a reduction of around 9% in ISS frequency by the end of the century is driven by the strong warming of the upper troposphere. In the Northern Hemisphere mid-latitudes the multi-model mean change is an increase in ISS frequency of 1%; however the sign of the change is not only model-dependent but also has a strong latitudinal and seasonal dependence. In the Northern Hemisphere polar regions there is an increase in ISS frequency of 5% in the annual-mean. These results suggest that over the 21st century climate change may have large impacts on the potential for contrail formation; actual changes to contrail cover will also depend on changes to the volume of air traffic, aircraft technology and flight routing. The effect of climate change on flight routing in the North Atlantic sector will also be briefly discussed.

Impact on clouds

Modelling of contrail cirrus: microphysical and optical properties

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The contrail cirrus parameterization (Burkhardt and Kärcher, 2011) was implemented in ECHAM5 and extended to include a microphysical 2-moment-scheme. This allows a more realistic representation of microphysical processes, such as deposition and sedimentation, and therefore of the microphysical and optical properties of contrail cirrus.

The first step was to modify the natural cloud scheme in ECHAM5-HAM by making fractional cloud coverage consistent with ice microphysics. This enables the introduction of contrail cirrus and their interaction with natural cirrus clouds. Therefore, we had to adapt the triggering of the ice nucleation parameterization in cirrus clouds.

For the extension of the contrail cirrus parameterization to a microphysical 2-moment-scheme, several processes important for the properties and life cycle of the contrails had to be newly implemented or improved. A crucial process for the initial development of contrails is the growth of contrail volume which could be represented more realistically due to the introduction of vertically fractional contrail coverage. The representation of water deposition was improved limiting the overall deposited water to an estimate of the diffusional growth of ice crystals, which is in particular important in the later stages of the contrail cirrus life cycle. Due to the improved microphysics the temporal evolution of contrail cirrus optical depth could be resolved, starting with many small crystals and eventually resembling more natural cirrus.

The global radiative forcing of contrail cirrus of 35.3mW/m2, estimated for the year 2002, is close to the results of Burkhardt and Kärcher (2011). Although in the new model the coverage of contrail cirrus with optical depth > 0.05 is significantly increased and the overlap of contrail cirrus with natural clouds decreased, the larger compensation of longwave and shortwave radiative forcing, estimated by the new radiation scheme, limits the radiative effect.

Impact on clouds

Process-based studies of the life cycle of contrail cirrus in a global climate model

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Contrail cirrus contribute significantly to the aviation climate impact. The surrounding atmospheric state and the aircraft emissions control their formation and properties. Our objective is to analyze the impact of reduced soot particle emissions, as expected from biofuels or lean combustion, on contrail cirrus properties and life cycle.

Our study is based on the contrail cirrus parameterization, using a double moment microphysics scheme, within the ECHAM5 climate model (Bock, 2014). This scheme allows the representation of microphysical changes, in particular changed ice crystal number concentration and sizes, expected due to the reduced soot emissions. The influence of a reduction in soot particle emissions (around 80%) is investigated within idealized studies at different atmospheric states and flight levels.

One controlling factor for the properties of persistent contrail cirrus is the ice crystal number concentration which is influenced by microphysical and dynamical processes. At low ice crystal number concentrations ice crystals grow faster and sedimentation is increased and, particularly in older contrails, deposition on ice crystals is limited by diffusional growth rather than by the water available for deposition. In long lived ice supersaturated areas sedimentation can cause the loss of the majority of ice crystals limiting the lifetime of contrail cirrus. In these areas, the influence of soot emission reductions is much larger than in short lived or small scale ice supersaturated areas. In contrails with lower initial number concentrations (80% less) ice particle loss due to sedimentation is increased by about 15%. This means that contrails formed in aircraft plumes characterized by lower soot particle emissions have a significantly shorter lifetime and lower optical depth and, therefore, a smaller climate impact than contrails formed in aircraft plumes with high soot number concentrations.

Impact on clouds

Impact of alternative jet fuels on contrails

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Alternative jet fuels result in reduced soot, other emissions relevant to contrail formation. This presentation will describe the estimates of the changes in emissions associated with the use of alternative fuels that are relevant to contrail formation. The newly developed CERM contrail model will also be applied to this problem with estimates for the net impact of alternative fuels on contrail coverage and radiative forcing given. Finally potential strategies for maximizing the impact of using alternative fuels will be discussed.

Impact on clouds

Simulations of dehydration effects from contrails in a global climate model

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We study the effects of humidity exchange between contrails and background atmosphere using the Contrail Cirrus Prediction Model CoCiP (Schumann, GMD, 2012) coupled with the climate model CAM3+/IMPACT (Penner et al., 2009; Zhou and Penner, JGR, 2014).

Contrail ice particles grow by uptake of humidity from ambient ice supersaturated air masses. By sedimentation, contrails contribute to dehydration of the upper troposphere and to humidity increases at lower levels. After advection in rising or subsiding air masses, contrail may release water at places higher or lower than where the contrail formed. The dehydration may reduce natural cloudiness and, hence, partly offset positive radiative forcing from contrail cirrus (Burkhardt and Kärcher, 2011). LES show thinner contrails when they overlap with others (Unterstraßer and Sölch, 2012).

