Atmospheric dust modeling
A way to better understand the Earth system

Bojan Cvetkovic ¹, Slobodan Nickovic ¹, Ana Vukovic ²,¹, Goran Pejanovic ¹, Mirjam Vujadinovic ²,¹, Vladimir Djurdjevic ³,¹, Yugoslav Nikolic ¹

¹ Republic Hydrometeorological Service of Serbia – South East European Climate Change Center, Belgrade, Serbia (bojan.cvetkovic@hidmet.gov.rs)
² Faculty of Agriculture, University of Belgrade, Belgrade, Serbia
³ Faculty of Physics, University of Belgrade, Belgrade, Serbia
• The error bars in the greenhouse gas forcing are very small. The biggest uncertainty in defining radiative forcing comes from aerosols, especially from the mineral dust.

• Large uncertainties in evaluation of the atmospheric dust transport interactions with the environment and its roll in the climate system (IPCC 2013) motivate the researchers to sophisticate the knowledge, based on the empirical and experimental experience, and to improve the numerical modeling of the dust cycle, since the models are the most promising tool in understanding and in quantifying the roll of the atmospheric dust cycle in the climate system.
DUST CYCLE INTERFEERS WITH OTHER COMPONENTS OF THE CLIMATE SYSTEM

DRIVING CYCLES ON WIDE RANGE OF TIME AND SPACE SCALES

DUST CYCLE
ENERGY CYCLE
WATER CYCLE
CARBON CYCLE

The research focus – INTERACTION OF MINERAL DUST PARTICLES WITH THE ATMOSPHERE AND OCEANS
Dust picked up by winds from the Sahara and other North African deserts is often carried to the Caribbean Sea and the Americas. In fact, dust events deliver about **40 million tons of dust each year** from the Sahara to the Amazon River Basin alone. Research has shown that part of the reason the Amazon region is so fertile is because of the vast mineral nutrients carried on the winds from Africa.
To understand and model dust aerosol transport and its role within the Earth system, processes ranged from micro to global scales must be considered, which explains complexity of the problem.
ATMOSPHERIC DUST MODELLING

Depending on the research goals, considering nowadays computer resources, dust models evolution is divided in:

(1) modelling of the long range transport (global with resolutions ~100km)

(2) modelling of the intense dust storms (regional of several tens of km)

LONG RANGE TRANSPORT:
Global and regional models
Coarse resolution (several 10km to ~100km)

SHORT RANGE TRANSPORT:
Nonhydrostatic regional models
High resolution (several km)
Forecast of the dust storms
Dust Regional Atmospheric Model (DREAM)

\[
\frac{\partial C_k}{\partial t} = -u \frac{\partial C_k}{\partial x} - v \frac{\partial C_k}{\partial y} - (w - v_{gk}) \frac{\partial C_k}{\partial z} - \nabla (K_H \nabla C_k) - \frac{\partial}{\partial z} \left( K_z \frac{\partial C_k}{\partial z} \right) + \frac{\partial C_k}{\partial t}_{\text{SOURCE}} - \frac{\partial C_k}{\partial t}_{\text{SINK}}
\]

- Driven by the non-hydrostatic atmospheric model NCEP NMME
- Simulates all major processes of the atmospheric dust cycle
- Includes 8 different dust particle bins
- Includes different dust mineral fractions
- Simulates ice nuclei concentration
Kernel of dust modeling – to solve equation:

\[
\frac{\partial C_k}{\partial t} = -u \frac{\partial C_k}{\partial x} - v \frac{\partial C_k}{\partial y} - (w - v_{gk}) \frac{\partial C_k}{\partial z} - \nabla (K_H \nabla C_k) - \frac{\partial}{\partial z} \left( K_Z \frac{\partial C_k}{\partial z} \right) - \frac{\partial C_k}{\partial t} + \left( \frac{\partial C_k}{\partial t} \right) - \left( \frac{\partial C_k}{\partial t} \right)
\]

update of dust concentration in every model time step and in every model point and level (same as atmospheric parameters)

using updated values of soil moisture and friction velocity calculate dust emission for each of 8 bins

loss through dry (gravitational settling) and wet (washed down by precipitation) deposition

Preprocessing: Very important is to define dust sources using land cover and soil texture data bases or other source of information, depending on area of interest ➔ prepare dust mask on model grid

C is calculated for each particle size category \(C_k(k=1,...,8)\) at each model grid point in every time step!

(Nickovic et al., 2001)
Dust storm forecast: Nonhydrostatic high resolution simulation of intense dust event (Vukovic et al. 2014)

**Haboob:** cold downdraft from supercell clouds forms strong surface winds, intensive dust uplift, forms wall of dust; temperature drops, humidity rises, pressure rises.

