

Research Grant Proposal to the Deutsche Forschungsgemeinschaft (New Proposal)

1. General Information

1.1 Principal investigators

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1.2 Research topic

Regional Modeling of the Saharan Dust Cycle

1.3 Keyword

Dust aerosol modeling

1.4 Subject area and research themes

Subject area: Atmospheric sciences

Research themes: Tracer transport, radiative transfer, mesoscale modeling

1.5 Estimated duration of the project

3 years + 3 years extension

1.6 Funding period

2004-2006, anticipated second phase: 2007-2009

This proposal is part of the research group proposal “Saharan Mineral dUst experiMent” (SAMUM)

Summary

The core of this project is the development of a physically based predictive mesoscale model system of the northern African dust cycle by integrating and adapting several existing and newly developed sub-models describing various aspects of dust emission, transport and deposition to simulate the spatial and temporary evolution of northern African dust properties. In addition, we will evaluate atmospheric response to the radiative forcing by Saharan dust, and simulate the influence of long-range transported African dust on cloud microphysics by accompanying Lagrangian process studies. Northern Africa is the major source of dust emissions under modern climate conditions. As part of the Research Group “SAharan Mineral dUst experiMent” SAMUM the project will capitalize on the planned field campaign, which will provide extensive datasets to validate and constrain the dust model. It is necessary to develop a fully mechanistic model in order to be able to predict future changes in the northern African dust cycle, which could, e.g., impact on the radiative budget and hence climate of Mediterranean Europe. However, as part of our model validation strategy, we will make simulations in which key components (e.g., source areas, vegetation cover) are prescribed using satellite derived and field derived data. This will enable us to determine how well individual components are simulated and provide guidelines for further model development. We will explore how the lessons learned in this modeling exercise can be reapplied in global models through extensive sensitivity tests examining methods of parameterizing small-scale variability in inputs and processes. An important issue of the project is the performance of process studies on the influence of long-range transported Saharan dust on atmospheric radiation and microphysics.

2. Status of Science, Expertise of the Participants

2.1 Status of science

Soil derived mineral dust contributes significantly to the global aerosol load and is suspected to impact the climate system by changing the energy balance of solar and thermal radiation (IPCC 2001). Radiative forcing by soil dust aerosol is complex, since dust not only scatters but also partly absorbs incoming solar radiation, and also absorbs and emits outgoing longwave radiation ('greenhouse effect'). Any changes in atmospheric dust loads would cause a change in the radiation balance, and consequentially, surface temperatures as well as atmospheric dynamics. The magnitude and even the sign of the dust forcing depends on the optical properties of the dust (which in turn depend on their size, shape, and refractive indices), on the vertical distribution of the dust, on the presence of clouds, and on the albedo of the underlying surface (Tegen et al., 1996, Sokolik and Toon, 1996, Liao and Seinfeld,

1998, Claquin et al., 2002). Dust can also influence the climate indirectly in several ways. The presence of dust may alter cloud optical properties, by increasing the number of cloud condensation nuclei (CCN) (Rosenfeld et al., 2001), or decreasing CCN through adsorption of sulfate particles (Levin et al., 1996, Zhang and Carmichael, 1999, Wurzler et al., 2000). Dust particles can potentially change chemical reactions in the atmosphere because of their large surface and may therefore have a significant impact on the ozone and nitrogen cycles (Dentener et al., 1996). Micronutrients (e.g., Fe) deposited with aeolian dust impact on the productivity of marine (Martin, 1991, Coale et al., 1996, Hutchins and Brunland, 1998) and terrestrial (Swap et al., 1992, Chadwick et al., 1999) ecosystems, thus influencing the carbon cycle and potentially changing the atmospheric greenhouse gas content.

A prerequisite for estimating the various effects and interactions of dust and climate is the quantification of atmospheric dust loads and physical and chemical properties of the dust particles. Large-scale dust distributions can be inferred from satellite retrievals, although these retrieval-based estimates so far are mostly qualitative because of uncertainties in the a-priori assumptions that have to be made about aerosol optical properties (King et al., 1999). On the other hand, the limited number of existing in-situ measurements of dust properties is insufficient to constrain estimates of dust, since airborne dust is highly variable in space and time. Therefore, dust distributions, which are being used in assessments of the effect of dust on global or regional climate, are usually estimated with dust cycle models, which predict dust emissions, transport within the atmosphere, and deposition. These models must be validated with available in-situ observations and/or remotely sensed aerosol products.

While global scale models are needed to evaluate the effects of dust on global climate, they are of limited use for investigation of regional scale processes (in particular for processes close to source regions) since the horizontal resolution of typically 3 to 5 degree and simplified emission and deposition parameterizations are too crude to compare to observations of small scale dust processes. A number of models have been developed to describe dust emissions, transport and deposition for the Sahara (Westphal et al., 1988, Nickovic and Dobricic, 1996, Marticorena et al., 1997, Guelle et al., 2000, Colarco et al., 2003), which is globally the most important dust source region. Such regional-scale models are well suited for simulation of individual dust storm events or for comparisons with in-situ observations made during field experiments. Improvements in the parameterization of dust processes that are obtained by such regional model investigations can help to improve parameterizations in global scale models, which is one of the aims of this project. Results of regional models can be used for subgridscale parameterization of global models. On the other hand, the results from such regional dust model can be used for improving remotely sensed aerosol data products by providing estimates about the refractive indices, shapes and size distribution of the dust aerosol particles. To understand the influence of dust aerosols on cloud development in-situ-measurements of aerosol size distributions, spaceborne cloud and aerosol observations and multiscale model studies on the activation of cloud droplets using sophisticated process are necessary.

