SAHARAN DUST TRANSPORT AND ITS IMPACT ON AIR QUALITY, ECOSYSTEMS AND REGIONAL CLIMATE

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As it is known desert dust can affect significantly:

- Radiative transfer (SW and LW)
- Clouds and precipitation (not necessarily one way)
- Ecosystems and marine environment (nutrient, radiation)
- Regional and global climate (atmospheric stratification, perturbations on energy balance)
- Atmospheric composition and physicochemical processes
- Urban air quality

Dust outbreaks can affect significantly human activities like agriculture and transportation
OBJECTIVES

The air quality in areas like the Mediterranean Region exhibit some unique characteristics due to:

- Regional climatic characteristics (Mediterranean weather)
- Long range transport of air pollution
- Long range transport of naturally produced PMs (mainly Saharan dust and sea-salt)
- Gas-phase processes
- Gas to particle conversion and aerosol formation

The phenomena, processes and impacts associated with the co-existence of gaseous and PM pollutants of various origins and stage of formation is the main objective of this talk.
Air quality problems related to coexistence of natural and anthropogenic origin pollutants are very complicated because they involve processes not well understood yet.

Desert dust can modify the photolysis rates due to the alteration of UV and visible radiation fluxes.

It can trigger various heterogeneous chemical processes that lead to the formation of new types of aerosols.

PM is generated at three different stages:
- the direct emissions from anthropogenic and natural sources
- the aqueous phase and gas-to-particle production processes
- the generation of new types of PM resulting from heterogeneous chemical processes
Why focus on the Euro-Mediterranean Region?

• Physiographic characteristics and climatic conditions in the Mediterranean Region are followed by excessive solar radiation leading to high photochemical activity in the Region.

• Sahara is the desert responsible for many severe dust outbreaks that influence the area.

• In addition long range transport of fine particles is very common in the area (Kallos et al. 1999; Luria et al. 1996).

• The coexistence of natural and anthropogenic sources of PM in the surrounding region.

• Due to this coexistence, heterogeneous chemical processes are leading to the production of new types of aerosols.
SOURCES OF DESERT DUST

The blue, green and grey arrows indicate transport paths of anthropogenic pollutants in the Euro-Mediterranean Region (ozone, sulfates etc). The grey arrows are associated mostly with the upper layer transport while, the blue and green ones with movement of pollutants in the lower troposphere layers. The red-brown arrows indicate transport of desert dust from Africa region.

PM AND GASEOUS POLLUTANTS IN THE ATMOSPHERE

PROCESSES AFFECTING AIR QUALITY AND CLIMATE

**STRATOSPHERE**

**Heterogeneous reactions**

\[
\begin{align*}
SO_2 + O_3 & \rightarrow DSO_4 \text{(dust+sulfate)} \\
NO_2 & \rightarrow DNO_3 \text{(dust+nitrate)} \\
HNO_3 & \rightarrow DNO_3 \text{(dust+nitrate)}
\end{align*}
\]

**UPPER TROPOSPHERE**

hv & OH

SO_2 HCl ash

SO_2 \rightarrow H_2SO_4

**LOWER TROPOSPHERE**

precipitation

Dust

Deposition

Cloud Modifications

Nucleation

cooling of the surface

warming

**INCOMING-OUTGOING SW RADIATION**

**LW RADIATION**
DUST DEPOSITION IN THE MEDITERRANEAN AND EUROPE

By utilizing the first 24-hours from the SKIRON/Eta forecasts, the geographical distribution of the total dust mass deposited on surface has been calculated on a monthly basis for the period January 2000 to December 2006.

The SKIRON/Eta system has the atmospheric model Eta as recoded in Athens and the DREAM sub-module for the dust cycle directly coupled. The entire system has been developed at the University of Athens at the framework of MEDUSE and ADIOS projects.
Derivation of Seasonal Amounts of Dust Deposited on Mediterranean Basin

By utilizing the first 24-hours from the SKIRON/Eta forecasts, the geographical distribution of the total dust mass deposited on surface has been calculated on a monthly basis for the period January 2000 to December 2006.

Since the model has the capability to calculate dry and wet deposition separately it was possible to derive the geographical distribution of these two components of the total dust deposition, for each month of the five-year period.

