Saharan Dust and Anthropogenic Aerosols – Regional Characteristics

George Kallos

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OBJECTIVES

Discuss the:

- 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 to particle conversion and aerosol formation
- Aerosol-cloud interaction processes
- New modeling tools

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.
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.

• The various generations of aerosols formed in the area have different characteristics and therefore impacts on cloud formation and processes.

• Perturbations in cloud and precipitation processes may affect the water budget of the area.
TYPICAL WEATHER PATTERNS DURING THE SUMMER PERIOD
Air pollutants released from Southern Europe and Mediterranean Sea are transported further to the South over Africa and Middle East.

Initially the transport is mainly within the lowest tropospheric layer (1-2 km).

Over North Africa are pumped up higher (4-6 km) due to deep mixing during the day-hours.

Kallos et al., 1997, GRL
Transport of 3rd generation species is a combination of the two transport paths.

**SUMMER SEASON**

**TRANSITION SEASONS**

**PATHS AND SCALES OF TRANSPORT AND TRANSFORMATION OF AIR POLLUTANTS AND DUST**

### Annual Dust Deposition (in $10^3$ tons) on the Mediterranean Sea and Europe

<table>
<thead>
<tr>
<th>Year</th>
<th>Europe</th>
<th></th>
<th></th>
<th>Mediterranean Sea</th>
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<tbody>
<tr>
<td></td>
<td>total (dry+wet)</td>
<td>dry</td>
<td>wet</td>
<td>total (dry+wet)</td>
<td>dry</td>
<td>wet</td>
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<tr>
<td>2000</td>
<td>3914</td>
<td>936</td>
<td>2978</td>
<td>3962</td>
<td>1541</td>
<td>2421</td>
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<tr>
<td>2001</td>
<td>2909</td>
<td>725</td>
<td>2184</td>
<td>2500</td>
<td>1255</td>
<td>1245</td>
</tr>
<tr>
<td>2002</td>
<td>4723</td>
<td>883</td>
<td>3840</td>
<td>5132</td>
<td>1546</td>
<td>3586</td>
</tr>
<tr>
<td>2003</td>
<td>1999</td>
<td>256</td>
<td>1743</td>
<td>6752</td>
<td>1828</td>
<td>4924</td>
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<tr>
<td>2004</td>
<td>4933</td>
<td>398</td>
<td>4535</td>
<td>9306</td>
<td>1504</td>
<td>7802</td>
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<td>3937</td>
<td>355</td>
<td>3582</td>
<td>6833</td>
<td>1601</td>
<td>5232</td>
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<td>2006</td>
<td>2849</td>
<td>256</td>
<td>2593</td>
<td>6361</td>
<td>1634</td>
<td>4727</td>
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## Contribution of dust particles to urban air quality

<table>
<thead>
<tr>
<th>Year</th>
<th>Stations</th>
<th>PM$_{10}$ average concentration (μg m$^{-3}$)</th>
<th>Dust average concentration (μg m$^{-3}$)</th>
<th>Dust contribution to PM$_{10}$ concentration (%)</th>
<th>Annual exceedances</th>
<th>Dust contribution to exceedances (%)</th>
<th>PM$_{10}$ residual contribution to exceedances (%)</th>
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<td>Heraklion</td>
<td>62.2</td>
<td>5.3</td>
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<td>31.7</td>
<td>2.4</td>
<td>7.6</td>
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<td></td>
<td>Patra</td>
<td>44.8</td>
<td>3.1</td>
<td>6.9</td>
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<tr>
<td></td>
<td>Volos</td>
<td>49.0</td>
<td>1.9</td>
<td>4.0</td>
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<tr>
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<td>32.2</td>
<td>4.9</td>
<td>15.0</td>
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<td>12.7</td>
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<td>70.0</td>
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<td>31.0</td>
<td>69.0</td>
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<tr>
<td></td>
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<td>55.0</td>
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<td>4.3</td>
<td>121</td>
<td>5.8</td>
<td>94.2</td>
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</table>
Typical daily exposure in Los Angeles basin: 294 μg day\(^{-1}\) *

16-h exposure to environmental tobacco smoke (ETS):

135 – 187 μg day\(^{-1}\) for adult males
76 – 106 μg day\(^{-1}\) for adult females

The calculated lung doses during severe and moderate dust episodes in Greece are comparable to those received during exposure in polluted urban and smoking areas as above (Mitsakou et al., ACPD 2008)

* (Venkataraman and Raymond, Inhalation Toxicology, Vol.10, 1998)
PM AND GASEOUS POLLUTANTS IN THE ATMOSPHERE