The coupled CoCiP-CAM model simulates all individual contrails forming globally using a Lagrangian contrail model. The coupling accounts for conservation of humidity during contrail formation and sublimation. In the coarse global model, local changes in humidity from contrail formation become notable only when many contrails form.

The simulated contrails agree well with observations. The amount of water stored inside contrails is 10-20 thousand times larger than the amount of water emitted. Contrail ice particles sediment typically 700 m. Because of local dehydration, less contrails form, with less cover of optically thick contrails, but individual contrails have larger life time and width. As all climate models, CAM suffers from climate noise. The interannual RF variability exceeds 0.2 W/m2. Even 30 years of simulation are insufficient to quantify the RF from dehydration by contrails accurately.

A. Clouds and cloud processes

The TC2 (Traînées de Condensation et Climat) project

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Aircraft emissions can have an impact on atmospheric chemistry and on the radiative balance of the atmosphere. For example, contrails formed by condensation of water vapour onto exhaust aerosols and soot particles trigger the formation of cirrus clouds. Emissions of nitrogen oxides perturb the natural chemical cycles and lead to ozone production or destruction depending on local air mass composition and insolation. These ozone perturbations along with the emissions of CO2, water vapour and ice particles formation, soot particles, sulphuric aerosols from the burning kerosene give an additional contribution to the greenhouse forcing.

Given the exponential increase of the air traffic it is anticipated that the aircraft emissions will double by year 2020 compared to present. Air traffic would then be a major player of the climate change.

To reduce the uncertainties associated with the impact of contrail formation on climate the French CORAC (Conseil pour la recherche aéronautique civile) has launched the TC2 (Contrails and Climate) project that combines the expertise of 7 partners: CERFACS, CNRM, DASSAULT-AVIATION, LaMP, LSCE, ONERA, SAFIRE. Activities of TC2 cover high-resolution numerical simulations of contrail formation and aging, simulation of their radiative forcing, in-situ measurements of contrail composition, and development of parameterizations of contrails effects on radiation and chemistry for large-scale climate models.

The project started in 2012 and will end at the end of the year 2015. Main activities and results will be presented.

A. Clouds and cloud processes

Modelling the chemistry in contrails from the vortex to the diffusion phase using a mesoscale model.

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Aircraft emit gases and particles directly into the upper-troposphere/lower stratosphere which is a region that is very sensitive to small changes in chemical composition. Through various chemical interactions, the emissions of NOx, CO2 and H2O perturb the concentrations of the radiatively active gases CO2, O3 and methane with consequences for climate. They may also trigger the formation of contrails and contrail induced cirrus, or modify the composition of aerosols, with further effects on climate. With increasing air traffic over the coming years, it is necessary to model these processes to give a better understanding of the effects of aircraft on climate. We present results from the project TC2, which aims to understand the physico-chemical processes throughout the evolution of contrails from the vortex phase (after several seconds) to the diffusion phase (several hours) where true atmospheric variability becomes important. We used the mesoscale model Meso-NH and introduced a specially adapted chemical scheme which included reactions with 13 gaseous species along with ice. First simulations show the interactions between NOx and atmospheric ozone during the vortex/dissipation phase and will later include heterogenous reactions on the surface of ice crystals that convert NOx species into HNO3.

A. Clouds and cloud processes

Global modelling of contrail cirrus for future scenarios

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We estimate the effect of a change in air traffic for the year 2050 within the climate model ECHAM5-CCMod, including a contrail cirrus parameterization with microphysical 2-moment scheme. We perform simulations for a base inventory for the year 2006 and for three scenarios for the year 2050 developed at the Volpe National Transportation Centre using the U.S. Federal Aviation Administration (FAA) Aviation Environmental Design Tool (AEDT). The 2050 baseline scenario describes the increase in air traffic volume, whereas the second 2050 scenario additionally considers the improvement in fuel efficiency. An additional reduction of soot emissions is included in the third 2050 scenario.

In our simulations we consider the change in climate simulated for 2050 assuming RCP 6.0., which leads to a warming of the upper troposphere and an associated lower frequency of ice supersaturation. However, due to increased air traffic the radiative forcing of contrail cirrus in 2050 is getting significantly larger. The relative increase in radiative forcing is largest in tropical regions, reaching a factor of eight in main air traffic areas. On the other hand an improvement in fuel efficiency leads to a higher critical temperature for contrail formation, as a result of which the contrail formation region increases. Nevertheless, this has a negligible effect on the global radiative forcing of contrail cirrus. Using the third scenario we study the impact of alternative fuels that are thought to cause a decrease in initial contrail ice particle number. We show that contrail cirrus microphysical processes are changed so that contrail cirrus life times and optical depth are significantly reduced, both leading to a strong decrease in the climate impact of contrail cirrus.