Since January 2003 calculations were performed using four particle size bins:

<table>
<thead>
<tr>
<th>K</th>
<th>Type</th>
<th>Centered particle radius µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Clay</td>
<td>0.73</td>
</tr>
<tr>
<td>2</td>
<td>Silt, small</td>
<td>6.10</td>
</tr>
<tr>
<td>3</td>
<td>Silt, large</td>
<td>18.00</td>
</tr>
<tr>
<td>4</td>
<td>Sand</td>
<td>38.00</td>
</tr>
</tbody>
</table>
Average deposition for 2003 – 2006

Average dry deposition in gr/m² for 2003-2006

Average wet deposition in gr/m² for 2003-2006

Average dry & wet deposition in gr/m² for 2003-2006

Scale: $10^{-3} - 10^{2} \frac{gr}{m^2}$
Average deposition for the four size bins (2003–2006)

Scale: $10^{-3} - 10^{2} \text{ gr/m}^2$
Average dry deposition for the four size bins (2003–2006)

Scale: $10^{-3} - 10^2 \text{ grams/m}^2$
Average wet deposition for each size bin (2003–2006)

Scale: $10^{-3} - 10^{2} \text{ gr/m}^2$
Mean Monthly Deposition for 2000 – 2006 for Europe and the Mediterranean Sea

Mean monthly total deposition rates

Mean monthly dry deposition rates

Mean monthly wet deposition rates

1 Particle Size

4 Particle Sizes

mg/m²

mg/m²

mg/m²

Europe

Mediterranean Sea
Mean Monthly Deposition for 2000–2006 for the 4 Mediterranean sub-Regions

Mean monthly total deposition rates

Mean monthly dry deposition rates

Mean monthly wet deposition rates

West · Central (south) · Central (north) · East
### Annual Dust Deposition (in $10^3$ tons) on the Mediterranean Sea and Europe

<table>
<thead>
<tr>
<th>Year</th>
<th>Europe</th>
<th>Mediterranean Sea</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>total (dry+wet)</td>
<td>dry</td>
</tr>
<tr>
<td>2000</td>
<td>3914</td>
<td>936</td>
</tr>
<tr>
<td>2001</td>
<td>2909</td>
<td>725</td>
</tr>
<tr>
<td>2002</td>
<td>4723</td>
<td>883</td>
</tr>
<tr>
<td>2003</td>
<td>1999</td>
<td>256</td>
</tr>
<tr>
<td>2004</td>
<td>4933</td>
<td>398</td>
</tr>
<tr>
<td>2005</td>
<td>3937</td>
<td>355</td>
</tr>
<tr>
<td>2006</td>
<td>2849</td>
<td>256</td>
</tr>
</tbody>
</table>
Air Quality Violations in Athens, Greece and the Association With Saharan Dust Transport for 2001-2005

During 2001-2005 in Athens, the PM records showed that there were 141, 201 and 135 days where at least in one monitoring station PM10 concentrations were above the EU imposed limits.

For those days with PM exceedances a systematic day to day analysis was performed based on:

- PM10 measurements in several stations in Attika Region (provided by Hellenic Ministry for the Environment, Physical Planning and Public Works)
- SKIRON/Eta Dust Forecasting System
- SeaWiFs Satellite Images Sea-viewing Wide Field-of-view Sensor, SeaWiFS Project, NASA (provided by Norman Kuring – Scientific Programmer at NASA/Goddard Space Flight Center)

The analysis showed an evident synergetic contribution of

- anthropogenic (urban and LRT) and
- natural sources (Saharan dust)

for 53-70% of the cases
Air Quality Violations in **Athens**, Greece and the Association With Saharan Dust Transport for 2001-2005

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of days of exceedances</th>
<th>Number of days with available SKIRON dust forecasts</th>
<th>Number of days with available SeaWiFs images</th>
<th>Number of days with available TOMS images</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>141</td>
<td>102</td>
<td>59</td>
<td>141</td>
</tr>
<tr>
<td>2002</td>
<td>201</td>
<td>178</td>
<td>192</td>
<td>201</td>
</tr>
<tr>
<td>2003</td>
<td>135</td>
<td>135</td>
<td>128</td>
<td>135</td>
</tr>
<tr>
<td>2004</td>
<td>223</td>
<td>223</td>
<td>176</td>
<td>223</td>
</tr>
<tr>
<td>2005</td>
<td>213</td>
<td>213</td>
<td>174</td>
<td>213</td>
</tr>
</tbody>
</table>

