Załącznik 3 do wniosku o wszczęcie postępowania habilitacyjnego

Scientific Curriculum Vitae

Contents

1. CURRICULUM VITAE

Krzysztof Mirosław Markowicz
University of Warsaw, Faculty of Physics
Institute of Geophysics

EDUCATION

1993	maturity exam at Adam Mickiewicz High School in Strzyżów, mathematical-physical class
1999	M.Sc, Faculty of Physics, University of Warsaw, master thesis „The role of vorticity on spectral evolution of droplet concentrations” supervisor Dr Konrad Bajer
2003	Ph. D. in Physical Sciences received from the Faculty of Physics, University of Warsaw Ph.D thesis „Experimental Determination of Solar and Infrared Radiative Forcing”, supervisor Prof. Krzysztof Haman and Dr Piotr Flatau

APPOINTMENTS

1999-2003	Ph.D in Physics, University of Warsaw
Since March 2004	Assist,. Prof., fixed-term (adiunkt) at Institute of Geophysics, Faculty of Physics, University of Warsaw

SCIENTIFIC VISITS ABROAD

1999-2001	Scripps Institute of Oceanography, University of California in San Diego, USA, several visits (5 months)
2002	Scripps Institute of Oceanography, University of California in San Diego, USA, 5-month visit
2002	Naval Research Laboratory, Monterey USA, 4-month visit

2003-2004	Naval Research Laboratory, Monterey USA, 4-month visit
2007-2008	Meteorology Department of Reading University, UK, 4-month visit

AWARDS

2010	Scientific award of Rector of the University of Warsaw
2006	Scholarship of Rector of the University of Warsaw
2005	Foundation for Polish Science Award for Young Scientists
2004	Foundation for Polish Science Award for Young Scientists
2001	Fulbright Junior scholarship, 2001
1999	Maria Bardadin-Otwinowska Prize for the best MSc Thesis “The role of vorticity on spectral evolution of droplet concentrations”
1997	Scholarship from the Minister of Education
1993	Polish Academy of Science award (First Step to Nobel Prize in Physics) for the paper „Extinction of visible solar radiation in the lower troposphere”
1993	Polish Academy of Science award (First Step to Nobel Prize in Physics) for the paper „Climate of Strzyzow”

COMUUNITY INVOLVEMENT

2011	founding member of the Institute for Solar Energy Association
2002-2008	member of the Scientific Council of the Institute of Geophysic, Faculty of Physics, University of Warsaw
2004-2008	member of the electoral commission of the Faculty of Physics, University of Warsaw
since 2000	coordinator of the Polish section of the atmosphere research in the GLOBE program

SCIENTIFIC PUBLICATIONS INCLUDED IN THE WEB OF SCIENCE DATABASE

(data on November 30, 2011)

#H index: 9

Number of publications: 18

Number of citations: 657

Number of citations without auto-citations: 641

2. SCIENTIFIC CAREER BEFORE RECEIVING PH.D

My interests in atmospheric physics started when I was 11 years old. In primary school I built a weather observatory in Strzyzow (south east region of Poland). Three times a day I measured major atmospheric conditions and climate parameters for the local Department of Plant Quarantine. Based on data collected over a seven-year period of observations, I wrote a paper on climate of Strzyzow and spatial variability of microclimate conditions in the Carpathian Foothills. In 1992 I began observations of solar radiation with a portable light meter. My observations were designed to estimate reduction in the solar radiation in the lowest troposphere due to the presence of anthropogenic aerosols emitted mainly by households. The main result of this study was the founding of a strong reduction of solar radiation reaching 10-15% in the first 150 meters of the atmosphere. Such conditions occurred during winter high-pressure weather with weak pressure gradients, which favored strong accumulation of air pollution in the valley of Strzyzow. The results are described in the work „Extinction of visible solar radiation in the lower troposphere". Both papers were awarded in the first Polish and in the first International Competition entitled „First Step to Nobel prize in Physics". In 1992 and 1993 I participated in a two-week research visit in the Institute of Physics of the Polish Academy of Science in Warsaw.

In 1993 I began studying physics at the Interfaculty Studies in Mathematics and Natural Sciences at Warsaw University. My M. Sc. dealt with the problem of cloud coagulation and evolution in the field of small scale turbulence caused by vorticity motion.
I carried out my master's thesis entitled „Effect of eddy motions on the evolution of droplet spectra in clouds" under the supervision of Konrad Bajer. The main result of this work was founding that cloud droplets of sufficient size are not randomly dispersed in cloud but are preferentially concentrated in regions of low vorticity in the turbulent flow field. Regions of high vorticity (low droplet concentration) would have a higher level of saturation than regions of low vorticity (high droplet concentration).

In 1999, I started Ph.D studies at the Faculty of Physics, University of Warsaw. The main objectives of my research became the atmospheric aerosol and its direct impact on the climate. Piotr Flatau from the Scripps Institute of Oceanography, University of California in San Diego, and Krzysztof Haman from the Institute of Geophysics, University of Warsaw were my scientific supervisors. During my Ph.D studies, I participated in three major research experiments: INDOEX (Indian Ocean Experiment), MINOS (Mediterranean Intensive Study oxidant) and ACE-Asia (Asian Pacific Regional Aerosol Characterization Experiment). The

main goal of the INDOEX experiment was to study how air pollution affects climate processes over the tropical Indian Ocean. During this campaign I was involved in the research on the NOAA research vessel RH Brown and civilian airport on the Mali island (Maldives).
I was a member of the research groups involved in the study of the ocean color, and my research focused on measurements of the ocean reflectance, the aerosol optical thickness using sun photometers, and profiles of the aerosol extinction coefficient using MPL lidar. Two years later, on the same ship, I participated in the ACE-Asia experiment. The ACE-Asia campaign was designed to study the complex outflow of mineral dust and air pollution from Asia at mid-latitudes. The East Asian coastal region is characterized by anthropogenic emissions that are already high in many localities and are rapidly growing throughout much of the region. During the trip between Hawaii and Japan I focused on observations of the radiative balance and the aerosol optical properties. The last experiment (MINOS) took place in July and August of 2001 on the Greek island of Crete. MINOS was a comprehensive field project aimed at investigation of anthropogenic contributions to the environment of the central Mediterranean, and provided measurements of aerosol chemistry, microphysics, and radiation. The analysis of the results obtained during these experiments was conducted partly at the Scripps Institute of Oceanography in San Diego and partly at the Institute of Geophysics. Between 1999 and 2003 I visited the Scripps Institute where I prepared 3 papers and I participated in preparation of 5 papers published in JCR journals. I conducted these works under the supervision of Piotr Flatau, and in collaboration with Veerabhadran Ramanathan, Paul Crutzen and Andrew Vogelmannem from Sripps Institute of Oceanography of the University of California in San Diego.