PROCESSES AFFECTING AIR QUALITY AND CLIMATE

Heterogeneous reactions

SO₂ + O₃ → DSO₄ (dust+sulfate)
NO₂ → DNO₃ (dust+nitrate)
HNO₃ → DNO₃ (dust+nitrate)

incoming-outgoing SW radiation

warming

LW radiation

cooling of the surface

Nucleation

Deposition

Cloud Modifications

precipitation

Dust

NaCl

hv & OH

SO₂ → H₂SO₄

SO₂, HCl, ash
MODELING PLATFORM

- DUST LOAD
- DUST OPTICAL DEPTH
- PHOTOLYSIS RATES
- HETEROGENEOUS CHEMISTRY

SKIRON/ETA MODELING SYSTEM With DUST MODULE

- DUST FLUXES
- DUST EMISSIONS
- SEA SALT EMISSIONS
- ANTHROPOGENIC EMISSIONS

CAMx AIR QUALITY MODEL

- METEOROLOGY

GAS PHASE POLLUTANTS
PARTICULATE MATTER (Sulfates, Nitrates etc)
CRUSTAL MATERIAL – DESERT DUST
NEW TYPES OF AEROSOLS
PROCESSES AND EFFECTS

✓ Shading effects of Saharan dust on photochemical processes

✓ Sea-salt production

✓ Heterogeneous processes and new particle formation
IMPACTS OF DESERT DUST ON PHOTOLYSIS RATES

**Vertical Distribution of Desert Dust for Athens for 17 April 2005, 12:00UTC**

- Literature:
  - J(NO2): $5 - 9.6 \times 10^{-3} \text{ sec}^{-1}$
  - J(O3): $0.45 - 3.5 \times 10^{-5} \text{ sec}^{-1}$
2h AVERAGE OZONE CONCENTRATION
EMEP SITE: Cabo de Creus, SPAIN
16-17 APRIL 2003

y = 0.73x + 0.0209
r = 0.8

y = 0.78x + 0.012
r = 0.88

IMPACTS OF DESERT DUST ON OZONE
SEA SALT PARTICLE PRODUCTION

Sea Salt Emissions are speciated into Na, Cl and SO4 aerosols by:

\[
\text{factor}_{Na} = 0.3856 \quad \text{factor}_{Cl} = 0.5389 \quad \text{factor}_{SO4} = 0.0755
\]

PERIOD OF SIMULATION: AUGUST 1-10, 2001

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

Diameter at each bin (μm): 0.03 – 0.1 – 2.5 – 10

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

**NaCl Aerosol:** Na + PCl 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 * Na

(N. Mihalopoulos, personal communication)

<table>
<thead>
<tr>
<th>CONFIGURATION</th>
<th>SKIRON/Eta</th>
<th>CAMx</th>
</tr>
</thead>
<tbody>
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<td><strong>Horizontal Resolution</strong></td>
<td>0.24 x 0.24 deg</td>
<td>0.235 x 0.18 deg</td>
</tr>
<tr>
<td><strong>Vertical Layers</strong></td>
<td>38 (up to 22km)</td>
<td>14 (up to 4km)</td>
</tr>
<tr>
<td><strong>Grid Points (Nx*Ny)</strong></td>
<td>135 x 213</td>
<td>200 x 108</td>
</tr>
<tr>
<td><strong>Latitude, Longitude</strong></td>
<td>34.7 , 8.4 (pole point)</td>
<td>28.0 , -7.0 (SW corner)</td>
</tr>
</tbody>
</table>
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>Cation</th>
<th>Reaction</th>
<th>Heterogeneous Reactions</th>
<th>Uptake Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO₂</td>
<td>DSO₄</td>
<td>1. SO₂ ---&gt; DSO₄ (dust+sulfate)</td>
<td>γ = 1.0*10⁻⁴</td>
</tr>
<tr>
<td>NO₂</td>
<td>DNO₃</td>
<td>2. NO₂ ---&gt; DNO₃ (dust+nitrate)</td>
<td>γ = 1.0*10⁻⁴</td>
</tr>
<tr>
<td>HNO₃</td>
<td>DNO₃</td>
<td>3. HNO₃ ---&gt; DNO₃ (dust+nitrate)</td>
<td>γ = 0.01</td>
</tr>
<tr>
<td>O₃</td>
<td>DO₃</td>
<td>4. O₃ ---&gt; DO₃ (dust+ozone)</td>
<td>γ = 5.0*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>
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<td>Horizontal Resolution</td>
<td>0.16 x 0.16 deg</td>
<td>0.235 x 0.18 deg</td>
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<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>
SEM analysis

Izaña

Sta. Cruz de Tenerife

COEXISTENCE OF MINERAL DUST, SULFATES AND CLOUD DROPLETS

(Alastuey et al. 2005)
COEXISTENCE OF MINERAL DUST, SULFATES AND CLOUD DROPLETS

A photomicrograph of drops and aerosol particles collected inside clouds
D: drops, P: dry interstitial particles

A photomicrograph of desert mineral dust with small sulfate particles on its surface.