- % of exceedances due to dust according to available SKIRON forecasts: 58.82%, 48.31%, 43.70%, 55.16%, 54.46%
- % of exceedances due to dust according to SeaWiFs images: 76.27%, 46.87%, 58.59%, 54.54%, 59.19%
- % of exceedances due to dust according to TOMS images: 47.86%, 37.31%, 40.74%, 39.46%, 28.17%

% of exceedances due to dust where at least **two** of the systems (SKIRON, SeaWiFs, TOMS) showed dust transport in Athens:

- 2001: 53.57%
- 2002: 54.72%
- 2003: 51.85%
- 2004: 46.64%
- 2005: 47.42%

% of exceedances due to dust where at least **one** of the systems (SKIRON, SeaWiFs, TOMS) showed dust transport in Athens:

- 2001: 62.14%
- 2002: 63.68%
- 2003: 65.92%
- 2004: 70.85%
- 2005: 52.58%
Modeled versus Observed dust concentrations during recorded episodes in Haifa, Israel

The monitoring site is located in Haifa, Israel (Barak Herut, personal communication)
Modeled versus Observed dust concentrations during recorded episodes in Greece

COMPARISON OF SIMULATED DUST CONCENTRATIONS WITH PM10 OBSERVATIONS AT HERAKLION, CRETE 2004-2005

\[ y = 0.47x + 2.02 \]
\[ r = 0.59 \]

COMPARISON OF SIMULATED DUST CONCENTRATIONS WITH PM10 OBSERVATIONS AT ATHENS, GREECE 2004-2005

\[ y = 0.44x - 0.1 \]
\[ r = 0.62 \]

The measurements from stations in Athens and Crete were provided by the Hellenic Ministry for the Environment, Physical Planning and Public Works.
COEXISTENCE OF SAHARAN DUST WITH ANTHROPOGENIC POLLUTANTS AND THE FORMATION OF VARIOUS GENERATIONS OF PM NATURAL EMISSIONS ANTHROPOGENIC EMISSIONS

GASES
SO₂, NO, NO₂, VOC
CO, NH₃, CO₂

PARTICULATE MATTER
PM2.5
PM10

AEROSOLS
DUST
SEA SALT (NaCl)

SECONDARY POLLUTANTS
O₃, SO₄, NO₃, NH₄

PARTICLES COVERED WITH GASES OR AEROSOLS

1st GENERATION POLLUTANTS
2nd GENERATION POLLUTANTS
3rd GENERATION POLLUTANTS
THE SKIRON/Eta – CAMx MODELING SYSTEM AND ITS NEW CAPABILITIES

- New dust production scheme based on a newer land classification refinement – usage of four-size bins (now eight sizes)
- New scavenging and wet deposition processes in SKIRON/Eta
- New dry deposition processes in SKIRON/Eta
- SKIRON dust fluxes / CAMx sources
- Dust optical depth calculation
- Saharan dust treatment as crustal material inside CAMx
- Modification of the photolysis rates according to dust optical depth
- Sea-salt production directly coupled with CAMx
- Incorporation of heterogeneous reactions leading to new aerosol formation
- In general, tight coupling of SKIRON/Eta - Dust with CAMx
MODELING PLATFORM

SKIRON/ETA MODELING SYSTEM
With DUST MODULE

DUST LOAD

DUST OPTICAL DEPTH

PHOTOLYSIS RATES

HETEROGENEOUS CHEMISTRY

METEOROLOGY

CAMx AIR QUALITY MODEL

DUST FLUXES

DUST EMISSIONS

SEA SALT EMISSIONS

ANTHROPOGENIC EMISSIONS

GAS PHASE POLLUTANTS

PARTICULATE MATTER (Sulfates, Nitrates etc)

CRUSTAL MATERIAL – DESERT DUST

NEW TYPES OF AEROSOLS

NEW TYPES OF AEROSOLS*NEW
SENSITIVITY TESTS – PRELIMINARY RESULTS

The following sensitivity experiments of the new development have been performed:

- Shading effects of Saharan dust on photochemical processes
- Sea-salt production
- Heterogeneous processes and new particle formation
SHADING EFFECTS OF SAHARAN DUST ON PHOTOCHEMICAL PROCESSES

Saharan dust can influence physicochemical processes on various ways such as the shading effects and the modification of the J values.