While the topography, soil conditions and small-scale extreme wind events are described better in regional than in global models, there are still large uncertainties in describing the dust source area, the surface conditions in the source area, and changes in size distribution and chemical composition during transport, because observational data of dust transport and deposition are insufficient to fully validate dust models. In particular very few measurements of dust vertical distributions exist, which is important for studying dust transport mechanisms on one hand, and its radiative effect on the other hand (Tegen and Lacis, 1996, Claquin et al., 1998, Liao and Seinfeld, 1998, Myhre and Stordahl, 2001). Key parameters to describe the dust cycle and the effect of dust on climate are size and mineral composition of the particles. Though Claquin et al. (1999) proposed a scheme to relate soil type in dust source regions to their mineralogy and thus their refractive indices (Sokolik and Toon, 1999), their results are limited by data. Recent field studies like the PRIDE (Reid et al., in press) and SHADE (Tanre

et al., in press) experiments have improved our knowledge of radiative properties of dust aerosols that have traveled several thousand kilometers from the source regions. However, to estimate dust effects and feedbacks in proximity to source areas, investigate changes of dust properties during transport, and improve dust emission parameterizations, investigations in closer proximity to source areas are urgently needed.

2.2 Expertise of the participants

2.2.1 Experience and expertise

BGC-Jena

The Max-Planck-Institute for Biogeochemistry (BGC) in Jena is a new interdisciplinary research institute of the German Max-Planck-Society, founded in 1997. Its research mission is the investigation of the global biogeochemical cycles and their multiple interactions with the climate system. The institute combines global scale modeling (e.g., vegetation dynamics, carbon cycle, aerosol modeling), observational and process-based studies (e.g., ecosystem dynamics, biospheric flux measurements), and data integration (e.g., satellite observations, palaeoenvironmental databases). The group headed by Prof. Sandy Harrison has pioneered the application of land-surface models to determine size-resolved dust emissions as a function of vegetation cover and the occurrence of preferential source areas (Mahowald et al. 1999, Tegen et al. 2002) and has produced the first plausible simulations of the impact of changes in atmospheric dust loading at the last glacial maximum on radiative forcing and the carbon cycle (Claquin et al. 2002, Bopp et al. (2002)).

The principal investigator for this project is Dr. Ina Tegen. Dr. Tegen is a senior scientist at the MPI-BGC. She is a physicist, specialized in the interactions of aerosols and climate. In particular, she has pioneered the model-based analysis of the role of dust (both natural and anthropogenic) on the earth's radiative budget (Tegen and Fung 1995, Tegen et al. 1996) and its influence on surface climates (Miller and Tegen 1998). She was responsible for the first parameterization of dust as a dynamic and radiatively interactive tracer in a GCM (Tegen and Miller 1998, Perlwitz et al. 2001), and has recently spearheaded the development of a new global dust source scheme relating dust emissions to vegetation phenology and the geomorphology of dust source regions (Tegen et al., 2002). So far, the newly developed dust model has been used at BGC to simulate the dust cycle at the last glacial maximum (Werner et al, 2002), re-evaluate the contribution of dust from anthropogenically disturbed soils to the global dust load and estimate future changes in dust emissions (Tegen et al., submitted). The dust emission scheme is also being implemented and tested into the ECHAM5 GCM. This scheme will be used and further refined in for the regional/mesoscale application of computing dust emission in the Sahara.

IfT-Leipzig

The modeling group of the Institute for Tropospheric Research (IfT) is experienced in multiscale atmospheric modeling of air pollution, aerosol dynamics, cloud microphysics, and turbulence-aerosol interactions using Eulerian and Lagrangian models of different complexity.

a) Mesoscale modelling

The MultiScale Chemistry Aerosol Transport Model MUSCAT, to be applied here, has been developed by Knoth and Wolke (1998a), staff members of the modeling group of IfT. This model has been online-coupled with the non-hydrostatic model METRAS (Schlünzen et al., 1996), and with the Lokal-Modell (LM) of the DWD, acting as meteorological drivers for transport processes. The forecast system has been used to study the influence of specific emitting groups in Saxony and neighboring areas on the air pollution.

Short-term simulation studies have been performed concerning air quality and the optimization of emission reduction in Saxony and in the Black Triangle area. Detailed emission inventories have been created in close cooperation with the "Sächsisches Landesamt für Umwelt und Geologie" and other cooperating partners.

The enhanced IfT model system LM-MUSCAT has been used for long-term air quality simulations of ozone and particulate matter within in the European model intercomparison study CityDelta, initiated by the JRC. In this project, the model has been evaluated with respect to the predictability of ozone and particulate matter (Benz, 2003).