A. Clouds and cloud processes

Uncertainties with respect to contrail coverage modelling in REACT4C

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The project REACT4C, an EU FP7 funded project, set out to demonstrate the feasibility of environmentally friendly flight routing. One of the tasks within the project is to provide an analysis of the uncertainties in contrail and contrail-cirrus modelling. To achieve this objective, two offline models were used; the Contrail Modelling and Analysis tool (COMA) and the Edward-Slingo radiative transfer model (ES-RTM). The focus of this study is to estimate the uncertainties due to differences in simulation parameters used to calculate linear contrail coverage. It is important to firstly understand the uncertainties in linear contrails, since contrail-cirrus are made up of linear contrails (young line-shaped contrails) and irregularly shaped contrails formed from aged contrails that persist and spread. Firstly, we will discuss the differences arising from the application of two emissions inventories used in REACT4C; AEM and FAST. We found that the differences seen are largely due to the spatial and vertical distribution of the distance travelled in the inventories. Then, we will assess the uncertainty that could arise from using different temporal resolutions for the emissions inventory. The contrail coverage and RF differences seen here are largely due to the diurnal variation of air traffic. We found that it is important to know the actual diurnal traffic variation throughout the day since this can significantly change the RF results, even when it is averaged on a global and annual basis. We also found that the monthly variation in air traffic did not significantly impact the coverage and RF results. The results presented here and a companion study where the uncertainties due to the adoption of different radiative transfer parameters, inform us on the range of values that we might expect from the assessment of different contrails and contrail-cirrus studies.

A. Clouds and cloud processes

Uncertainties with respect to contrail radiative modelling in REACT4C

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One task of the EU FP7 funded project REACT4C, set out to demonstrate the feasibility of environmentally friendly flight routing, involves assessing the uncertainties in the way we model contrail radiative effects. We present the results from several radiative sensitivity tests using a 3D contrail cover for year 2006, calculated off-line with the Contrail Modelling and Analysis tool (COMA) and described in a companion study.

The tests incorporated common assumptions made in large-scale models, including simplifications such as using fixed values of the contrail's optical depth, effective particle size, altitude, and physical thickness. In the reference case, the same ice water content and effective particle size dependence on ambient temperature is assumed for both persistent contrails and natural cirrus.

The fixed optical depth tests produced differences compared with the reference case of around +5%, -44% and +50%, for optical depths of 0.2, 0.1 and 0.3, respectively; while the sensitivity tests on the prescribed ice water content produced differences of around +42% when replacing the database's median by the mean. The large sensitivity to the optical depth and ice water content contrast with a dependence of around 1%, obtained when assuming a fixed particle size.

A. Clouds and cloud processes

The life cycle of cirrus clouds from a combination of active and passive satellite sensors

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Cirrus clouds play an important role in climate due to their effect on radiative forcing. Nevertheless, the understanding of the physical processes that govern their life cycle is still poorly understood, as is their representation in climate models. My PhD thesis, which started in January 2015, aims to improve the knowledge about the life cycle of cirrus clouds through the retrieval and analysis of the temporal evolution of various cirrus cloud properties from a combination of active and passive satellite sensors aboard polar orbiting and geostationary satellites.

The initial steps are to validate the “cirrus optical properties derived from CALIOP and SEVIRI algorithm during day and night” (COCS) algorithm (Kox et al., 2014) using simulated Meteosat Second Generation (MSG) SEVIRI radiances and to develop a cirrus cloud tracking algorithm that can be applied together with COCS (and other cloud property retrieval algorithms) in order to monitor the temporal evolution of natural cirrus clouds from the formation to the dissolution. Furthermore this combination of algorithms shall be able to follow the temporal evolution of contrail cirrus from the non-linear stage until dissolution. On the conference I want to present the first results of my work.

Kox, S., Bugliaro, L. and Ostler, A.: Retrieval of cirrus cloud optical thickness and top altitude from geostationary remote sensing, Atmos. Chem. Phys., 7, 3233–3246, doi:10.5194/amt-7-3233-2014, 2014.

A. Clouds and cloud processes

Simulating contrails with COSMO-ART based on real time flight tracks

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Condensation trails (contrails) from aircrafts are among the most obvious indications showing anthropogenic activities impacting the atmosphere.

A parameterization to simulate the formation and life cycle of contrails has been implemented into the high resolution regional numerical model system COSMO-ART (Vogel et al., 2009).

Using a relatively simple parameterization whether the environmental conditions are favourable for the formation of contrails known as the Schmidt-Appleman criterion (Schumann, 1996), the parameterization computes additional ice water content and number concentrations. The following life cycle, consisting of processes like advection, deposition of water vapour and sublimentation is described using the two moment cloud microphysical scheme of Seifert and Beheng (2001) in which the new parameterization scheme is embedded.

This method allows also the treatment of so called contrail cirrus that is basically aged contrails which more and more develop into wide spread and optical thin cirrus.

A basic data set provided by the German Aerospace Center - Institute of Air Transport and Airport Research contains the spatial and temporal high resolved trajectories of a limited number of sample flights over Middle Europe

First model results are compared with satellite pictures for the simulated days. Besides the conditions and life cycle of contrails and contrail cirrus, the influence on the upper tropospheric cloud coverage of these man-made clouds over Germany is examined.