Dust Optical Depth = Dload(g/m²)*Extinc.Coefficient(m²/g)

The photolysis reactions are:

\[ \text{NO}_2 \rightarrow \text{NO} + \text{O}(3\text{P}) \]
\[ \text{CH}_2\text{O} \rightarrow \text{H} + \text{HCO} \]
\[ \text{CH}_2\text{O} \rightarrow \text{H}_2 + \text{CO} \]
\[ \text{O}_3 \rightarrow \text{O}_2 + \text{O}(1\text{D}) \]
\[ \text{CH}_3\text{CHO} \rightarrow \text{CH}_3 + \text{HCO} \]
\[ \text{ISPD}^* + \text{hv} \rightarrow \text{products} \]

PHOTOLYSIS RATES ARE CALCULATED FOR MORE REACTIONS, BUT THE ABOVE ARE USED FOR CAMx

*ISPD=Isoprene product (lumped methacrolein, methylvinyl ketone, etc)

CALCULATION OF DUST OPTICAL DEPTH (DOD)

\[ \text{DOD} = \text{Dload}(g/m^2)\times\text{Extinc.Coefficient}(m^2/g) \]

<table>
<thead>
<tr>
<th>DUST PARTICLE RADIUS (µm)</th>
<th>EXTINCTION COEFFICIENT (m²/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.73</td>
<td>0.8912</td>
</tr>
<tr>
<td>6.10</td>
<td>0.0782</td>
</tr>
</tbody>
</table>

#Extinction coefficient is relevant to particle size and wavelength number (GFDL radiation - Anderson et al. 2004)

Simulations for Saharan Dust Episode

SIMULATION #1 = NORMAL (run with usual j-values)
SIMULATION #2 = WITH DUST (run with altered j-values due to dust optical depth)
SHADING EFFECTS OF SAHARAN DUST ON PHOTOCHEMICAL PROCESSES

SAHARAN DUST EPISODE DURING FEBRUARY 24, 2006

Dust Storm in Northern Africa: picture taken from NASA/GSFC satellite
Synoptic conditions during the Saharan dust episode of February 24, 2006 as simulated from SKIRON/Eta modeling system
SAHARAN DUST EPISODE DURING 23-24 FEBRUARY, 2006
FROM SKIRON/ETA MODEL - DUST LOAD.
SAHARAN DUST OPTICAL DEPTH DURING 24 FEBRUARY, 2006
SKIRON/ETA-CAMx SYSTEM vs AERONET MEASUREMENTS

AERONET SITES

COMPARISON OF DOD WITH AOD FROM AERONET SITES
24 FEBRUARY 2006
340nm

\[ y = 0.8343x - 0.0547 \]
\[ R^2 = 0.8544 \]
\[ r = 0.92 \]
Difference in O3 concentration

Negative values denote O3 reduction

FEBRUARY 24, 2006
12:00 UTC

% change in O3 initial concentration
Difference in fine sulfate concentration

Negative values denote sulfate reduction

FEBRUARY 24, 2006
12:00 UTC

% change in fine sulfate initial concentration
SEA SALT PARTICLE PRODUCTION

THEORETICAL FORMULATION

1. OPEN OCEAN SOURCE FUNCTION

(Monahan et al. 1986; Gong 2003; Zhang et al. 2005)

\[
\frac{dF}{dr} \bigg|_{80} = 1.373 \ U \ \frac{3.41}{10} \ r_{80}^{-A} \left(1 + 0.057 \ r_{80}^{3.45}\right) 10^{-0.607} \ e^{-8^2} \\
A = 4.7 \left(1 + \Theta \ r_{80}\right)^{-0.017} \ r_{80}^{-1.44} \quad (\text{Units: particles/m}^2 \ \text{s} \ \mu\text{m}) \\
B = \left(0.433 - \log r_{80}\right) / 0.43 \\
\Theta = 30
\]

\(r_{80}\) = particle radius at 80% RH

2. SURF-ZONE SOURCE FUNCTION

(de Leeuw et al. 2000; Gong et al. 2002)

\[
\frac{dF}{dr} \bigg|_{o} = 0.7 \ e^{0.23} \ U \ \frac{10}{0.65} \ r_{o}^{-1.65} \quad (\text{Units: particles/m}^2 \ \text{s} \ \mu\text{m})
\]

\(r_{o}\) = particle radius at formation

\(C_{o}\) = Correction factor for Relative Humidity

The coding of sea salt emissions in CAMx model is similar to the coding of sea salt in CMAQv4.5.1 model (Shankar et al. 2005; Bhave et al. 2003, 2005).
Sea Salt Emissions are speciated into Na, Cl, and SO4 aerosols by:

- \( \text{factorNa} = 0.3856 \)
- \( \text{factorCl} = 0.5389 \)
- \( \text{factorSO4} = 0.0755 \)

**PERIOD OF SIMULATION:** AUGUST 1-10, 2001

CAMx v4.31 CMU aerosol approach, with 3 aerosol size bins.