The investigation of aerosol dynamical processes in the atmosphere is one of the main research interests at the IfT Leipzig. For their numerical description the model hierarchy MADMacS has been developed (Wilck and Stratmann, 1996, 1997). Particle size distribution and aerosol dynamical processes are described using the modal technique. The model MADMacS I, where the mass fractions of all particles are assumed to be identical within one mode, has already been included in MUSCAT. In the first mesoscale applications, transport has been considered as well as coagulation, deposition, and sedimentation.

b) Cloud process modeling

For process studies in a box and/ or for Lagrangian simulation studies an air parcel model has been developed for the description of cloud processes. The performance of the model was shown for simple chemical mechanisms (with only inorganic chemistry) as well as for very complex mechanisms of the CAPRAM family (Herrmann et al.), which contain a detailed description of the carbonaceous chemistry. The model is evaluated with data from the FEBUKO¹ field campaign.

c) Modeling of aerosol-turbulence interactions

Further project relevant experiences concern the development of parameterization methods to consider the influence of subgrid-scale turbulence on the development of the mixing height, grid-scale gas-to-particle conversion (nucleation), and the determination of turbulence-length scales for application in meso- and large-scale models (Hellmuth and Renner, 2000; Hellmuth and Renner, 2001; Hellmuth and Helmert, 2001a,b, Helmert and Hellmuth 2003).

To investigate the influence of aerosol-turbulence interactions on aerosol dynamics the model TOPCAM (Third-Order Planetary Boundary Layer-Chemistry-Aerosol Model, Hellmuth, 2003) has been developed. The model is suitable for process studies on the vertical exchange of aerosols between the PBL and the Free Troposphere (FT).

2.2.2 Description of available models and model components

The model system LM-MUSCAT to be used here will be supplemented with a state-of-the-art dust emission module based on a dust emission scheme available at BGC to provide dust

¹ http://projects.tropos.de:8088/afo2000g3/FEBUKO_dateien/febuko.html

fluxes. The model system will be run with a grid resolution of 7.5 km for the northern African model domain. In the following, a description of the existing model components is given:

BIOME4 (Biogeography model, available at BGC)

The equilibrium terrestrial biogeography model BIOME4 (Kaplan, 2001) is used to determine the distribution of vegetation types (biomes). It predicts the distribution of 27 biomes (including 10 non-forest biomes which are potential dust sources) as a function of monthly mean temperature, precipitation, net radiation and soil type. The model currently works on a 0.5 degree grid but will be downscaled to the resolution of the regional model.

Dust emissions from these biomes are possible under the condition of low vegetation and dryness. An effective area of dust emission within a model grid cell is determined on the base of a combination of a satellite-based and a model-based approach. NDVI data from the AVHRR satellite instrument have been used to parameterize the seasonal and interannual changes in vegetation cover. These parameters are used in combination with BIOME4-based predictions of the relative coverage of shrub and grass vegetation for each biome type to estimate the effective surface for dust emissions (Tegen et al., 2002). A vegetation phenology model (Werner et al., 2002) is used to predict daily changes in vegetation cover. This scheme predicts the timing of vegetation growth by a combination of temperature, soil moisture and day length.

HYDRA (Water routing and storage model, available at BGC)

In those areas where the phenology model predicts potential dust areas, a high-resolution water routing and storage model (HYDRA: Coe, 1998) will be used to specify the location and extend of preferential dust source regions, such as dry lake beds. HYDRA uses land surface topography at 5' resolution to determine the location and extent of lakes and wetlands as a function of runoff, precipitation, and surface evaporation. Assuming that high precipitation occurred during past wetter climate periods, the potential maximum spatial extent of former lakes has been estimated.

The difference between the simulated maximum areas of lakes and their actual present day values, predicted on the base of actual precipitation, indicate the extent of paleo-lake deposit formed under wetter climate conditions at some time in the recent geological past. These exposed paleo-lake areas are considered to be preferential source areas for dust emission, and are initially assumed to consist of silt-sized clay aggregates, which can be easily deflated. In these areas the soil size distribution from the input data used in the dust emission scheme will be modified.

Dust Emission Scheme (DES) (available at BGC)

The dust emission scheme developed at BGC-Jena (Tegen et al., 2002) is a modified version of the scheme proposed by Marticorena and Bergametti (1995). The DES needs the surface wind stress, surface roughness, soil size distribution, vegetation cover, and soil moisture as input. It considers the influence of surface features to compute the erosion threshold and the intensity of the dust emission. Dry paleo- and temporal lakebeds have been identified as preferential sources for dust emission ('hot spots') because they contain easily deflatable fine sediment. Recently, Zender et al (in press) have shown that the implementation of similar topography-based dust emission schemes into a global dust cycle models results in simulated dust concentrations that agree better with observations than an emission scheme neglecting the regional topography. The model has been applied to compute dust emission at the last glacial maximum (Werner et al., 2002). It has recently been implemented in the ECHAM5 general circulation model (Roeckner et al., 2002), where initial tests of its performance show good agreement with observations (P. Stier, personal communication).

The DES includes the following parameterizations:

(a) Parameterization of the erosion threshold wind friction velocity:

The threshold wind friction velocity above which dust emission takes place is parameterized depending on the soil particle diameter based on Iversen and White (1982). The soil size distribution is assumed to be composed of several size modes (corresponding to clay, silt, small sand and large sand particles), which are derived from the soil texture. Initially either texture distribution from TERRA (see below) or the FAO global soil texture dataset (Zobler, 1996) will be used.

(b) Parameterization of the size-resolved quantity of soil particles mobilized by wind (horizontal flux):

The flux formulation is proposed by White (1979). The vertically integrated horizontal flux represents the total quantity of material in movement in the saltation layer, and depends on the third power of surface wind stress. It accounts for the selective mobilization of the soil particles according to their size.

(c) Parameterization of the size-resolved flux of fine dust particles emitted into the atmosphere (vertical flux): The empirical dust flux parameterization applied here is based on the assumption that the capacity of a soil to release fine particles depends on the texture, and is initially based on wind tunnel measurements by Gillette (1978). If available, the ratio of vertical dust flux to horizontal sand flux will be replaced by new wind tunnel measurements from 'typical' source regions.