A. Clouds and cloud processes

Detection of contrails on biofuel emissions by aviation

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There is a growing need to understand the climate effects caused by the projected increase in the combustion of alternative fuels by aviation. Ground based engine tests show reduction in soot emissions, when burning specific biofuels. This change in emissions is expected to affect contrail formation and life cycle with potential relevance for climate.

Contrail formation on emissions from biofuels has been investigated during the ACCESS2 mission in the Los Angeles area coordinated by NASA. In May 2014, the NASA DC8 source aircraft burned a HEFA blend (Hydroprocessed Esters and Fatty Acids synthetic paraffinic kerosene) in one engine and specified JET-A1fuel in the other 3 engines. Its emissions were probed at cruise altitudes by instruments onboard the DLR research aircraft Falcon-20 and the NASA's Falcon HU25, including two FSSP forward scattering spectrometer probes versions 300/100 and two CAS-DPOL cloud and aerosol spectrometers. Contrail formation has been observed during two flights at pressures near 230 hPa and temperatures of 216 and 220 K. Distances less than 300 m to the contrail producing aircraft correspond to contrail ages of less than 1 sec. Interestingly, we do not find a dependence of the effective diameter of the young contrails on the type of kerosene or on engine settings. We derive an apparent emission index of the number of contrail ice crystals produced per kg fuel burned and investigate its dependence on the soot emission index, temperature and thrust settings.

Our observations will provide a first experimental data base of contrails nucleated on biofuel emissions for process studies to enhance our understanding of contrail formation. The data will be used for a contrail parameterization for a global model in order to assess their climate impact.

B. Emissions

Transport pollution in India

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Road dusts contribute a large fraction (> 30%) of air pollution in urban environment. Population growth and economic development in India are contributing many serious environmental calamities i.e. air, water and soil pollution, global warming, climate change, etc. Motored vehicles for land transportation are the foremost transportation method now-a-days and contribute a major fraction of air pollution. Road transport air pollution includes vehicle exhaust (i.e. NOx, SOx, VOCs, PAHs, etc.), non-vehicle exhaust (i.e. tire abrasion, wear of certain vehicle parts, brakes, engine parts, etc.) and road related (i.e. degradation of the road pavement, corrosion of crash barriers, road and roadside maintenance-related causes, etc.) emissions. Road dusts are fugitive and traffic-related pollutants in the environment, especially in urban areas adjacent to traffic activities are consistently rising every year due to increase in number of vehicles. In the present work, the composition and sources of metals and ions in the dusts of high way road of the most industrialized area, Raipur city, India (21° 8′ 24″ N, 81° 22′ 48″ E) are described. The mean content of As, Cr, Mn, Fe, Ni, Cu, Zn, Pb, Hg, F-, Cl-, NO3-, SO42-, NH4+, Na+, K+, Mg2+ and Ca2+ in the dust (n = 5) 22.0±2.4, 138±34, 11357±10616, 145517±55664, 59±6, 491±518, 322±136, 270±166, 0.11±0.08, 279±95, 4355±2436, 805±330, 2909±1360, 219±136, 4090±1482, 1330±587, 956±202 and 9471±2046 mg/kg, respectively. The highest content of the chemical species (i.e. Cl-, NO3-, SO42-, Na+, K+, Mg2+, Ca2+, Cu, Zn and Pb) was seen in the heavily rushed bus and truck stand sites. The brake dust, motor vehicle wheel weights, tire tread, automobile rust, road and combustion exhaust were expected main source for emission these ions and metals in the road dust. The enrichment, spatial and temporal variations, correlation and sources are discussed.

B. Emissions

Contamination assessment of ions in road dust of India

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Air pollution has become a growing problem in megacities and large urban areas of India due to transport pollution. The estimated number of vehicles in the country is >100 million with an increasing rate of ≈8% per year. The transport system contribute >30% of air pollution in the urban environment in gaseous, liquid and road dust forms. The road dusts (RD) generated from different sources on the roads has become a valuable archive of environmental information. The RD gets washed down to surface and travels to subsurface with rain water and becomes a potential health hazard for the humans and all other biota. In the present work, contamination assessment of ions (i.e. F-, Cl-, NO3-, SO42-, NH4+, Na+, K+, Mg2+ and Ca2) in 42 road dust samples of the country are presented. The content (n=42) of ions i.e. F-, Cl-, NO3-, SO42-, NH4+, Na+, K+, Mg2+ and Ca2+ in the road dusts is ranged from 75 – 895, 276 – 12718, 48 – 1423, 243 – 10580, 11 – 539, 290 – 46484, 110 – 7716, 84 – 1771 and 595 - 15955 mg kg-1 with mean value of(at 95% probability) 224±43,3734±895, 592±895, 2859±662, 143±29, 4826±2049, 1565±411, 837±121 and 8545±1288 mg kg-1, respectively. The ions such as calcium, sodium, chloride and sulfate are dominating species in the dusts. The concentration, variation, correlation and sources of the ions are discussed.