The main results obtained during my Ph.D studies contribute to better understanding of the atmospheric aerosols influence on the optical and radiative properties of the Earth's atmosphere bringing a number of new results, which in some respects, change or extend the views present in the literature of this subject. The main outcomes:
- aerosols near industrialized areas of the world (e.g. the northern part of the Indian Ocean, and Eastern Mediterranean) have strong absorption properties. This leads to a significant reduction in solar radiation arriving at the Earth's surface (approximately 5-8%) [A1, A2, A3]
-there is a strong relationship between the relative humidity (and also the total precipitation of water) and the aerosol optical thickness. The observations carried out on the Sea of Japan during the ACE-Asia experiment show the existence of a strong correlation between the single-scattering albedo and the relative humidity, which in turn indicates a relationship

between the relative humidity and the aerosol radiative forcing efficiency [A5].
- aerosol radiative forcing, in the surveyed areas of the world, significantly exceeds the mean global value of the anthropogenic greenhouse gases radiative forcing [A1, A6, A7, A8].
- contrary to current views, the impact of aerosols on the balance of long-wave radiation cannot be neglected - both natural aerosol (especially sand desert) and human activities can significantly affect the value of this balance. It was shown that the aerosol radiative forcing in the far infrared, in contrast to the shortwave, is positive both on the Earth's surface and at the top of the atmosphere, and the absolute value can have a value of up to 20% of the shortwave radiative forcing [A4, A6].

A1 Markowicz, K. M., P. J. Flatau, M. V. Ramana, P. J. Crutzen, and V. Ramanathan (2002), Absorbing mediterranean aerosols lead to a large reduction in the solar radiation at the surface, *Geophys. Res. Lett.*, 29(20), 1968, doi:10.1029/2002GL015767.

A2 Lelieveld, J., H. Berresheim, S. Borrmann, P.J. Crutzen, F.J. Dentener,H. Fischer, J. Feichter, P.J. Flatau, J. Heland, R. Holzinger, R. Korrmann,M.G. Lawrence, Z. Levin, K. Markowicz, N. Mihalopoulos, A. Minikin,V. Ramanathan, M. de Reus, G.J. Roelofs, H.A. Scheeren, J. Sciare,H. Schlager, M. Schultz, P. Siegmund, B. Steil, E.G. Stephanou, P. Stier,M. Traub, C. Warneke, J. Williams, H. Ziereis (2002), Global air pollution crossroads over the Mediterranean, *Science*, 298 (5594), 794-799, doi:10.1126/science.1075457.

A3 Welton, E. J., K. J. Voss, P. K. Quinn, P. J. Flatau, K. Markowicz, J. R. Campbell, J. D. Spinhirne, H. R. Gordon, and J. E. Johnson (2002), Measurements of aerosol vertical profiles and optical properties during INDOEX 1999 using micropulse lidars, *J. Geophys. Res.*, 107(D19), 8019, doi:10.1029/2000JD000038.

A4 Vogelmann, A. M., P. J. Flatau, M. Szczodrak, K. M. Markowicz, and P. J. Minnett (2003), Observations of large aerosol infrared forcing at the surface, *Geophys. Res. Lett.*, 30(12), 1655, doi:10.1029/2002GL016829.

A5 Markowicz, K. M., P. J. Flatau, P. K. Quinn, C. M. Carrico, M. K. Flatau, A. M. Vogelmann, D. Bates, M. Liu, and M. J. Rood (2003), Influence of relative humidity on aerosol radiative forcing: An ACE-Asia experiment perspective, *J. Geophys. Res.*, 108(D23), 8662, doi:10.1029/2002JD003066.

A6 Markowicz, K. M., P. J. Flatau, A. M. Vogelmann, P. K. Quinn, E. J. Welton (2003),. Clear-sky infrared radiative forcing at the surface and the top of the atmosphere, *Q. J. R. Meteorol. Soc.* , 129 , pp. 2927-2947 doi: 10.1256/qj.02.224.

A7 Conant, W. C., J. H. Seinfeld, J. Wang, G. R. Carmichael, Y. Tang, I. Uno, P. J. Flatau, K. M. Markowicz, and P. K. Quinn (2003), A model for the radiative forcing during ACE-Asia derived from CIRPAS Twin Otter and R/V *Ronald H. Brown* data and comparison with observations, *J. Geophys. Res.*, 108(D23), 8661, doi:10.1029/2002JD003260.

A8 Seinfeld J, G Carmichael, R Arimoto, W Conant, F Brechtel, T Bates, D Cahill, D Clarke, S Doherty, P Flatau, Huebert J, J Kim, K Markowicz, P Quinn, L Russell, P Russell, A Shimizu, Y Shinozuka, C Song, Y Tang, J Uno, A Vogelmann, R Weber, J Woo, X Zhang (2004), ACE-Asia: Regional Climatic and Atmospheric Chemical Effects of Asian Dust and Pollution, *Bull. Am. Met. Soc.*, 85(3), 367-380.

3. SCIENTIFIC CAREER AFTER RECEIVING PH.D

My research, after receiving the Ph.D may be subdivided into four topics:

- global scale modeling of aerosol single-scattering properties and radiative forcing
- optical properties and radiative forcing of non-spherical aerosols
- synergy of the in-situ and remote sensing observation of aerosol optical properties
- study of the ice crystal shape effect on optical properties and radiative forcing of contrails.

Besides, I dealt with the analysis of renewable energy resources in Poland.

3.1 Global scale modeling of aerosol single-scattering properties and radiative forcing

The research I conducted just after receiving Ph.D was related to the grant of the Office of Naval Research in cooperation with the Naval Research Laboratory (NRL) in Monterey (USA). Being the Principal Investigator of this project I worked with Marcin Witek (at the time a Ph.D student at the Institute of Geophysics, University of Warsaw), Joanna Remiszewska (at the time a Ph.D student at the Institute of Geophysics, Polish Academy of Sciences), and Aneta Maciszewska (master student) and scientists from the NRL. The project dealt with validation of the Navy Aerosol Analysis and Prediction System (NAAPS) based on observation within Aerosol Robotic NETwork (AERONET) and the construction of the so-called off-line model to determine the radiative forcing. For the NAAPS validation I developed, wrote and used the so called „optical package" code, which, on the basis of the aerosol mass concentration predicted by the model and OPAC (Optical Properties of Aerosols and Clouds) database, is used to determine the optical thickness, the single-scattering albedo, and the asymmetry parameter as well as the profiles of the aerosol extinction coefficient. During the model validation process we focused on the aerosol optical thickness in Central Europe, mineral dust concentration transported to the US from China deserts and sea salt concentration above the Pacific Ocean. Due to the fact that the NAAPS did not have a class of the marine aerosol having an important contribution to the total optical thickness globally, Marcin Witek developed and implemented this type aerosol. [B1]. Despite of this, through investigations, it was found that the NAAPS model systematically underestimated the aerosol optical thickness as compared to the observations [B2]. The model deficiencies influenced simulations accuracy, especially insufficient representation of anthropogenic aerosols, simplified parameterization of the aerosol optical properties, poor horizontal resolution model

(1deg), and outdated information on emissions of sulphates in Europe. Despite these drawbacks, the model results provide valuable information on spatial and temporal variability of aerosol distribution over Europe.