Mesoscale atmospheric model (available at IfT)

The LM is the central part of the new Numerical Weather Prediction (NWP) system of the German Weather Service (DWD). It is a non-hydrostatic limited area atmospheric prediction model, based on the primitive thermo-hydrodynamical equations describing compressible flow in a moist atmosphere.

It is designed to predict accurately the evolution of atmospheric flow on scales from 50 m to 50 km. It predicts near-surface weather with emphasis on clouds, precipitation, local wind systems, and on severe weather events such as super-cell thunderstorms, intense mesoscale convective complexes, and prefrontal squall-line storms. The impact of topography on the organization of penetrative convection by, e.g., channeling effects, is represented realistically. For a comprehensive description we refer to the publication by Doms and Schättler (1999).

The atmosphere and the underlying surface in LM are coupled using a stability and roughness-length dependent surface flux formulation, which determines the lower model boundary conditions. The ground temperature and soil moisture, required to specify surface fluxes, are predicted by the soil model TERRA which consists of a set of balance equations describing various thermal and hydrological processes within the soil, as well as exchange processes between plants, ground and air.

Chemistry-transport- and aerosol model (available at IfT)

The Eulerian chemistry-transport-model MUSCAT (MUltiScale Chemistry Aerosol Transport) is based on mass balances, which are described by a system of time-dependent, three-dimensional advection-diffusion-reaction equations. MUSCAT is parallelized and coupled to LM. The coupling scheme simultaneously provides time-averaged wind fields and time-interpolated values of different meteorological fields. Mass is always conserved in this scheme.

MUSCAT has the following specific features (Knoth and Wolke, 1998a):

(a) Multiblock approach:

Different horizontal resolutions can be used within sub domains. This allows a fine resolution for the description of the dispersion in source regions (Mensink, 2000).

(b) Spatial discretization:

The spatial discretization is performed by a mass-conservative finite-volume scheme. For the discretization of the advection terms a third order upwind procedure with additional limiting (Hundsdofer et al., 1995) is used.

(c) IMEX time integration scheme:

Chemical reactions are described by large systems of extremely stiff ordinary differential equations. The time integration is performed using an efficient implicit-explicit method (Wolke and Knoth, 1999; Verwer et al., 1998). Higher order accuracy and stability conditions for this class of IMEX schemes are investigated in Knoth and Wolke (1998b).

(d) Gas phase chemistry:

Several gas phase mechanisms (e.g. RACM, RADM2, CBM IV) have been used successfully in 3D case studies. Time resolved anthropogenic emissions are included in the model.

The multiblock technique combined with IMEX time integration schemes are well suited for the numerical treatment of strong gradients and scale interactions.

For the numerical description of aerosol dynamical processes the model hierarchy MADMAcS (Multicomponent Aerosol Dynamics Modelling - Modal Approach System), developed by Wilck and Stratmann (1996, 1997), has been included in MUSCAT. Primary emitted aerosol particles as well as secondary generated aerosol particles are taken into account. The aerosol dynamical processes are directly coupled to the gas phase via condensation and nucleation processes. The particle size distribution and aerosol dynamical processes are described using the modal technique (Ackermann et al. (1998), Binkowski and Shankar (1995); Wilck and Stratmann (1996, 1997), Whitby and McMurray (1997)) where the particle size distribution is approximated by a small number of distinct particle populations, distinguished by size and/ or chemical composition. The module accounts for coagulation and gas to particle conversion. All processes, are treated explicitly and fully coupled. In the first mesoscale applications, transport has been considered as well as coagulation, deposition, and sedimentation.

Cloud process model (available at IFT)

This Lagrangian model allows a detailed description of the processing of gases and particles shortly before cloud formation, during the cloud lifetime and shortly after cloud evaporation. The consideration of convective, stratiform and orographic clouds is possible depending on the dynamic forcing of the parcel. The cloud process model combines a complex multiphase chemistry with detailed microphysics (SMCCM – Spectral Multiphase Chemistry Cloud Model). External and internal mixing of aerosol can be taken into account. Therefore, drops of the same size can have different gas uptake behavior and condensation growing factors. Either the movement of the air parcel can follow a predefined trajectory or the vertical velocity is calculated based on the parcel updraft compared to prescribed environment conditions. Entrainment and detrainment processes are included in a parameterized form.

The activation of droplets is described explicitly in the microphysical model. The coupling between microphysical and multiphase chemical models provides time-interpolated values of the microphysical parameters. In the multiphase-chemistry module the aqueous phase concentrations are coupled via the gas phase and via microphysical exchange processes of liquid water between different droplet classes. Changes of the chemical aerosol composition by gas scavenging and chemical reactions feed back on the microphysical processes (e.g., water condensation growth rates via changes in surface tension and the Raoult term). The model is highly flexible concerning changes in the chemical mechanism or the replacement of the entire reaction system.

Turbulence-aerosol model TOPCAM (available at IFT)

The model TOPCAM (Third-Order Planetary Boundary Layer-Chemistry-Aerosol Model, Hellmuth, 2003) has been developed to investigate the influence of PBL processes such as shear- and buoyancy driven turbulence, aerosol-turbulence interactions, local emissions, deposition, entrainment, radiation etc. on the time-height evolution of aerosols for a wide

range of atmospheric conditions. It is based on a third-order turbulence closure in a set of meteorological, chemical and aerosol rate equations. To calculate radiation induced diabatic heating/ cooling rates the state-of-the-art radiative transfer model STREAMER (Key, 2001) is used.