B. Emissions

Influence of Jet Fuel Composition on Aircraft Engine Emissions: A Synthesis of Aerosol Emissions Data from the NASA APEX, AAFEX, and ACCESS Missions

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We statistically analyze the impact of jet fuel properties on aerosols emitted by the NASA Douglas DC-8 (Tail No. N817NA) CFM56-2-C1 engines burning 15 different aviation fuels. Data were collected for this single engine type during four different, comprehensive ground tests conducted over the past decade, which allow us to clearly link changes in aerosol emissions to fuel compositional changes. It is found that the fuel aromatic and sulfur content most affect the volatile aerosol fraction, which dominates the variability (but not necessarily the magnitude) of the number and volume emissions indices (EIs) over all engine powers. Meanwhile, the naphthalenic content of the fuel determines the magnitude of the nonvolatile number and volume EI as well as the black carbon mass EI. Linear regression coefficients are reported for each aerosol EI in terms of these properties, engine fuel flow rate, and ambient temperature and show that reducing both fuel sulfur content and naphthalenes to near-zero levels would result in roughly a 10-fold decrease in aerosol number emitted per kilogram of fuel burned. This work informs future efforts to model aircraft emissions changes as the aviation fleet gradually begins to transition toward low-aromatic, low-sulfur alternative jet fuels from biobased or Fischer–Tropsch production pathways.

B. Emissions

Examining the role of aviation NOx emissions as a short lived climate forcer

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Aviation impacts the atmosphere on a global scale and its effects on the climate are still somewhat uncertain. International aviation is currently not included in the Kyoto protocol, and as a result is also not included in international emissions reductions policies. This study focuses on aviation CO2 and NOx emissions which in turn increase ozone concentration, and decrease methane concentrations, both of which impact on radiative forcing calculations. This study will use a suite of models and international aviation fuel inventories to examine these effects over different time scales. The main aim of this study is to determine whether reduction of short-liver climate forcers such as aircraft NOx, at the expense of CO2 emissions is a potentially worse or better outcome for global climate in the longer (>100 years) term, and therefore examine whether controlling aviation NOx emissions would reduce or limit global warming, using the global warming potential (GWP) and global temperature change potential (GTP) metrics. The MOZART CTM will be used to study the impact of aviation scenarios on varying background NOx levels and then the LinClim simple climate model (SCM) is used to forecast the effects of aviation out into the longer term.

B. Emissions

Volcanic and air transport effects on atmospheric composition

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Volcanic effects have been observed in Europe originating either from European (Icelandic, Italy) or from distant large volcanic eruptions (e.g. Kasatochi in the Aleutians and Africa). The interference of the volcanic plumes with air traffic corridors have been studied thoroughly in the case of 2010 eruptions of Eyafallajokull which caused major air travel disruptions across Europe. There have been similar eruptions that have not interfered with air traffic in the past decade such as the recent Bardarbunga (September 2014) whose forward trajectories where below 6000m. The case of Eyafallajokull in 2010 offers us the possibility to study changes in aerosols and cirrus clouds over major air traffic corridors in Europe before and after the air traffic shutdown, and therefore to assess effects of air transport on atmospheric composition. Changes observed before the air traffic shutdown can be assumed to be affected both by air transport and volcanic activity whereas changes observed after the airspace closure are assumed to be free from air transport effects and mainly affected by volcanic activity. The changes are also compared with changes observed during similar volcanic eruptions that did not interfere with air traffic. For the determination of aerosols and cirrus clouds we make use of the aerosol optical depth and cirrus reflectance level-3 data products from MODIS Terra. Daily data are analysed in four bi-monthly periods, namely August-September 2008, April-May 2010, May-June 2011 and September-October 2014, which include the volcanic eruptions of Kasatochi (2008), Eyafallajokull (2010), Grimsvotn (2011) and Bardarbunga (2014), respectively. Also, we look into changes in columnar SO2 amounts that have followed excursions from these volcanic eruptions. Columnar SO2 records from remote sensing spectrophotometers over Europe and from space are compared. The columnar SO2 measurements are also compared with ground based SO2 monitors from the Airbase dataset.

B. Emissions

A modelling study of the impact of land transportation on Arctic black carbon and solar radiation transfer

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Market strategies have greatly incentivised the use of diesel engines for land transportation. These engines are responsible for a large fraction of black carbon (BC) emissions in the extra-tropical northern hemisphere with significant effects on both air quality and global climate. In addition to direct radiative forcing, planetary-scale transport of BC to the Arctic region may significantly impact the surface albedo of this region through wet and dry deposition on ice and snow. A sensitivity study is made with the University of L'Aquila climate-chemistry-aerosol model by eliminating on-road diesel emissions of BC (which represent approximately 50% of BC emissions from land transportation). According to the model and using emission scenarios for the year 2000, this would imply an average change in top-of-atmosphere direct radiative forcing (RF) of -0.066 Wm-2 (globally) and -0.11 Wm-2 over the Arctic region, with a peak of -0.32 Wm-2 during Arctic springtime months. These RF values increase to -0.075, -0.24 and -0.67 W/m2, respectively, when also taking into account the indirect effect of BC deposition on snow/ice albedo. The calculated BC optical thickness decrease is 0.48×10-3 (globally) and 0.74×10-3 over the Arctic (i.e., 10.5% and 16.5%, respectively), with a peak of 1.3×10-3 during the Arctic springtime. On annual basis, the calculated normalised radiative forcing (NRF), i.e., RF normalised to the BC optical depth change at λ=0.55 μm, accounts for 200 and 140 over the Arctic and globally, respectively, and increases to 420 and 155 when considering the indirect effect on snow/ice albedo. During springtime months with highest BC RF, the NRF accounts for 310 and 175 over the Arctic and globally, respectively; these values increase to 660 and 215 when considering the BC/albedo effect.