The final task of this project was to develop a model linking the aerosol optical properties predicted by the NAAPS model with radiative transfer model. In order to simulate global radiative fluxes, this model required a relatively fast but accurate radiative transfer code. For this purpose, we selected two-stream Fu-Liou model. Simulations of radiation fluxes and the aerosol radiative forcing required setting not only the aerosol single-scattering properties but also thermodynamic profiles, and the land surface optical properties. Three-dimensional meteorological fields were obtained from the model NOGAPS (Navy Operational Global Atmospherics' Prediction System). Due to the fact that the aerosol radiative forcing is a function of surface albedo, the off-line model was linked with a surface module based on a satellite ground classification. This off-line model was used for further studies carried out in other grants.

B1 Witek, M. L., P. J. Flatau, J. Teixeira, **K. M. Markowicz** (2011), Numerical investigation of sea salt aerosol size bin partitioning in global transport models: Implications for mass budget and optical depth, *J. Aerosol Sci*., 45(3), 401–414.

B2 Maciszewska, A., **K. Markowicz**, M. Witek (2009), A Multiyear Analysis of Aerosol Optical Thickness over Europe and Central Poland Using NAAPS Model Simulation. *Acta Geophysica*, 58(6), 1147-1163.

3.2 Optical properties and radiative forcing of non-spherical aerosols

My research related to the study of optical properties and radiative forcing of non-spherical particles started in the summer of 2004 during the United Arab Emirates Unified Aerosol Experiment (UAE^2) in the United Arab Emirates. They were continued in the spring of 2005, during the measurement campaign "Sahara dust over Warsaw" (SAWA). During the first experiment I was involved in the observation of the aerosol optical properties in a mobile laboratory named MAARCO (Mobile Atmospheric Aerosol Characterization And Radiation) located approximately 10 meters from the shoreline (the Persian Gulf). The most important sources of aerosols were the surrounding deserts and oil wells located both on land and at sea.

Therefore, the aerosol single-scattering properties showed significant variation depending on the direction of flow advection and stratification of the lower troposphere. Due to the surrounding desert the significant part of observed particles were of non-spherical shape.
I conducted numerical simulations of the radiative forcing based on MODTRAN code, and the aerosol optical properties for spherical and spheroid particles derived from CIMEL sun photometer measurements. The results of these studies showed about 10% difference between the radiative forcing efficiency of spherical and spheroid particles [B3]. The effect of non-spherical particles on the radiative forcing appeared to be smaller than that of the spherical ones. We found out that the aerosol single-scattering properties were strongly influenced by local-scale circulation. At night, stagnating air caused gradual accumulation of pollution with maximum absorption in the early morning hours. Onshore winds brought cleaner air resulting in decreasing values of the absorption coefficient and increasing values of the single-scattering albedo. Following this study, the impact of breezes on the aerosol optical properties and their radiative forcing was described [B4].

These studies were continued during the second experiment in 2005. The SAWA field campaign was organized in cooperation with the Scripps Institute of Oceanography in San Diego, the Institute of Oceanology, Polish Academy of Sciences in Sopot, Institutes of Experimental Physics, Faculty of Physics of the Free University in Berlin and Warsaw University. The main objective of this study was to determine the optical properties and the radiative forcing of non-spherical mineral dust particles transported over Poland from the regions of the Sahara. The non-spherical particles were observed by the depolarization lidar system developed by Kamil Stelmaszczyk at the Free University in Berlin. We focused on strong Sahara dust event observed between 13 and 14 April of 2005. It was characterized by large depolarization ratios (0.2-0.25) and the Ǻngstrom exponent (1.2-1.4), suggesting small and non-spherical particles [B5]. Estimated the radiative forcing efficiency was lower (in absolute value) by about 5-7% in comparison to the spherical aerosol case [B6]. Numerical simulations performed using the T-matrix method and MODTRAN radiative transfer model for spheroid particles showed that non-spherical particles with sizes below 0.5 μm had smaller radiative forcing than spherical particles, which was consistent with the results obtained during the UAE^2 experiment.

B3 **Markowicz, K. M.**, A. E. Kardaś, C. Hochherz, K. Stelmaszczyk, Anna Rozwadowska, Tymon Zieliński, G. Karasiński, J. Remiszewska1, M. Witek, Sz. Malinowski, T. Stacewicz, and L. Woeste (2006), Observation of optical properties and Radiative forcing

of nonspherical particles over Poland, GRA vol. 8, 06233, EGS - AGU - EUG Joint Assembly, Vienna, 2006.

B4 **Markowicz, K.M**., P.J. Flatau, J. Remiszewska, M. Witek, E.A. Reid, J.S. Reid, A. Bucholtz, and B. Holben, 2008: Observations and Modeling of the Surface Aerosol Radiative Forcing during UAE^2, *Journal of the Atmospheric Sciences*, 65, 2877–2891.

B5 Kardas, A. E., **K. M. Markowicz**, K. Stelmaszczyk, G. Karasinski, S.P. Malinowski, L. Woeste, C. Hochhertz, 2010: Saharan aerosol sensed over Warsaw by depolarization lidar, *Optica Applicata*, 40, 219-237

B6 **Markowicz, K. M**., A. E. Kardaś, C. Hochherz, K. Stelmaszczyk, A. Rozwadowska, T. Zieliński, G. Karasiński, J. Remiszewska, M. Witek, Sz. Malinowski, T. Stacewicz, L. Woeste (2005), Observation of optical properties and radiative forcing of nonspherical particles over Poland, ACCENT symposium, Urbino.

3.3 Synergy of in-situ and remote sensing observation of aerosol optical properties

Another research topic is related to the synergy of the in-situ observations and remote sensing methods aimed at improving determination of the aerosol optical properties. The main disadvantage of the remote sensing methods is a significant sensitivity of retrieved quantities resulting from measurement errors and uncertainties of additional a priori information. This sensitivity results from ill-conditioned inverse problem. One method of improving this situation is to use measurements from different instruments. For this purpose, we developed a method of determining profile of the aerosol extinction coefficient on the basis of simultaneous measurements of two remote sensing devices (ceilometer and sun photometer) as well as on the basis of connecting ceilometer measurement and in-situ observation performed by nephelometer and aethalometer [B7].