Diameter at each bin (\( \mu \text{m} \)):
- 0.03 – 0.1
- 2.5 – 10

**Total Na Aerosol:** sum of the 3 bins from the model output.

**NaCl Aerosol:** Na + PCI from the model output

3h AVERAGE MEASUREMENTS ARE AVAILABLE FROM A COASTAL SITE IN NORTHERN CRETE, GREECE

- **Na aerosol:** Bulk concentration
- **NaCl Aerosol:** \( 1.8 \times \text{Na} \)

(N. Mihalopoulos, personal communication)

**CONFIGURATION**

<table>
<thead>
<tr>
<th>SKIRON/Eta</th>
<th>CAMx</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal Resolution</td>
<td>0.24 x 0.24 deg</td>
</tr>
<tr>
<td>Vertical Layers</td>
<td>38 (up to 22km)</td>
</tr>
<tr>
<td>Grid Points (Nx*Ny)</td>
<td>135 x 213</td>
</tr>
<tr>
<td>Latitude, Longitude</td>
<td>34.7, 8.4 (pole point)</td>
</tr>
</tbody>
</table>
MODELED versus MEASURED SODIUM AEROSOL CONCENTRATIONS
PERIOD: August 1-20, 2001

MEASUREMENTS vs MODELED VALUES OF SODIUM AEROSOL (µg/m³) AT FINOKALIA
2-20 AUGUST 2001

NA AEROSOL (µg/m³)

Measurements (NA)

MODEL (NA)

CAMx-NA total vs MEASUREMENTS-bulk Na
**THEORETICAL FORMULATION**

1. **1st ORDER KINETIC RELATIONSHIP**

\[
\frac{dC}{dt} = -k_{g,s} C_{gas}
\]

\[g = \text{gas}\]

\[s = \text{particle}\]

\[\delta_{g,s} = C_{gas} \left(1 - e^{-k_{g,s} dt}\right)\]

\[C_{gas} = C_{gas} - \delta_{g,s}\]

\[C_{aero} = C_{aero} + \delta_{g,s}\]

\[Kn = \frac{\frac{g}{r_s}}{\frac{L}{r_s}}\]

\[D_g = \frac{3}{8\pi d_g \rho_{air}^2} \left[\frac{RT_m}{m_{air} + m_{gas}}\right]\]

\[\lambda_g = \frac{3D_g}{\frac{vel}{g}}\]

\[A = \text{Avogadro number}\]

\[d_g = \text{diameter of a gas molecule (4.5A)}\]

\[\rho_{air} = \text{density of air}\]

\[T = \text{air temperature}\]

\[R = \text{gas constant}\]

\[m_{air} = \text{molecular weight of air}\]

\[m_{gas} = \text{molecular weight of gas}\]

\[vel = \text{mean speed of gas molecules}\]

\[Kn = \text{Knudsen number}\]

\[\lambda_g = \text{mean free path of a gas in air (m)}\]

\[r_s = \text{particle radius (m)}\]

\[N_s = \text{particle density (parts/m}^3) = \text{Concentration/(mass of one particle)}\]

\[\gamma = \text{uptake coefficient, different for each gas}\]

\[D_g = \text{gas-phase molecular diffusion coefficient in air}\]
HETEROGENEOUS PROCESSES AND NEW PARTICLE FORMATION

ASSUMPTIONS
1. IRREVERSIBLE UPTAKE OF GAS SPECIES ONTO DUST PARTICLES
2. PRODUCTION OF NEW AEROSOLS
3. DUST PARTICLES OF SPHERICAL SHAPE
4. MONODISPERSE AEROSOL POPULATION
5. HETEROGENEOUS REACTIONS ON DUST OCCUR WHEN RH>40%