B. Emissions

The impact of biofuel blend ratio on gaseous emissions and smoke from an aircraft APU

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Framed within European policy and Flightpath 2020, the ITAKA project seeks to address many of the remaining difficulties in the development of an aviation biofuel value chain. To realize this vision, sustainable biofuels must be integrated into existing fuel infrastructure and so may be present at a relatively small blend fraction within a future comingled supply of Jet A-1. Understanding how this change in fuel composition might affect aircraft emissions together with the downstream impact on air quality and climate change is therefore important.

To date there has been no comprehensive mapping of the relation between fuel composition and the emissions from a gas turbine engine, although some basic principles of understanding are beginning to emerge. In this contribution we report experimental emissions data from a fully instrumented APU gas turbine test-bed engine when powered by a sustainable HEFA biofuel derived from used cooking oil at a number of different blend ratios and referenced to a standard Jet A-1 fossil fuel. Fuel blend ratios in the range from 0% to 100% were considered at three standardised APU engine operating conditions (No Load, Environmental Control Systems, and Main Engine Start), and the four standard ICAO engine database species NOx, CO, UHC, and smoke number have been measured. For each of these species, the data show a linear relation between the Emission Index and the fuel blend ratio; which must infer a similarly linear relation with fuel chemical composition. The data will be discussed in detail and in relation to fuel flow which scales linearly with energy content in the blend. The large number of collected data points (n=15) enable even relatively modest trends to be visualised and presented as statistically significant. In assessing the impact of fuel chemistry on emitted species, APU engine tests are advantageous over full scale rig tests in that a comparatively modest quantity of fuel is required and tests are relatively low cost.

C. Impact on climate, metric and mitigation

Towards uncovering the origin of efficacy differences for different radiative forcing contributions related to transport emissions

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The total climate impact of any transport sector consists of several individual contributions from, e.g., various trace gases, aerosols, or cloudiness changes. Ranking such contributions according to their quantitative importance in terms of radiative forcing requires that each component has the same efficacy, i.e., that for all forcings the global mean surface temperature response is linked to the radiativ forcing with the same climate sensitivity parameter. Experience has shown that this crucial assumption is not always true. The physical reasons of different efficacies for different forcing mechanisms are still insufficiently explored.

Here, we investigate the potential of radiative feedback analysis to explain efficacy variations. As an example, we have analysed equilibrium climate change simulations forced by a radiative forcing from CO2 increase and by a radiative forcing from enhanced NOx and CO surface emissions (via ozone changes). We find that forcing dependent efficacies can be traced back to a forcing dependence of certain feedback mechanisms, like the stratospheric temperature feedback or the cloud feedback. However, for a successful analysis it is important to comply with certain methodological constraints and to scale the forcing to a level that allows to separate statistically significant feedback changes from the natural variability. The latter is found to differ substantially for the various global radiative feedback parameters.

C. Impact on climate, metric and mitigation

Brief review of the Forum AE workshop on Aviation transport impact on climate change – role of NOx emissions

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European aviation industry, supported by research institutes and universities, has been working to make air-transport greener in order to develop sustainable mobility. The FP7 coordination action FORUM‐AE, co-ordinated by Olivier Penanhoat from SNECMA, aims at addressing main issues and open questions linked to environmental impacts from aviation emissions. Focused workshops are FORUM‐AE's main instrument to collect expertise from stakeholders and technical experts on aviation emissions and environmental impact issues. Besides offering the European technical forum for information exchange and discussion, FORUM‐AE pursues a deeper understanding of the impacts, identifies mitigation solutions and provides recommendations on regulatory issues. Moreover, the workshops contribute to the progress assessment of European RTD programs against ACARE goals, and its outcome will include recommendations in terms of future RTD priorities.

A thematic workshop on 'Aviation Climate impact by NOx emissions and contrails' was hosted in Oberpfaffenhofen on 2nd and 3rd of April 2014 by DLR. The focus of the workshop was to provide a general understanding and in‐depth insight in CO2 and in particular non‐CO2 climate impacts of aviation, by introducing the topic, presenting fundamental concepts, evaluating metric concepts, but also showing recent results from campaigns and modelling studies. Each of the two sessions was completed with a general discussion. In this poster we will provide a short overview of the topics, and the open questions identified to direct further research.

C. Impact on climate, metric and mitigation

Aviation impacts on climate: Where are we heading?