The study of the synergies of the remote sensing observations has been continued under the grant of the National Science Centre „Determination of aerosol optical properties based on the synergy of remote sensing measurements". This project refers to combining satellite measurements by the SEVIRI instrument with measurements performed using ground-based solar photometers, and in-situ observation performed by nephelometer and atehalometer. The innovative aspect of the research being conducted under this grant involves the use of geostationary satellite measurements that allow determination of optical properties with time resolution of 15 minutes in contrary to 1 or 2 observations per day made by polar satellites [B8].

The research conducted within the frame of this project is performed in the Laboratory of Radiation Transfer (LTR) at the Institute of Geophysics, Faculty of Physics, University of Warsaw and the research station SolarAOT in Strzyzow. The LTR was established in 2005 before the SAWA campaign. The main goal of this Laboratory is to study the single-scattering properties of the atmosphere particles and radiation balance on the Earth's surface. From the very beginning, my work at the Institute of Geophysics was to establish a team focused on physics of atmospheric aerosols. An important element of this plan was to develop in-situ measurements and remote sensing methods in the LTR. Since 2005, the LTR has been systematically equipped with devices containing both commercially available apparatus and instruments built at the Institute of Geophysics. In 2011, the LTR was significantly improved after obtaining the state-of-the-art equipment financed by the Polish Science and Technology Foundation. In 2012, the equipment list will be expanded with Aerosol-Raman-Depolarization lidar which is currently under construction in the Troposphere Research Institute in Leipzig, in collaboration with Iwona Stachlewska (the Institute of Geophysics, University of Warsaw).

In 2003, after 10 years of break, I restarted atmospheric measurements in the Carpathian Foothills (Strzyzow). I established a private research station of Radiation Transfer SolarAOT. This station is located at the top of a small mountain (443 m.a.s.l). This localization was chosen to minimize local emissions of atmospheric aerosols, thus allowing the study of aerosol transported across Europe, and, on the other hand, to allow uninterrupted (terrain obstacles) measurements radiation fluxes. The station was equipped with a basic meteorological equipment, a 24-meter mast to study wind and temperature profile, a radiometer for measuring solar radiation and longwave radiation, a sun photometer, the whole sky camera, and homemade instruments such as lightning detectors, a detector of the atmospheric electric field, a detector of snow depth, and so on. This place is used for sun photometer and radiometer calibration which are used in LTR in Warsaw and the Institute of Oceanology in Sopot.

In 2010, on the premises of the station, a field campaign took place (Radiation Forcing over Poland), during which, among others, a prototype of micropulse lidar constructed at the Institute of Geophysics and the Institute of Experimental Physics and a radiosonde sounding system were tested. Data collected in the station are used not only by people from the University of Warsaw and the Institute of Oceanology in Sopot but also from others institution. All in all, they have been used in 10 undergraduate and graduate works and doctoral and habilitation thesis in the field of renewable energy and agro-meteorology and climatology.

In October 2011 we established a Polish network of aerosol measurements named Poland-AOD. The network currently consists of three measuring stations: LTR in Warsaw, the station at the Institute of Oceanology in Sopot and my Radiative Transfer Station SolarAOT in Strzyżów. Informally, the network has already worked several years in cooperation with the Institute of Oceanology Research in Sopot. Since 2005, I have been cooperating with Tymon Zielinski, Tomasz Petelski, Anna Rozwadowska and several graduate students. The main objective of the network is to conduct and maintain a continuous range of remote sensing measurements of the aerosol single-scattering properties and radiative balance of the Earth's surface, uniform system of data collection and processing of measurement and instruments calibration. Within the network there is a full exchange of information, including measurement data, which are transmitted in real time. Between 2010 and 2011 I have built an interactive system for data sharing, storing and processing in a database. In the future, it will be expanded to allow wider access for people outside the Poland-AOD network. Currently, data collected in the network are available in the form of so-called quick-looks on the website http://www.igf.fuw.edu.pl/meteo/stacja/PolandAOD.php.

B7 **Markowicz, K. M.**, P.J. Flatau, A.E. Kardas, J. Remiszewska, K. Stelmaszczyk, and L. Woeste, 2008: Ceilometer Retrieval of the Boundary Layer Vertical Aerosol Extinction Structure. *Journal of Atmospheric and Oceanic Technology*, 25, 928–944.

B8 Zawadzka, O., **K. M. Markowicz** (2011), Wyznaczanie grubości optycznej aerozoli atmosferycznych na podstawie pomiarów teledetekcyjnych, *Przeglad Geofizyczny*, 1-2, 3-26.

3.4 Study of ice crystal shape effect on optical properties and radiative forcing of contrails.

The studies on impact of the shape of the particles forming linear contrails on their optical properties and radiative forcing were carried out within the frame of the international project QUANTIFY (Quantify the Climate Impact of Global and European Transport Systems). This project was founded by the European Commission within the 6th research framework programme and took place from 2005 to 2010. The main goal of QUANTIFY was to quantify the climate impact of global and European transport systems on the present situation and on several scenarios of future development. The climate impact of various transport systems (land surface, shipping, aviation) were assessed, including those of longlived greenhouse gases like CO_2 and N_2O, and in particular the effects of emissions of ozone precursors and particles, as well as of contrails and ship tracks.

The first part of the project dealt with a comparison of the radiative forcing simulated by different radiative transfer models. This task was associated with estimation errors in simplified radiative transfer models that are used in global climate models (GCM). The research conducted in the Institute of Geophysics was related with three radiative transfer models: Fu-Liou, Streamer, and MODTRAN. The research group consisted of Aleksandra Kardaś of the Institute of Geophysics, Grzegorz Karasinski from the Institute of Experimental Physics, and Paulina Wolkenberg of the Space Research Centre of the Polish Academy of Sciences. We studied radiative forcing of contrails, lower stratosphere and upper troposphere water vapor emitted by the aviation. Moreover, we focused on the sensitivity of the single-scattering properties and surface albedo and emissivity parameterization of the radiative forcing.

In the framework of the international cooperation, I was in a scientific internship program at the Department of Meteorology at the University of Reading in UK for four months, where I worked with Keith Shine, Gaby Radel and Gunar Myhre from the Department of Earth Sciences, University of Olso, or with Yves Balkanski from Lab. des Sciences du Climat et de l'Environnement. The result of this collaboration was a joint publication on the effects of radiative transfer models for the radiative forcing errors [B9]. The study shows that the radiative transfer models are an important source of uncertainty even in the determination of the radiative forcing, which is a manifestation not only of differences in the methods of solving the radiative transfer equation but also in how the parameterization of optical properties of the atmosphere, and differences in the way they define by users.