*Problem for modeling: mapping position and strength of dust sources!*
*Problem with verification methods, DOUBLE PENNALTY PROBLEM!*

**Study case:** 5 JULY 2011 Phoenix (Arizona); model simulation 4km resolution

- Tucson – Phoenix; Front wide ~150km; travelled distance ~250km; Dust wall height ~1500-2000m
- 02UTC 6. JULY reached SE Phoenix; 02-04 UTC cross over Phoenix
Successful simulation of the Phoenix haboob 6th July 2011 (Ana Vukovic, Mirjam Vujadinovic Mandic ...)

NASA Applied Science support led to this high-resolution forecast and simulation capability.
STUDY CASE: TEHRAN DUST STORM 2\textsuperscript{ND} JUNE 2014

Simulation of small scale (local; several 100km), intense (several 1000ug/m3 PM10) & short lived (few hours) dust storms
Information from reports
• reached city at 04:50 p.m. local time;
• passing of the sand storm over the fixed site lasted about 15 min;
• storm duration less than 2 h;
• reduction of visibility to ~10 m; wind velocity reached 110 km/h;
• temperature dropped from 33°C to 18°C in several min;
• at least 5 deaths, 82 injured; multiple vehicle collision;
• 50 000 residential units lost power.

Theory
• Intensive cold downbursts from convective cells produced high velocity surface wind, creating cold front which was lifting, mixing and pushing dust towards the city;
• Expected: high wind speed, drop in temperature, rise in humidity, rise in pressure, reduction of visibility.
Until 12 UTC, 13 UTC, and 14 UTC.

Imam Khomeini airport OIIE

Visibility reduced to 20m at 12:30 UTC. Model output data available on 1h.
Vertical cross section along 35N

Streamlines (u,w) and vertical wind velocity

Values are on model levels, altitude of model levels are in black lines.

Temperature

Dust PM10 concentration

DNC – dust number concentration
NMME-DREAM (SEEVCCC) simulation results for the period June 2\textsuperscript{nd} 2014 06-20 UTC
Heterogeneous cold clouds formation

- Mineral dust particles act as efficient heterogeneous ice nuclei in the tropospheric cold and mixed-phase clouds
- Dust particles lifted to the cold cloud layer effectively glaciate supercooled cloud water

Koop and Mahowald, Nature, 2013

Ice formation and precipitation
Recent findings from observations
(Ice Nuclei in ice crystals)

Cziczo at al., Science (2013)

- 2/3 of residues in ice crystals from high clouds are dust+dust metallic oxides particles
- Small dust concentration needed to trigger the process
- Heterogeneous freezing is dominant process
- Minimal surface coating (no dust aging observed)
- Dust as ice nuclei found far from any of major desert sources (Asian, Saharan)

Flight tracks of ice cloud residual measurements for four aircraft campaigns spanning a range of geographic regions and seasons
Improving precipitation forecast
‘Cooking’ cold clouds: our recipe

DREAM model

- Empirical parameterizations for immersion and deposition ice nucleation, which include dust concentration as a dependent variable for cloud glaciation process, are implemented in NMM/DREAM. Ice nucleation concentration is calculated as a prognostic parameter depending on dust and atmospheric thermodynamic conditions.
- Instead of a predefined IN typically used in cloud microphysics we predict IN.

Parameterization of IN in DREAM

\[ n_{IN} = p S_{dust} \exp\left(-q(T-273.16)+r(\text{RH}_{ice}-100)\right) \]

\[ n_{IN} = C(n_{dust}) \alpha(273.16-T)+\beta) \exp(\gamma(273.16-T)+\delta) \]

NMM model

Dust C

T, RH

NOTE: IN is fraction of aerosol capable to glaciate cloud water!

Nickovic et al., 2016, Atmos. Chem. Phys., 16, 11367–11378
Model well reproduced timing, duration and position of #IN

Vertical distribution
Data for model validation:
Lidar and cloud radar
CNR-IMAA Atmospheric Observatory CIAO, Potenza, Italy

- Model #IN (shaded)
- MIRA55 Ice Cloud Water (black contours)

Daily averaged vertical loads
Potenza, May 2010 & Sep 2012
MODEL vs LIDAR – Cyprus, April 2016
BACCHUS-INUIT-ACTRIS field campaign

a) DREAM8-assim: Dust concentration [µg/m³]
Cyprus/Agia Marina (lat=35.06N lon=33.05E)

b) Linear volume depolarization ratio at 532nm
Nicosia PoliVXT NOA lidar (35.140°N, 33.381°E)
BACCHUS-INUIT-ACTRIS field campaign: April 2016
Remote sensing (LIDAR)

Range corrected signal @1064nm PollyXT_NOA, Nicosia, Cyprus

Volume depolarization ratio: cross/total @532nm
Model number of Ice nuclei load (left) vs MSG-SEVIRI satellite Ice water path (right)
Daily IN maps

http://dream.ipb.ac.rs/ice_nucleation_forecast.html

NWP groups interested to use daily #IN forecasts will soon have it available through the WMO SDS-WAS (dust) project
Is there any connection between these two pictures/locations?