The aerosol model is based on prognostic equations for the total number concentration, and the surface area concentration. The model is used to predict first, second and third order moments of meteorological, chemical, and aerosol properties. Higher order moments provide useful information for the specification of the probability density function of highly nonlinear processes, such as nucleation, emission fluxes etc.

3. Objectives and Work Plan

3.1 Objectives

There are three main goals of the modeling project:

1. Development of a regional model of dust emissions, transport and deposition for the northern Sahara suitable for simulation of individual dust events and direct comparison with observations.
2. Computations of the mesoscale space-time distribution of dust properties (including size distribution) for use in radiative transfer calculations and for improving dust parameterizations in global climate models.
3. Quantification of radiative effects from evaluated mesoscale simulations of Saharan dust storm events, and estimation of climate effects of refined dust parameterization.

The present project includes contributions from microscale to large-scale modeling, considering both Eulerian and Lagrangian approaches. The central part of the planned modeling activities is the simulation of northern Saharan dust events using a state-of-the-art mesoscale model system in the context of the SAMUM Saharan field study. Model results will be 4D fields of size-resolved dust concentration that can be used as input fields for radiative transfer calculations, and for interpretation of field measurements. The links to the partners of the research group are described in Table 1.

The link between the mesoscale modeling and the Moroccan field study carried out by other members of the proposed Research Group will be as follows: On one hand, the model system will be extensively evaluated using results of the field campaign in Morocco (and the far-field study in the second phase of the project). On the other hand, the model system will provide additional information for the interpretation of the results of the field experiments, for example, for the estimation of the radiative effects of the dust particles.

The model domain will encompass the Saharan region, including the source regions for aerosols arriving at Morocco. The domain will extend downwind of the African continent to include those areas where observations for model validation will be available, i.e. the Cap Verde and Canary islands. Model validation will be initially by comparison with satellite data, aerosol optical thickness (AOT) data from the sun photometer network AERONET, surface concentration measurements, and deposition measurements. When they become available, an extensive validation is planned using results from the Moroccan field experiments, which will give detailed information about dust microphysical and geochemical properties, vertical distribution of dust and dust optical thickness.

The model strategy is described in greater detail in the Work Plan (Section 3.2). The model especially considers physical processes of entrainment and deposition and includes microphysical and chemical processes affecting mineral dust particles during transport in an adequate manner. Model validation by field measurements of properties of transported dust aerosol will lead to a stepwise improvement of the regional dust model, and thus improve our understanding of the global dust cycle.

Compared to the grid resolution of state-of-the-art large-scale models, the proposed mesoscale dust model can be considered as a “high-resolution model”. Thus, it is an ideal tool to

generate high-resolution data of meteorological fields (wind, temperature, humidity, diffusivity, clouds), aerosol size distributions etc. under preferential dust emission conditions. Together with the planned multisensoral and multitemporary measurements from cooperating project groups these data represents the base for the development of improved parameterizations of subgridscale dust transports and multiscale process studies of the dust radiative effects. Eulerian and Lagrangian process studies of the direct and indirect Saharan dust effect in the mesoscale and large scale and modeling the aerosol-radiation (direct effect) and aerosol-cloud feedback (indirect effect) in the regional model will improve our understanding of the role of dust aerosol in climate. Ultimately the improved dust parameterizations will be applied to the dust model currently implemented and tested within the ECHAM5 general circulation model (Roeckner et al., 2002), which uses the same emission scheme as will be included in the mesoscale modeling system (Werner et al., in prep.). This will allow to explore the impact of Saharan dust forcing on meteorological fields and large scale atmospheric dynamics.

Table 1: Links of the proposed project and the partners of the research group SAMUM

#	Acronym	PI's	Title	Deliverables to partners	Input from partners
1	DLR	Petzold, Ehret, Schumann	Airborne in situ and remote sensing studies on the vertical and areal distribution of microphysical and optical properties of Saharan dust	<ul style="list-style-type: none"> Regional distribution of desert dust from mesoscale models, transformation of aerosol properties during atmospheric transport from mesoscale models 	<ul style="list-style-type: none"> Vertical aerosol profiles up to 11.5 km Aerosol optical thickness (AOT) Optical and microphysical aerosol properties Regional variability of aerosol properties Validation data for atmospheric transport models Input data for an improved representation of aged desert dust layers in models
2	DLR-L	Trautmann, Wendisch, Heintzenberg	Radiative properties of Sahara dust: In-situ aircraft measurements and model calculations	<ul style="list-style-type: none"> First order estimate of dust source regions 	<ul style="list-style-type: none"> Vertical aerosol profiles, Aerosol optical thickness (AOT), optical and microphysical particle properties, spectral surface albedo, vertical profiles of radiative fluxes and meteorological fields as model input/validation
3	J-L	Tegen, Heintzenberg, Renner	Regional modelling of the Saharan dust cycle		
4	L-M	Ansmann, Wiegner	Vertically resolved characterization of Saharan dust based on observations with multiwavelength Raman lidar and multichannel depolarization lidars	<ul style="list-style-type: none"> Modelled dust plumes (air mass transport) for all measurement cases to support interpretation of findings 	<ul style="list-style-type: none"> Vertical profiles of extinction coefficient, Optical and microphysical aerosol properties, Temporal variability of aerosol properties, 4 D dust plume evolutions
5	L-JH/AW	Heintzenberg, Wiedensohler	Aerodynamic, hygroscopic, and optical dust properties	<ul style="list-style-type: none"> 	<ul style="list-style-type: none"> settling properties, hygroscopic growth factors, absorption and scattering coefficients of dust particles
6	MZ-DA	Jaenicke, Schütz, Weinbruch	Physico-chemical parameters of desert aerosols	<ul style="list-style-type: none"> First order estimate of dust source regions for soil sample selection 	<ul style="list-style-type: none"> Size distribution and composition of dust aerosols near-surface and in the boundary layer, measurements of size distribution and composition of soil material, hygroscopicity of dust particles
7	UHB	Burrow, v. Hoyningen-Huene	Dust aerosol Retrieval from spaceborne instruments (DREAMS)	<ul style="list-style-type: none"> Predicted meteorological fields and 4D aerosol distributions from mesoscale modeling as input for computing aerosol radiance fields 	<ul style="list-style-type: none"> Distribution of AOT and TOA radiances over land, and over ocean areas adjacent to the African continent, ground based AOT data, phase function and single scattering albedo