One of the main objective of the QUANTIFY project was to analyze the contrail optical properties and radiative forcing. To this end, together with Marcin Witek, I conducted a series of numerical simulations of optical properties of ice crystals using the method DDSCAT (Discrete Dipole Approximation for Scattering and Absorption of Light by Irregular Particles) in the longwave spectrum and the method of geometric ray-tracing in the shortwave range. Based on the calculations, I built a database of optical properties of ice crystals and analyzed 10 types of particle shapes, including spherical particles, hexagonal plates and columns with different relative short and long driveshaft. The results of this analysis showed that although the ice crystals were randomly oriented, the ice crystals had a crucial impact on the contrail optical properties (the single scattering albedo and the asymmetry parameter). The last task of the study was to analyze the impact of the shape of ice crystals on the uncertainty of the contrail radiative forcing. For this purpose, I used an off-line model which was created under the first research task. This model, which in the original version was used to determine the flow of radiation in the case of a cloudless sky, was extended to parameterization of cloud optical properties to take into account natural clouds and contrails. The information on clouds optical properties, cloud cover and cloud altitude were obtained from the satellite cloud climatology ISCCP (International Satellite Cloud Climatology Project). The contrails cover was taken from the AERO2K database, which is a combination of aviation emissions, meteorological data (ECMWF re-analysis) and satellite observation. I studied the impact of contrail altitude on the radiative forcing, depending on the parameterization of ice crystals optical properties. These simulations were designed to examine the extent to which it was possible to reduce the contrail radiative forcing by changing altitude of airplane corridors. The main results of these simulations are presented in the paper [B10] and [B11].

B9 Myhre, G., M. Kvalevag, G. Rädel, J. Cook, K. P. Shine, H. Clark, F. Karcher, **K. Markowicz**, A. Kardas, P. Wolkenberg, Y. Balkanski, M. Ponater, P. Forster, A. Rap, R. Rodriguez De Leon (2009), Intercomparison of radiative forcing calculations of stratospheric water vapour and contrails, *METEOROL Z*, 18(6), pp585-596.

B10 **Markowicz, K. M**., and M. L. Witek (2011), Simulations of Contrail Optical Properties and Radiative Forcing for Various Crystal Shapes, *Journal of Applied Meteorology and climatology*, *50*(8), 1740-1755.

B11 **Markowicz, K. M**., M. Witek, Sensitivity study of the global contrails radiative forcing due to particle shape. *Journal of Geophysical Research*, doi:10.1029/2011JD016345, in press.

3.5 Study of renewable energy resources

I worked on renewable energy resources before and after receiving the Ph.D. My study in this topic was related to solar and wind energy in Poland. I participated in a project called „Database of Renewable Energy Sources in Podkarpacie" (http://www.baza-oze.pl/bazadanych.php) coordinated by the Center for Economic Consultancy and Subcarpathian Energy Agency. In this project, I prepared a database on spatial and time variation of solar radiation in the region of Podkarpacie. For this purpose, I applied observation from the SolarAOT station in Strzyżów and from three stations (Lesko, Przemysl and Jasionka) of the Institute of Meteorology and Water Management as well as the numerical simulation by the radiative transfer model. Simultaneously, I worked on estimation of wind energy based on observation performed at SolarAOT station. Together with Andrzej Tomczewski from the Poznan University of Technology, I published an article on the analysis of wind data for wind power [B12]. Moreover, I lectured on the use of wind energy and solar radiation during several conferences organized for local government.

B12 **Markowicz K**., A. Tomczewski (2010), Computer aided analysis of wind energy resources, Napędy i sterowanie, nr 2, 80-82.

4. INTRODUCTION AND OVERVIEW OF THE CANDIDATE'S ACHIEVEMENTS IN THE DOMAIN

The applicant's contribution to achievements in the domain of „**Single-scattering properties and radiative forcing of non-spherical particles**" consists in the following eight thematic publications.

C1 Remiszewska, J., P. J. Flatau, **K. M. Markowicz**, E. A. Reid, J. S. Reid, and M. L. Witek (2007), Modulation of the aerosol absorption and single-scattering albedo due to synoptic scale and sea breeze circulations: United Arab Emirates experiment perspective, *Journal of Geophysical Research*, 112, D05204, doi:10.1029/2006JD007139.

C2 **Markowicz, K.M.**, P.J. Flatau, J. Remiszewska, M. Witek, E.A. Reid, J.S. Reid, A. Bucholtz, and B. Holben, 2008: Observations and Modeling of the Surface Aerosol Radiative Forcing during UAE^2, *Journal of the Atmospheric Sciences*, 65, 2877–2891.

C3 **Markowicz, K. M**., P.J. Flatau, A.E. Kardas, J. Remiszewska, K. Stelmaszczyk, and L. Woeste, 2008: Ceilometer Retrieval of the Boundary Layer Vertical Aerosol Extinction Structure. *Journal of Atmospheric and Oceanic Technology*, 25, 928–944.

C4 Kardas, A. E., **K. M. Markowicz**, K. Stelmaszczyk, G. Karasinski, S.P. Malinowski, L. Woeste, C. Hochhertz, 2010: Saharan aerosol sensed over Warsaw by depolarization lidar, *Optica Applicata*, 40, 219-237

C5 **Markowicz, K. M.**, T Zielinski, S. Blindheim, M. Gausa, A. K. Jagodnicka, A. Kardas, W. Kumala, S. P. Malinowski, T. Petelski, M. Posyniak, T. Stacewicz (2011), Study of vertical structure of aerosol optical properties by sun photometers and ceilometer during macron campaign in 2007, *Acta Geophysica, in press*.

C6 **Markowicz, K.M.** ,T. Zielinski, A. Pietruczuk, M. Posyniak, O. Zawadzka, P. Makuch, I.S. Stachlewska, A.K. Jagodnicka, T. Petelski, W. Kumala, P. Sobolewski, T. Stacewicz, Remote sensing measurements of the volcanic ash plume over Poland in April 2010, *Atmospheric Environment*, In Press, 10.1016/j.atmosenv.2011.07.015.

C7 **Markowicz, K. M**., and M. L. Witek (2011), Simulations of Contrail Optical Properties and Radiative Forcing for Various Crystal Shapes, *Journal of Applied Meteorology and Climatology*, *50*(8), 1740-1755.

C8 **Markowicz, K. M**., M. Witek, Sensitivity study of the global contrails radiative forcing due to particle shape. *Journal of Geophysical Research*, doi:10.1029/2011JD016345, in press.