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Aircraft emit species that directly impact climate such as carbon dioxide (CO2), water vapour, nitrogen oxides (NOx) and aerosols. To estimate the climate impacts from aviation, it is necessary for us to know the aviation emissions trends. Over the years, there have been several widely-used emissions scenarios (IPCC, 1999; Lee et al. 2009; Owen et al. 2010; ICAO/CAEP, 2009). They provided an outlook of future aviation emissions and their contribution to total anthropogenic emissions. The IPCC Special Report on Aviation (IPCC, 1999) provided forecasts from base year 1992 to 'future' years 2000, 2015 and 2050. We are now at a point in time where we can compare these 'forecasts' against reported traffic activities and see how good these estimates actually are. Aviation emissions are highly dependent on demands and these in turn can be easily influenced by factors such as ticket prices or disease outbreak (e.g. SARS), making it difficult to make reliable long-term forecasts. The objectives of this study is to review widely-used aviation emissions scenarios, assess the accuracy of earlier forecasts to reported level of aviation emissions and estimate the climate impacts of these scenarios using a simple climate model, tuned with parameters from recent scientific literature. The results from the study would be used to inform policy makers on whether mitigation efforts are likely to meet the targets set out back in the 1990s or whether more stringent legislations/policies are required to achieve them.

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Owen et al., 2010: Flying into the Future: Aviation Emissions Scenarios to 2050. Environ. Sci. Technol. 44, 2255-2260

C. Impact on climate, metric and mitigation

TransClim: A fast climate-response-model for evaluating new developments in road traffic

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Emissions of road traffic produce ozone which are not only harmful to human health if exceeding certain thresholds, but also acts as a greenhouse gas increasing the anthropogenic climate warming. To mitigate the influence of ozone on climate, it is necessary to evaluate the climate impact of new technological and regulatory trends in road traffic. Current approaches utilise detailed atmosphere-chemistry models, which are time consuming and inhibit the analysis of a large set of emission scenarios. However, to evaluate a large range of future scenarios as well as the impact of uncertainties on the results a fast and effective tool is required. Thus, we develop such a suitable tool, the climate-response-model TransClim. It is based on an approach which utilises a set of emission dependent climate responses, precalculated by the global climate-chemistry model EMAC. By combining these precalculated climate impacts, the climate impact of each emission scenario can be determined. Using this approach, TransClim does not explicitly calculate physical and chemical processes and thus, is very numerical effective. Hence, TransClim is well-suited for sensitivity and error propagation studies. Here we present the first steps of an idealised and simplified environment to prepare the setup of the model TransClim.

C. Impact on climate, metric and mitigation

REACT4C: Simplified Mitigation Studies

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The EU FP7 project REACT4C explored the feasibility of operational measures such as flight altitude and route changes to reduce the climate impact from aviation. Simplified mitigation studies were conducted as part of the project to quantify the environmental benefit of simplified Air Traffic Management (ATM) measures and use the results to formulate general principles of environmentally-optimized flight for specific timescales and climate effects. The emissions model, FAST, was used to estimate the global emissions from civil aviation for the year 2006 and two mitigation scenarios, where the cruise altitudes were shifted higher (plus) and lower (minus) by one flight level, i.e. 2,000 ft. These emissions were used to identify and quantify mitigation possibilities from cirrus-changes, which may be triggered by aircraft aerosols (soot-cirrus) and spreading contrails (contrail-cirrus). The radiative forcing changes from aviation-induced cloudiness were estimated using the ULAQ model (soot-cirrus) and the ECHAM4-CCMod model (contrail-cirrus). The changes in the atmospheric chemical composition caused by aviation NOx emissions such as ozone (short- and long-lived), methane and stratospheric water vapour, were identified and quantified by the OSLO CTM2/3, ULAQ-CTM, EMAC and MOZART-3. These short-term impacts were also compared with the longer term CO2 impacts using other metrics such as Global Warming Potential (GWP) and Global Temperature Potential (GTP). The case for cruising at 'lower' altitudes was found to produce less non-CO2 effects, largely due to contrails (consequently, contrail-cirrus) that are less likely to form at lower altitudes. However, these mitigation scenarios are idealised and were devised to formulate general principles of climate-optimized flight. In reality, the implementation of such simplified measures may not be feasible due to ATM restrictions.

C. Impact on climate, metric and mitigation

Assessing the climate impact of a multi-fuel blended wing body: Results from the AHEAD EU-project

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The hybrid engine proposed in the EU project AHEAD is a novel propulsion system with a different architecture as compared to the conventional turbofan engine. The hybrid engine uses several unique technologies like shrouded contra-rotating fans, bleed cooling, dual hybrid combustion system (using hydrogen/methane and biofuel under flameless conditions to reduce CO2 and NOx emission respectively). The hybrid engine proposed in AHEAD will constitute a leap forward in terms of environmental friendliness, will use advanced multiple fuels and will enable the design of fuel-efficient Blended Wing Body (BWB) aircraft configurations.

In cooperation of Delft University of Technology, TU Berlin and Technion, and the DLR-institute of atmospheric physics, we estimated the possible reduction in climate warming by introducing this technology in comparison to a future reference based on the B787-8. A clear reduction in the climate impact of around 10% to 25% of is found. The climate impact calculation includes atmospheric changes from CO2, NOx, water vapour and particle emissions in addition to contrail-cirrus.