3.2 Work Plan

We propose a three-year project which includes model development, sensitivity studies, extensive model evaluation and validation of the modeled dust distributions, and implementation of improved radiative parameters of dust, as explained in detail below. A second project phase of another three years (years 4-6) is planned, where (1) results from a far-field study will be used to improve model parameterizations and constrain changes in dust properties during transport, (2) a biomass burning parameterization will be included in the mesoscale model system to enhance its performance in the southern Saharan/Sahelian region, and (3) dynamic feedback of predicted 4D dust distributions onto LM radiation and cloud fields (consideration of the direct and indirect effect in LM) will be computed and simulations of the direct effect of Saharan dust on the climate using ECHAM5 will be carried out.

3.2.1. Regional model development

Integration of model components to predict dust emissions

A starting point of the model development will be the integration of the dust emission scheme in to the LM, and the development of versions of the existing models designed to run with higher resolution input data sets. The regional dust model is considered as a collection of different submodels with a process specific interplay between the different components. The model will be run several times for a dust episode with a staggered physical performance:

- (I) In the first step, the model configuration Global Model (GME)/ Lokal Modell (LM) will be run to provide the required hydrological information to setup the emission model:
Forced by the Global Model, which is initialized by making use of the global 4D data assimilation of the operational weather service, the LM will be run to obtain realistic rainfall estimates as an input parameter for the model HYDRA to determine lake levels, and for the vegetation phenology model to determine potential vegetation cover.
- (II) The dust prediction will be performed with the model configuration GME-LM-MUSCAT-DES and the input data provided by the previous step. It will be used to predict the spatio-temporal distribution of dust aerosols as a tracer in a mesoscale model domain.
- (III) Extensive comparison of model results with data from field experiments and satellite measurements will result in improvements of the dust parameterizations as well as point out areas where the input data sets are insufficient to accurately predict dust distributions.

With this approach it is possible to benefit from several very sophisticated submodels and standardized evaluation techniques without the necessity to integrate a full 'supermodel'.

Input datasets of potential dust source areas

To initially determine potential dust source regions we will use the equilibrium vegetation model BIOME4 (Kaplan, 2001) in connection with the vegetation phenology model to predict vegetation-free areas, using meteorological fields and soil texture information provided by LM. In these vegetation-free regions we will perform preliminary identification of 'hot spots' of dust emission by using a model-based determination of dust sources using the water routing and storage model HYDRA. The model HYDRA (Coe, 1998) is currently being used at BGC-Jena to determine the localization of the major (lacustrine) dust sources (Tegen et al, 2002), which have particularly high emission rates in areas of low vegetation. Both BIOME4

and HYDRA will be modified to run under the resolution of the regional model.

In addition, in connection with the project "*Physico-chemical parameters of desert aerosol*" (Jaenicke, Schütz, Weinbruch) we will utilize measurements of dust microphysical properties from samples of the "Mainz Sandbank", which is a collection of 160 soil samples from different desert regions to obtain input data for the dust model. For this purpose we will identify samples from preferential dust source regions, which will be analyzed to obtain size distributions for particles >10 nm, as well as size resolved information about particle shape, dominant mineral groups with emphasis on Fe-containing minerals, together with total absorption by particles. This will on one hand provide updated input information for the DES, and on the other hand provide information on radiative properties of dust from key regions, which will also serve to test previous assumptions on Saharan dust radiative properties.

Parameterization of dry and wet deposition of dust

The aerosol deposition scheme in MUSCAT will be modified for mineral dust particles. For these particles gravitational settling is a major sink. It will be parameterized within LM/MUSACT using a Stokes-Cunningham formulation (e.g. Tegen et al, 2002), in addition to dry deposition by turbulent diffusion. Changes in dust size distribution due to faster settling of larger particles will be computed explicitly. Wet deposition of dust by rainfall will be parameterized with a scavenging ratio, also removal by ice nucleation. The change in dust hygroscopicity by cloud cycling will also be taken into account (Wurzler et al, 2000). When they become available, measurements of aerosol particle hygroscopicity from the Moroccan field study which are planned in the project "*Physico-chemical parameters of desert aerosols*" (Jaenicke, Schütz, Weinbruch) will be used to modify the wet deposition parameterization.