The articles have been written to a large extent by the applicant himself or with some cooperation or supervision. Therefore, the applicant would like to emphasize the role of the co-authors, which has been considerable, and the collaboration, which is of great value. The scientific input of every co-author is specified in a separate certificate attached to this application. The articles describe results of the study of the single-scattering properties and the radiative forcing of non-spherical particles in the atmosphere. The series of publications includes the analysis of optical properties based on the performed measurements and numerical simulations. In addition, it describes methods that can be used to determine optical properties on the basis of in-situ measurements and remote sensing observations. Two papers deal with contrails and the remaining ones are related to the atmospheric aerosol.

Non-spherical particles, being the theme of this series of publications, occur as a specific types of atmospheric aerosols and ice crystals. Non-spherical aerosols, in the vast majority, are of natural origin: they are emitted during volcanic eruptions, and lifted from the surface of deserts during strong winds. These are not the only examples of non-spherical aerosols since, in the atmosphere, particles of anthropogenic origin may become coagulated with natural aerosol, which leads to formation of particles of complex geometric structure. Non-spherical ice crystals occur mainly in the clouds and contrails.

For many years scientists have been of great interest in the role of aerosols, natural clouds, and contrails in the climate system. Despite the undoubted progress in understanding physical processes involving aerosols and clouds, the current state of knowledge on their effects on observed climate change leaves much to be desired. According to the IPCC[1] report, the effect of aerosols and clouds on radiation equilibrium is one of the most important sources of uncertainties in predicting climate changes. In large part, this is due to insufficient knowledge on scattering and absorption processes by non-spherical particles. While, in the case of spherical particles, modeling optical properties based on the Lorenz-Mie[2] theory gives the intended results, lack of effective method for solving scattering of non-spherical particles and observational difficulties with estimating the shape of the particles has been a serious problem in radiative transfer studies so far. The methods currently used to solve scattering problems of non-spherical particles are constructed for specific shapes, such as the T-matrix[3]

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[1] Intergovernmental Panel on Climate Change (2007), The physical science basis: working group I contribution to the Fourth Assessment Report of the IPCC, *Cambridge University Press*, London.

[2] Bohren, C. F. and D. R. Huffmann (1983), Absorption and scattering of light by small particles. *Wiley-Interscience*, New York.

[3] Mishchenko M.I., Travis L.D., Capabilities and limitations of a current FORTRAN implementation of the T-matrix method for randomly oriented rotationally symmetric scatterers, Journal of Quantitative Spectroscopy and Radiative Transfer 60(3), 1998, pp. 309–324.

for rotating spheroids. They are also very computationally expensive methods that can be applied to any geometry, such as Finite-Difference Time Domain (FDTD)[4] or the Discrete Dipole Approximation (DDA)[5], especially in the case of calculating the single-scattering properties of particles with different spatial orientations. Although these exact methods are efficient for calculation of the optical properties of particles with small size parameters, they are impractical and computationally inefficient for large size parameters (larger than 20). This means that determination of optical properties for particles with an effective radius greater than 1 μm, is much more difficult in the visible range. While, in the case of non-spherical aerosols whose sizes do not generally exceed 10 μm, the use of FDTD method or the DDA is still possible, the use of such methods for ice crystals, which often reach sizes of 100 μm, is not possible. In practice, the most effective approach to deriving the solution to light scattering by ice particles over a large size parameter range is a geometric optics approximation for moderate-to-large sized particles (at least 100). Thus, in the middle infrared range (3-7 μm) we do not have any method that would let us effectively set optical properties of large ice crystals. As a result, the optical properties of contrails are determined on the basis of inconsistent assumptions. Identifying optical properties of crystals in a longwave range, it is assumed that they are spherical in shape. The same crystals for the needs of shortwave calculations have a shape of hexagonal plates or columns. Lack of studies on optical properties of contrails of ice crystals and significant simplification of parameterization of their optical properties have become one of the main motivations of my research.

Another motivation were insufficient quantity and quality measurements which largely decide on large uncertainties of non-spherical particle impact on the climate, which results, among others, from the methods of observation themselves being mostly remote sensing measurements. Determination of physical properties of spherical and non-spherical particles requires in this case the use of so-called inverse methods. Inverse problems in atmospheric remote sensing are often ill-conditioned, which often makes it impossible to obtain a unique solution. Significant improvement in this state can be achieved through synergy of measurement data from different instruments covering research methods in-situ and remote techniques. Additionally, this type of method used to process the measurement data allow the

[4] Yang P, Liou KN. Finite-time domain method for light scattering by small ice crystals in three-dimensional space. J Opt Soc Am A 1996;13:2072–85

[5] Purcell, E.M. and C. R. Pennypacker. Scattering and absorption of light by nonspherical dielectric grains. Astrophysical Journal, 186:705, 1973.

estimation of others (non-optical) physical quantities such as parameters describing particle shape and particle size distributions. Observational problems associated with non-spherical particles also apply to in-situ measurements. In this case, instruments are usually calibrated taking into account only spherical particles. For example, the scattering factor correction for integrating nephelometer, resulting from the lack of technical detection of diffuse radiation in certain directions, is limited only to spherical aerosols.

Due to inhomogeneous temporal and spatial variability of aerosols sources, the study of aerosol effects on climate requires well-developed monitoring system. Despite the development of surface measuring networks and satellite methods observed in recent years, the amount of gathered data turns out to be not sufficient. The situation in April 2010 when a volcanic ash cloud appeared over Europe proves it emphatically. Decisions to close the airspace over Europe were taken solely on the basis of results from very inaccurate transport models. In the presented series of publications, the use of existing and operationally acting ceilometers (simple lidars to observe clouds) for monitoring of the aerosol optical properties have been suggested. It is shown that this type of equipment is a good source of qualitative data of the aerosol optical properties and its incorporation into the appropriate measurement networks would allow low input extension of atmospheric aerosol monitoring.

The monothematic cycle of the publication pertains to the role of aerosols and contrails. The role of natural clouds containing non-spherical ice crystals has been omitted. However, optical properties of ice crystals obtained from numerical simulations can be also used to describe the single-scattering properties of Cirrus clouds containing ice crystals with a length that does not exceed ~ 100 μm. Although the role of high natural clouds in the climate system is important, the current state of knowledge cannot clearly identify whether there has recently been a trend of the degree of cloudiness or other parameter describing optical properties of clouds. Thus, we do not know if the high clouds radiative forcing (relative to the reference period) has a nonzero value. The situation is further complicated by the effects of contrails on natural clouds. Contrails develop in the atmosphere only in conditions (sufficiently low temperatures and high relative humidity) which favor the formation of high clouds. This aspect has not been studied in this series of publications. The situation is otherwise with contrails, whose presence in the atmosphere leads to a positive anthropogenic radiative forcing. The development of air transport observed in recent years has contributed to the growth of the contrails cover and the radiative forcing.