HETEROGENEOUS REACTIONS

<table>
<thead>
<tr>
<th>Reaction</th>
<th>UPTAKE COEFFICIENT</th>
<th>( \gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( SO_2 \rightarrow DSO_4 ) (dust+sulfate)</td>
<td>( \gamma )</td>
<td>( 1.0 \times 10^{-4} )</td>
</tr>
<tr>
<td>( NO_2 \rightarrow DNO_3 ) (dust+nitrate)</td>
<td>( \gamma )</td>
<td>( 1.0 \times 10^{-4} )</td>
</tr>
<tr>
<td>( HNO_3 \rightarrow DNO_3 ) (dust+nitrate)</td>
<td>( \gamma )</td>
<td>( 0.01 )</td>
</tr>
<tr>
<td>( O_3 \rightarrow DO_3 ) (dust+ozone)</td>
<td>( \gamma )</td>
<td>( 5.0 \times 10^{-5} )</td>
</tr>
</tbody>
</table>

LARGE SCALE SIMULATION WITH THE AIR QUALITY MODEL CAMx
WITH THE NEW DEVELOPMENT
1-20 APRIL 2003

<table>
<thead>
<tr>
<th>CONFIGURATION</th>
<th>SKIRON/Eta</th>
<th>CAMx</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal Resolution</td>
<td>0.16 x 0.16 deg</td>
<td>0.235 x 0.18 deg</td>
</tr>
<tr>
<td>Vertical Layers</td>
<td>38 (up to 22km)</td>
<td>22 (up to 8km)</td>
</tr>
<tr>
<td>Grid Points (Nx*Ny)</td>
<td>245 x 318</td>
<td>305 x 231</td>
</tr>
</tbody>
</table>
3 – 13 APRIL 2003

CRUSTAL LOAD (g/m²)

VERTICAL COLUMN: 0 - 4km

(size bin: 0.1-2.5μm diameter)
3 – 13 APRIL 2003

ANTHROPOGENIC PARTICULATE SULFATE

PSO$_4$ LOAD (g/m$^2$) (size bin: 0.1-2.5μm diameter)

VERTICAL COLUMN: 0 - 4km

PSO$_4$ _2 (0.1-2.5um)

VERTICAL COLUMN: 0-4km

April 3, 2003 0:00:00
Min = 0.000 at (1,1), Max = 0.036 at (135,150)
3 – 13 APRIL 2003

PARTICULATE SULFATE FORMED ON DUST

DSO4 LOAD (g/m²) (size bin: 0.1-2.5µm diameter)

VERTICAL COLUMN: 0 - 4km
Two hour average modeled sulfate concentration (PSO$_4$ and DSO$_4$) for two grid cells in the domain affected by desert dust transport.

- **Erdemli, Turkey**
  - 2h Average CAMx Sulfate Concentration
  - Layer 1: 0-50m
  - 1-9 April 2003

- **Saudi Arabia (near Red Sea)**
  - 2h Average CAMx Sulfate Concentration
  - Layer 1: 0-50m
  - 1-10 April 2003
AIR QUALITY AND CLIMATE

This effort continues at the framework of FP6 project CIRCE.

The new model development includes the direct coupling of all these submodules in to RAMS model in order to study impacts of mixture of desert dust, sea salt and PM of anthropogenic origin (sulfates, nitrates) on cloud formation and precipitation.
The naturally-produced particulate contributes significantly on air quality degradation, especially in Southern Europe and of course, North Africa.

Violations of air quality standards due to high PM concentrations in South European cities are associated to Saharan dust transport episodes for 30-70% of the cases, depending on the location.

Desert dust anti-correlates with O3 (reduction of 1-6% at the surface).

This is considered as an important issue in many European cities because it is difficult to meet EU air quality standards not only for O3 but also for PM.

Of course, dust affects meteorology by reducing the surface heating and warming mid-tropospheric layers leading in stabilization.

Although, these processes have not simple links between them.
The generation of new aerosols on dust surfaces can be significant for both the middle and the upper troposphere, not because of the high amounts of produced species, but due to the different properties of such generation.

This new 3rd generation aerosol (DSO4) can be higher than the sulfate produced from anthropogenic sources (PSO4), depending on the weather and air quality conditions.

Heterogeneous chemical processes in the region are more complicated and their implications on air quality, water budget and climate are not well known.
ACKNOWLEDGEMENTS

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