3.2.2 Investigation of the scale dependency of dust emission

One aim of the investigation is a suitable description of surface dust fluxes for both mesoscale and large-scale atmospheric motions. The investigations will be based on multiscale numerical simulations and accompanying field studies. The high resolution of the mesoscale dust model is expected to produce a realistic simulation of Saharan dust events. However, if the same method of computing dust processes is applied in global models, the coarser grid resolution will require the parameterization of subgridscale processes. Especially the non-linearity of the dependency of dust emissions on surface winds, but also on soil and vegetation type, and terrain shape, necessitates including subgridscale variability in large-scale models. Considering the physical features of the emission model as well as the designated grid resolution of 7.5 km, the mesoscale forecast system is capable to provide the required "high resolution" wind data to provide basic data for the development of an improved flux parameterization.

In numerical grid point models considered here, the forecast variables represent spatio-temporal average values over the model integration time step and the grid cell volume. Subgridscale effects, reflected in the occurrence of second- and higher order moments, such as dust emission fluxes, can not be resolved and must be parameterized. In large-scale models, unresolved local dust sources are a part of the physical parameterization. Dust emission flux parameterizations that have been fine-tuned for mesoscale applications must not be inevitably valid for large-scale models.

A virtual grid cell of a large-scale model will be covered by a refined, mesoscale grid to resolve subgridscale emission parameters. On this base, averaged gridscale variables and fluxes will be derived for such a "super grid cell". A flux parameterization valid for the large-scale grid resolution will be established and/ or reexamined. Among others, the portability of the mesoscale dust emission scheme to other scales will be assessed.

The subgridscale dust emission parameterization of the regional model will be verified and

enhanced using TOPCAM. It will also be used for sensitivity studies on the direct effect of aerosols on the PBL dynamic. The comparison with collocated data allows an empirical adjustment of the new dust emission scheme to regional conditions by extrapolation from local findings.

3.2.3 Model evaluation and validation, link to project partners of the Research Group

The regional dust model will be used to compute the spatial and temporal distribution of dust aerosol for the North African model domain for key periods where observational data are available, in particular for the period of the Moroccan field study.

Initial model validation in year 2 will be carried out using:

- TOMS satellite retrievals (absorbing aerosol index from Earth Probe TOMS from the difference between the measured spectral contrast of the 331 and 360 nm wavelength radiances, detection of absorbing aerosols over ocean, evaluation of pattern and timing (Herman et al. 1997))
- Aerosol optical thickness (AOT) data from sun-photometer sites (AERONET: Holben et al., 1998), 4 sites (Izana, Tenerife, El Arenosillo, and Kolimbari) with quality assured optical thickness measurements are available downwind of source regions of the model domain. Such sun-photometer data give an upper limit for dust optical thickness (contribution of other aerosol species (e.g., sea salt particles, sulfates) can be expected to contribute to the AOT).
- Surface concentration (climatological) from remote surface sites (Izana, Bermuda, Miami stations) (AEROCE: Prospero, 1996).

A more vigorous model validation will be possible when the results from the planned Moroccan field experiments of the individual projects become available. In particular the following measurements will be used:

- The project "*Physico-chemical parameters of desert aerosol*" (Jaenicke, Schütz, Weinbruch) will provide surface measurements of aerosol concentration, composition, size distribution, mineral composition (with emphasis on Fe-containing minerals), and particle hygroscopicity, which will be used to validate dust properties simulated in the regional model and will be related to the particle properties at the source areas. Additional aircraft measurements planned in this project to completely characterize dust properties (concentration, size distribution, composition and shape) will provide a unique opportunity for model validation. Additional to these measurements near the source region, the project "*Airborne in situ and remote sensing studies on vertical distribution and spatial variability of aerosol microphysical properties of Saharan desert dust*" (Petzold, Ehret, Schumann) will provide vertically resolved aircraft measurements of microphysical dust properties during its transport up to some thousand kilometers downwind of the source regions, thus allowing to track changes in microphysical properties of dust, which would influence the radiative effect and deposition of dust. The impact of hygroscopic growth on dust radiative properties will be evaluated in the project "*Hygroscopicity and spectral light absorption of dust particles*" (Heintzenberg, Wiedensohler), which will add an aspect to the estimation of the radiative effect of mineral dust aerosol that has not been considered so far. This will also provide new information on settling properties and wet deposition efficiencies of dust.
- Spectral AOT, inverted from top-of-atmosphere radiances using new multi-spectral space-borne radiometers (SCIAMACHY and MERIS on ENVISAT), will be retrieved in the project "Dust aerosol REtrieval from space-borne instruMentS (DREAMS)"

(Burrows, von Hoyningen-Huene). With this method, AOT over both sea and land surfaces will be derived. The region of interest is approximately every two days covered by satellite observations. The ground resolution of SeaWiFS and MERIS is $0.25 \times 0.25 - 4 \times 4 \text{ km}^2$. To compare modelled and satellite-based AOT maps, a pattern recognition method will be applied to quantify the similarity of 2D structures in a complex manner. Measurements of the field studies will also be used to examine the assumptions made to determine the spectral AOT from the regional model (e.g., refractive index). At a later stage, the mesoscale model results will be used to compute TOA radiances at the wavelengths of the satellite sensors, which then can be used to measured satellite radiances directly.