A brief description of the publications presented below does not intend to become its summary, but rather aims at pointing the importance of a specific work.

C1 Remiszewska, J., P. J. Flatau, **K. M. Markowicz**, E. A. Reid, J. S. Reid, and M. L. Witek (2007), Modulation of the aerosol absorption and single-scattering albedo due to synoptic scale and sea breeze circulations: United Arab Emirates experiment perspective, *Journal of Geophysical Research*, 112, D05204, doi:10.1029/2006JD007139.

This paper uses a new method for determining the aerosol single-scattering albedo based on simultaneous measurements of multichannel aethalometer and nephelometer. The main problem in these types of measurements is determination of light scattering by aerosols deposed on an aethalometer filter. Using a two-layers model (aerosol plus filter), the single-scattering properties are determined. This method was applied to the data obtained during the United Arab Emirates Unified Aerosol Experiment (UAE^2). The results of monthly measurements documented a significant impact on synoptic scale and land-sea breeze circulation on the single-scattering properties. The variability of the aerosol optical properties is a result of changes in aerosol transport processes, aerosol emission and deposition near the ocean surface. Showing, among other, that the highest aerosol absorption coefficients occur at night and in the morning hours. After the change of circulation (in the morning), aerosol shows significantly lower absorption coefficient.

C2 **Markowicz, K.M.**, P.J. Flatau, J. Remiszewska, M. Witek, E.A. Reid, J.S. Reid, A. Bucholtz, and B. Holben, 2008: Observations and Modeling of the Surface Aerosol Radiative Forcing during UAE^2, *Journal of the Atmospheric Sciences*, 65, 2877–2891.

The paper presents the study of variation of the direct aerosol radiative forcing in the Persian Gulf region during the UAE^2 experiment. It has been shown that the land-sea breeze circulation modulates diurnal variability of the aerosol properties and the aerosol radiative forcing. We found an increase of the aerosol forcing efficiency during the land breeze. On the basis of model calculations and observed diurnal variability of the aerosol forcing efficiency, we show that its change is due to a reduction of the single scattering albedo and an increase of the asymmetry parameter during the land breeze. It is related to transport of mineral dust which has low absorption coefficient and of highly absorbing anthropogenic aerosols emitted from nearby oil wells. Aerosol particles lead to a significant reduction of the incoming solar radiation at the surface (about 9%). Obtained values of the aerosol direct radiative forcing show that aerosol significantly influences the local radiative budget, partially because we observed mostly clear-sky conditions (85%). The results indicate a relatively small value of the aerosol forcing efficiency at the surface (-53 W/m^2, compared to values obtained in other heavily polluted areas in the world.), although the single-scattering albedo at 550 nm is not very high (0.92 on the basis of surface in-situ observation, and 0.93 on the basis AERONET retrieval). The reason for this is a large average optical thickness (0.45 to 500 nm) and the nonlinear dependence of the radiative forcing and the aerosol optical thickness.

C3 **Markowicz, K. M**., P.J. Flatau, A.E. Kardas, J. Remiszewska, K. Stelmaszczyk, and L. Woeste, 2008: Ceilometer Retrieval of the Boundary Layer Vertical Aerosol Extinction Structure. *Journal of Atmospheric and Oceanic Technology*, 25, 928–944.

In this paper we describe a new method used to determine profile of the aerosol extinction coefficient based on the synergy of measurements performed with a ceilometer and a sun ceilometer or aethalometer and nephelometer. The ceilometer is a general-purpose cloud height sensor employing lidar technology for detection of clouds. On the basis of two international research experiments, we discovered that ceilometer can also be used to retrieve the aerosol optical properties in the boundary layer and in the middle troposphere at night (e.g. desert dust or volcanic).

The main limitation to use the CT25K (Vaisala) ceilometer to retrieve the aerosol optical properties is laser wavelength (around 905 nm) located near the water vapor absorption band. Therefore, we suggested a method of correcting the ceilometer signal based on water vapor profile from radio sounding. As compared with the field measurements during the UAE^2 experiment, it has been shown that an assumption about specific particle shape is important for the extinction profile inversions. The authors indicate that this limitation of detection is a result of the relatively small sensitivity of this instrument in comparison to more sophisticated aerosol lidars. However, in many cases this does not play a significant role because globally only about 20% of the aerosol optical depth is above the boundary layer.

C4 Kardas, A. E., **K. M. Markowicz**, K. Stelmaszczyk, G. Karasinski, S.P. Malinowski, L. Woeste, C. Hochhertz, 2010: Saharan aerosol sensed over Warsaw by depolarization lidar, *Optica Applicata*, 40, 219-237

The paper contains an analysis of optical properties of Saharan dust observed over Warsaw on 13 and 14 April 2005 during the SAWA experiment (Saharan Dust over Warsaw). We proposed a new method for determining the aerosol extinction coefficient profiles based on the division of the troposphere into three or four layers. Within each of these the lidar ratio is constant but can vary between layers. The lidar ratio for each layers is computed from adjusting the aerosol optical thickness (from sun photometer) to lidar signal. This method improved the standard Klett-Fernalda Sasano technique which assumes constant the lidar ratio with the altitude. In case of mineral dust event in the middle troposphere, using classical technique leads to larger uncertainties because dust particles usually have substantially different optical properties than particles in the boundary layer.

Having calculated vertical distributions of the aerosol extinction coefficients, profiles of the local Ångstrom exponent were estimated. Independent information on depolarisation of 532 nm lidar returns, together with the assumption about the spheroidal shape and random orientation of aerosol particles, allowed to estimate the aspect ratio and size of particles on the basis of numerical calculations with transition matrix (T-matrix) algorithm by M. Mishchenko. The results indicate the mode radii of spheroids in the range of 0.15–0.3 μm, and their aspect ratio in the range of 0.6–0.8 or 1.3–2.2 (two solutions are allowed). A small size of the particles is explained by dust deposition and mixing with boundary layer aerosol in the Mediterranean region.

C5 **Markowicz, K. M.**, T Zielinski, S. Blindheim, M. Gausa, A. K. Jagodnicka, A. Kardas, W. Kumala, S. P. Malinowski, T. Petelski, M. Posyniak, T. Stacewicz (2011), Study of vertical structure of aerosol optical properties by sun photometers and ceilometer during macron campaign in 2007, *Acta Geophysica*, *in press*.