Jungfraujoch Swiss Alps

Sahara desert
FRIDGE INP concentration [INP/\text{std L}] and NMME-DREAM const \times \log_{10}(\text{load IN})
sliding average over five days

Note constant temperature -25°C and constant RH=101%

Jungfraujoch INUIT campaign
January – February 2017

\textbf{Corr}=0.75
Jungfraujoch time serie RHi and temperature at MODEL levels
Atmospheric iron transport modeling

Example of mineral database application

CASE STUDY

Dust storm induced chlorophyll bloom near Canary Islands, July 2004

During July and August 2004, numerous dust storms occurred in northwestern part of Africa during which Saharan dust was blown towards the Atlantic ocean. Mineral rich dust aerosol was deposited mainly along the northwest African shelf, supplying the ocean with nutrient necessary for phytoplankton growth. During August, a massive occurrence of cyanobacteria was reported near Canary Islands (Ramos et al., 2005).

According to the iron hypothesis (Martin, 1994), the deposition of iron, along with dust aerosol, might increase biological productivity of the ocean and might enhance chlorophyll concentration. Therefore, we simulated this event using DREAM-Iron. The integration covers the period between 15th and 31st of July. Here we present preliminary results for dust load and iron deposition and surface concentration which is in good agreement with observed pattern of chlorophyll a concentration, observed with MODIS Aqua satellite.
OLD APPROACH
- Fe total - 3.6 % CONST
- K (decay rate) is ONLY function of cloud interaction, effects and pollution

NEW APPROACH
- Fe spatially distributed (source map)
- K depends also on Fe mineralogy
- Free iron fraction
- Solubility

\[
\left(\frac{dS}{dt}\right) + K(S - T) = 0
\]

\[K \text{ parameterized as a function of soil mineralogy}\]

\[
\frac{\partial C_k}{\partial t} + C_k \frac{\partial T_k}{\partial t} = \frac{\partial F_k}{\partial t}
\]

\[\frac{\partial T_k}{\partial t} + \Delta [T_k] = \left(\frac{\partial T_k}{\partial t}\right)_{\text{SOURCE}}\]

\[\frac{\partial F_k}{\partial t} + \Delta [F_k] = \left(\frac{\partial F_k}{\partial t}\right)_{\text{SOURCE}}\]

Dust concentration

Total Fe concentration

Free Fe concentration

\[f = \frac{\text{FREE IRON}}{\text{TOTAL IRON}}\text{ ratio}\]

\[K = \frac{1}{\tau} \left[ \alpha_C + \alpha_R - \ln \left(1 - \frac{-22.1 \times f + 15.8}{100}\right) \right]\]
Why to deal with the Icelandic volcanic dust?

• **Scientific challenges**
  – Specifics:
    • sources,
    • emission,
    • mineralogy,
    • particle properties,
    • seasonality
  ... quite different features from other desert particles

• **Practical effects**
  – Impacts on:
    • marine environment
    • climate
    • flight safety
    • human health
NEW  HIGH LATITUDE DUST FORECAST – NMME-DREAM-Iceland
Operational products available daily at http://www.seevccc.rs/?p=8

NMMEDREAM-Iceland vs MODIS AOT (Aerosol Optical Thickness)

Dust sources re-mapped from the Arnalds (2010) soil erodibility map to the DREAM numerical grid

Intensity of soil erosion based on Arnalds (2010)

Icelandic volcanic dust

Dust sources in DREAM

Figure 6. Number of dust days per month (bars) and monthly mean dust visibility (bars) in the southeastern part of Iceland, 1949-2011.

Long-term variability of dust events in Iceland (1949-2011)

Retrieved AOT (at 0.55 micron) partitioned by mode index (for Average solution)

Retrieved AOT (at 0.55 micron) partitioned by mode index (for Average solution) (None)
New seasonal forecast available each month for next seven months:

Operational products available daily at http://www.seevccc.rs/?p=8
Thank you kindly for your attention!