C. Impact on climate, metric and mitigation

The global impact of weather-dependent climate-optimal trajectories in the North Atlantic

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The EU FP7 project REACT4C explored the feasibility of operational measures such as flight altitude and route changes to reduce the climate impact from aviation. For this purpose a feasibility study on climate-optimized flight planning was performed for the North Atlantic flight corridor (NAFC). In this paper we present results from an evaluation of climate impact of such climate-optimized trajectories with a set of chemistry-transport models.

Such climate-optimized flight routing is performed by taking into account prevailing synoptical weather pattern. For winter five distinct patterns were identified, hence accordingly five emission inventories were generated for the NAFC region. Subsequently an experiment design was developed, in order to evaluate climate impact of these optimized routings for a specific winter season. The weather-dependent optimized inventories were integrated in the chemistry-climate models by respecting corresponding prevailing pattern. Specifically, two study periods were selected, one, for the winter periods in 2004/2005 and, a second one, 2006/2007. On a daily basis prevailing weather patterns were analysed as defined in 5 distinct patterns, and the corresponding optimized traffic inventory was integrated in the time series of aviation emissions. Simulations were performed by a set of chemistry-climate models which are OSLO CTM2/3, ULAQ-CTM, EMAC and MOZART-3, producing a multi-model estimate. Each model simulated two numerical simulations, one using economically optimized inventories and another using climate-optimized inventories. The comparison of atmospheric concentrations between both simulations determines the impact of climate-optimal routing. Results will be shown of changes in atmospheric concentrations of reactive species, focusing in particular on NOx, NOy, O3 and HOx, of these weather-dependent climate-optimized inventories.

D. Miscellaneous

Evaluation of the July 2013 MACC simulations of Canadian forest fires with ceilometer profiles

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Aerosol forecasts of the Monitoring of Atmospheric Composition and Climate MACC reanalysis (run

'fbov') and the operational global model (run 'fnyp') are compared to profiles from the German Meteorological Agency (DWD) ceilometer network. Three case studies evaluate modelling of long-range transport and vertical exchange processes. One case investigates Canadian forest fire (FF)

smoke, transported to Europe in July 2013, one compares long-term records of Saharan dust (SD) inferred for Germany for the period 2003-2012, and thirdly the models analysis of the depth of the planetary boundary layer (BLH) is compared to (likewise errorprone) observations. Owing to the realistic wind fields in the ECMWF model, long-range transport of tracers like FF and SD is mostly captured but not always positioned accurately. Representation is better, for direct advection, while simulating the scale cascade during dispersion/stirring remains a challenge. Partly, even details of the plume shape are reproduced. The peak mass concentration of smoke plumes at model resolution, here expressed in terms of extinction, is often simulated within a factor of 2-3.

D. Miscellaneous

The DLR-Project Transport and the Environment – Building competency for a sustainable mobility future

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Ensuring mobility whilst also protecting people, resources and the environment is one of the greatest challenges facing us. The DLR Transport Programme´s research project "Transport and the Environment" (VEU) has been created to investigate the transport and environmental chain. The VEU project involves twelve scientific institutions (ten DLR institutes and two further Helmholtz institutes) in a unique research network. The project is thematically organized in a framework of mobility scenarios for Germany and Europe in the year 2040. It integrates the study of new and innovative mobility technologies and concepts with socio-economic research on behaviour, acceptance and use of these options. It continues its analysis by creating models for future mobility trends and their impacts on people and the environment. The VEU project uses a cross-disciplinary scientific approach incorporating social-sciences, mathematics, engineering, physics and atmospheric chemistry. Furthermore it integrates medical research related to transport noise as well as specific economic analysis. This approach acknowledges the inter-disciplinary nature of mobility and its environmental effects, creating a comprehensive and reactive instrument for transport analysis. Our presentation describes the goals of the project and lays out the methodological approaches used to ensure the reliability of trans-disciplinary scientific research. It illuminates the organizational approach, which employs scenario-techniques to achieve a common understanding. The method of linking empirical research results with several models on different spatial scales in a classified manner is further explored. The VEU project creates platforms for scientific exchange and enables the integration of multi-disciplinary research on mobility.

D. Miscellaneous

A Survey of Occupational Exposure to Inhalable Wood Dust Among Workers in Small- and Medium-Scale Wood-Processing Enterprises in Ethiopia

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A study of wood dust exposure in 20 small- and medium-scale wood-processing enterprises was performed

in Ethiopia. Sampling was conducted daily from January to June, 2013 and a total of 360 samples

from 113 workers were collected with Institute of Occupational Medicine (IOM) personal samplers.

Eight-hour time-weighted average exposure to wood dust ranged from 0.24 to 23.3 mg m3 with a geometric

mean (GM) of 6.82 mg m3 and a geometric standard deviation of 1.82. Although Ethiopia did

not have any defined standard of Occupational Exposure Limit for wood dust exposure, 71% of the

measurements exceeded the limit of 5 mg m3 set by the European Union (EU). Higher than the EU

exposure limit was measured while workers perform sanding and sawing activities with a GM of 9.72

and 7.60 mg m3, respectively. In conclusion, wood workers in the small- and medium-scale enterprises

are at a higher risk of developing different respiratory health problems with continuous exposure trends.