In this paper we discuss the results of the measurements of the aerosol optical properties carried out during a three-week long field campaign (MACRON) which took place in July and August 2007 in the area of ALOMAR observatory in the northern Norway. A significant large value of the aerosol optical depth for the Arctic region (exceeding 0.4 at 500 nm) was observed on 7 and 8 August 2007. The analyses of ceilometer signals supported by the transport model NAAPS (Navy Aerosol Analysis and Prediction System) and by the back trajectory HYSPLIT model showed transport of Saharan dust and sulfates from Western Europe between 1 and 3 km above the sea level. During this event the extinction coefficient reached 0.05-0.08 km^{-1} (1064 nm) at around 1.5 km a.s.l. We found significant difference in the aerosol volume size distribution defined in atmospheric column from the sea level up to the top of the atmosphere and in the lower PBL between the sea level and 380 m a.s.l. The lower atmosphere was dominated by the coarse mode particles while the columnar size distribution by the fine aerosols. A significant difference between the aerosol optical properties was observed during the marine aerosol cases (4 and 11 August 2007). The effective particle radius in the lower PBL (0-380 m) estimated from the sun photometer retrieval varied from 0.4 to 1.7 μm while the columnar effective radius changed from 0.17 to 0.27 μm. The ceilometer backscatter signals in the PBL showed the presence of sea salt particles during these days. The extinction coefficient in the lower PBL obtained from ceilometer and sun photometer measurements varied between 0.02 and 0.04 km^{-1} (at 1064 nm). The atmosphere above the PBL was relatively clean with the aerosol extinction coefficient less than 0.01 km^{-1} (1064 nm). In this paper we present a method to retrieve the single-scattering albedo from the Microtops sun photometer and the Particle Soot Absorption Photometer (PSAP) observation. In the case of the Microtops, the measurements carried out at different altitudes between the seal level and 380 m allow to estimate the extinction coefficient. The stationary observation by PSAP allows to compute the aerosol absorption coefficient. Retrieved the single-scattering albedo was a few percent lower during long term transport when compared to the typical marine air masses.

C6 **Markowicz, K.M.** ,T. Zielinski, A. Pietruczuk, M. Posyniak, O. Zawadzka, P. Makuch, I.S. Stachlewska, A.K. Jagodnicka, T. Petelski, W. Kumala, P. Sobolewski, T. Stacewicz, Remote sensing measurements of the volcanic ash plume over Poland in April 2010, *Atmospheric Environment*, In Press, 10.1016/j.atmosenv.2011.07.015.

The paper provides information on selected optical parameters related to volcanic ash emitted during the eruption of the Eyjafjöll volcano in Iceland in April 2010. The observations were made at four stations representative for northern (Sopot), central (Warsaw, Belsk) and south-eastern (Strzyzow) regions of Poland. The largest ash plume (in terms of the aerosol optical thickness) over Poland was observed at night of 16/17 April 2010 in the layer between 4 and 5.5 km a.s.l. The highest values of the aerosol extinction coefficient reached 0.06-0.08 km^{-1} at 532 nm. The corresponding optical thickness due to volcanic ash reached values of about 0.05 at 532 nm and about 0.03 at 1064 nm. The estimated ash mass concentration based on the maximum aerosol extinction coefficient reached 0.22±0.11 mg/m^3. This value is significantly lower than the limit (2 mg/m^3) for aircraft operations. In this paper we critically referred to a previous study (Ansmann et al., 2010) published in the Geophysical Research Letters. Ansmann et al., use wrong methodology during processing lidar and sun photometer data from a Leipzig station. The published results were obtained on the basis of AERONET not cloud-screened data from the so-called 1.0 level. Therefore, the reported aerosol optical thickness at 500 nm was very large (around 1.0) as well as the ash optical thickness which was about 0.7. However, when the AERONET published their final data product (lev. 2.0), the values of the aerosol optical thickness were similar to our results from the Polish territory.
The indication is obvious that clouds interrupted the measurements and Ansmann et al. did not eliminate cloud contamination in the sun photometer and the lidar data.

C7 **Markowicz, K. M**., and M. L. Witek (2011), Simulations of Contrail Optical Properties and Radiative Forcing for Various Crystal Shapes, *Journal of Applied Meteorology and Climatology*, *50*(8), 1740-1755.

The aim of this study is to investigate the sensitivity of the radiative forcing computations to various contrail crystal shape models. The contrail optical properties in shortwave and longwave ranges are derived using a ray-tracing geometric method and a discrete dipole approximation method, respectively. Both methods present good correspondence of the single-scattering albedo and the asymmetry parameter in a transition range (3–8 mm).
We found substantial differences in the single-scattering properties among 10 crystal models investigated here (e.g., hexagonal columns and plates with different aspect ratios, and spherical particles). The single-scattering albedo and the asymmetry parameter both vary by up to 0.1 among various crystal shapes. The computed the single-scattering properties are incorporated in the radiative transfer code to simulate solar and infrared fluxes at the top of the atmosphere. Particle shapes have a strong impact on the contrail radiative forcing in both shortwave and longwave ranges. The differences in the net radiative forcing among optical models reach 50% with respect to the mean model value. The observations of ice crystals during the contrails growth show their shape evolutions. Young contrails consist of crystal shape close to spherical, while contrails in the later phase are dominated by hexagonal crystals. Therefore, commonly used simplification of parameterization of optical properties of contrails is not realistic and lead to significant errors when calculating the radiative forcing.

C8 **Markowicz, K. M**., M. Witek, Sensitivity study of the global contrails radiative forcing due to particle shape. *Journal of Geophysical Research*, doi:10.1029/2011JD016345, in press.

This publication is the second part of the article [C7] and deals with the estimation of the contrail radiative forcing globally. In the first part we focused on local effect of the contrail radiative forcing for selected sun positions, surface albedo etc. In this paper we used the off-line model to simulate the global contrail radiative forcing. The effect of the ice crystals shape, optical thickness, the occurrence of contrail altitude, and natural clouds on radiative forcing are discussed. The knowledge of the first two parameters is weak due to a small number of observations. Model simulations show a 27% difference in the radiative forcing related to a change of the contrail optical depth by ±0.1 from the reference value of 0.3 (at

550 nm). This value is almost invariant to the choice of crystal model, ranging between 25 and 28%. A ratio of the radiative forcing standard deviation to the mean value, derived using 10 different ice particle models, is about 0.2 for the shortwave, 0.14 for the longwave, and 0.23 for the net radiation. We found out that the background cloudiness has a small effect on the global and the annual mean contrail radiative forcing die to the strong cancellation of the LW and SW of the radiative forcing. However, this is quite an accidental result due to the value of the contrail optical thickness and the vertical distribution of cloudiness. In a region where low or high cloud dominated, the natural cloud effect is not as well balanced. The average global contrail radiative forcing estimated on the basis of the simulation was 11.1 ± 2.1 mW/m^2. This value is relatively small, especially when compared to the maximum radiative forcing, which in some areas of the United States or Western Europe can reach 300-400 mW/m^2.

Warsaw, 1 December 2011

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