- Vertical distribution of dust properties is of particular importance for estimating dust radiative forcing and to estimate the relationship between dust optical thickness and the TOMS satellite absorbing aerosol index, which is depending on the vertical dust distribution. Lidar measurements at 6 wavelengths from instruments operated aboard the DLR research aircraft Falcon will be provided by the project "*Airborne in situ and remote sensing studies on vertical distribution and spatial variability of aerosol microphysical properties of Saharan desert dust*" (Petzold, Ehret, Schumann). This will provide vertically resolved aerosol properties and their regional variability up to 11.5 km height. The project "*Radiative properties of Saharan dust: In-situ aircraft measurements and model calculations*" (Trautmann, Wendisch, Heintzenberg) will in addition to providing vertically resolved optical and microphysical dust properties provide spectral surface albedo, necessary for computations of dust radiative effects. In-situ lidar measurements from the project "*Vertically resolved characterization of Saharan dust based on observations with multiwavelength Raman lidar and multichannel depolarization lidars*" (Ansmann, Wiegner) will be used to validate profiles of dust vertical distribution, optical and microphysical properties, and their temporal variability. Lidar measurements from the CALIPSO mission which will be available for the period of the field studies will provide a unique opportunity to evaluate the computation of the development of dust plumes in the model domain.

3.2.4 Studies on the direct radiative effect of dust aerosols

On the base of previous sensitivity studies regarding the influence of aerosol properties on the radiation fields in the meteorological driver LM, the meteorological feedback of predicted aerosol distributions onto LM forecast fields will be modeled. To accomplish this, the present LM radiation scheme has to be enhanced. Dust radiative properties will be prescribed/improved using results from the field studies. The revision of the present scheme will be realized in close cooperation with the German Weather Service. As the result, the LM-MUSCAT will be qualified for mesoscale simulations of the direct radiation effect with online modeling of the aerosol-radiation feedback, which will be carried out for a series of case studies for which the dust distribution is constrained by observations, varying the dust radiative parameters within limits consistent with measurements. The influence dust radiative forcing on the atmospheric dynamics in the mesoscale modeling system will be evaluated (this is planned for the second phase of the project).

Ultimately the improved parameterizations for the computations of the dust cycle and radiative properties will be implemented in the ECHAM5 GCM to improve the simulation of large-scale dust effects and feedbacks. A series of GCM model experiments is also planned for the second project phase (years 4-6).

3.2.5 Process studies on aerosol-gas-cloud interactions

To investigate aerosol effects on cloud microphysics, sensitivity studies of the influence of Saharan dust on cloud development, both close to and far from source regions, will be carried out. Mesoscale fields of predicted wind, temperature, humidity, diffusivity and dust size distributions from previous LM-MUSCAT runs will be used to calculate trajectories of long-range dust transports for periods of interest. Using the model SMCCM to describe the microphysics in the air parcel, the study focuses on a sophisticated description of the cloud activation process. This includes the consideration of the influence of aqueous phase chemical processes on aerosol-gas-cloud interactions, the development of appropriate parameterizations of these processes for the use in regional and global codes and testing of these parameterizations in the IfT modeling system LM-MUSCAT. The influence of predicted aerosol size distribution on cloud microphysics along trajectories from previous regional modeling will be investigated. This study will mainly be part of the second project phase (year 4-6).

Time schedule

Year 1 and 2: Regional model development

- Regridding of input parameters with the required resolution (e.g., soil parameters, topography, land use)
- Linking existing model schemes, integrating the dust emission scheme into the regional (mesoscale) model, rescaling of model components to a common grid
- Development of input data sets at the appropriate scale
- Necessary model development, e.g. wet and dry deposition, modal scheme for emissions

Year 2 and 3: Sensitivity studies with emphasis on subgridscale processes, refining source parameterization and direct effect

- Subgridscale processes using a consistent data set including measurements as well as TOPCAM simulations
- Source parameterization
- Synthetic aerosol masks for LM radiation parameterization (scenario simulations with different characteristic temporary and spatial distributions of aerosol optical depth)

Year 2 and 3: Model validation

- Initial model validation using available data sets (e.g., AERONET, AEROCE, SeaWiFs, MODIS) (year 2)
- Moroccan field study phase: extensive validation with results from field experiments, providing model results to participants of field study (aerosol size distributions, vertical aerosol distributions, optical depth) (year 3)
- Revision of model parameters (input parameter, transport parameterization) on the base of a comparison with measurements (year 3) (CALIPSO, Lidar, aerosol size distribution and composition, hygroscopicity)

Year 3: Influence of dust on climate

- Adjustment of the radiation parameterization in the dust model of ECHAM5 to measured and derived values
- Sensitivity studies on the influence of realistic spatio-temporal dust distributions on modeled radiation fields (and thus temperature, precipitation and advection) in the LM.

- Extension and enhancement of the existing LM radiation and microphysical parameterisation to consider the feedback of the aerosol evolution onto clouds (direct and indirect effect)

Year 4-6 (Continuation)

- Integration of the parameterisation of the biomass burning aerosol into the regional model
- Coupling between MUSCAT aerosol modul and revised radiation/ cloud routines of LM Lagrangian process study on long-range transport and cloud modification (indirect effect)
- Quantification of the influence of Saharan dust on the temperature, wind and cloud prediction using the revised LM
- Model evaluation using results of the far field experiment
- Performance of modeling experiments on climatic effects and feedback of dust (control experiment with external dust distribution from the regional model and control experiment with internal simulated dust distributions using the same dust emission scheme in ECHAM5 as in the regional model)

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