(Levin et al. 1996, 2006)
PM10 Na (sodium) LOAD (mg/m²)
5 – 20 APRIL 2003

Layer: 0 - 4 km

Layer: 4 - 8 km
PM10 PSO4 (anthropogenic + sea salt) LOAD (mg/m²)  
6 – 20 APRIL 2003

Layer: 0 - 4 km

Layer: 4 - 8 km
3rd GENERATION POLLUTANTS
PM10 DSO4 (formed on dust) LOAD (mg/m²)
5 – 20 APRIL 2003

TOTAL DSO4 LOAD (0-4km)

TOTAL DSO4 LOAD (4-8km)
Distribution of mean PM concentration compared to the size section for the specific model domain

A

3 - 20 APRIL 2003

MEAN CONCENTRATION (μg/m³)

0,00 0,10 0,20 0,30 0,40 0,50 0,60 0,70

Size bins (diam-μm)

PCL NA PSO4 DSO4 PNO3 DNO3(NO2)

B

3 - 20 APRIL 2003

MEAN CONCENTRATION (μg/m³)

0,00 5,00 10,00 15,00 20,00 25,00 30,00

Size bins (diam-μm)

PCL NA PSO4 DSO4 PNO3 DNO3(NO2) CRST DNO3b
Cross-Atlantic Desert Dust and Aerosols
On June 1993 a major dust episode was recorded in Europe and by the IMPROVE network over the Atlantic Ocean and East USA. This was a “binary” type of Saharan dust transport episode.

PATHS OF LONG RANGE TRANSPORT OF PM IN THE MEDITERRANEAN REGION AND THE NORTH ATLANTIC OCEAN

W-E vertical cross-section of dust concentration (in μg m-3) for 23 June 1993, 12:00 UTC

Centered diameter: (a) 1.5 μm and (b) 12 μm

Kallos et al., JGR, 2006

Daily surface dust concentration (μg m-3) model-estimated (coloured fields) and measured at IMPROVE observation stations (white values in borders) for:
(c) 23 June 1993,
(d) 30 June 1993.
SKIRON/Dust daily forecasts

University of Athens (AM&WG)  SKIRON Forecast

Total Dust Load (mgr/m²)  Sat 31/05/08 at 00 UTC

Near-Ground Dust Concentration

Dust Load

SKIRON Forecast

(lgr/m³)  31/05/08 at 00 UTC
SULFATE LOAD (PM10) FOR LAYER 1: 0-4km (1-7 August 2001)
SULFATE ON DUST LOAD (PM10) FOR LAYER 1: 0-4km (1-7 August 2001)
DESERT DUST LOAD (PM10) FOR LAYER 2: 4 - 8km (1-7 August 2001)
SULFATE LOAD (PM10) FOR LAYER 2: 4 - 8km (1-7 August 2001)
SULFATE ON DUST LOAD (PM10) FOR LAYER 2: 4 - 8km (1-7 August 2001)
Mechanical Processes

Molecular Processes

Chemical transformation of gases, coalescence, condensation, homogeneous nucleation

Interaction

SCHEMATIC REPRESENTATION OF PM MASS-SIZE DISTRIBUTION

SULFATES FORMED ON DUST

NITRATES FORMED ON DUST

SULFATES

NITRATES

DUST

+ SEA SALT

+ SODIUM AEROSOL

+ CHLORIDE AEROSOL

sedimentation

rain

Interaction

PARTICLE DIAMETER (μm)

0.001 0.01 0.1 1 10 100

FINE PARTICLES COARSE PARTICLES
The links between air quality and meteorology (and regional climate) are many and not necessarily on one way.

The feedbacks between the various processes are many and complicated.

The existing modeling tools like SKIRON/Dust with CAMx are not able to describe some important feedbacks and especially aerosol – radiation – cloud and precipitation.

At the framework of the CIRCE project an effort is devoted on developing the Integrated Community Limited Area Modeling System (ICLAMS) to study such processes.
ICLAMS development is on RAMS ver. 6 modeling system

RAMS is a multi-scale modeling system and can be configured to run with resolution from a few meters to tens of kilometers on a two-way interactive nesting mode

It has detailed cloud microphysical scheme with 8 microphysical categories, detailed surface parameterization and many other features that make it an advanced limited area meteorological model

The cloud microphysical scheme includes prognostic equations for mass mixing ratios of the various forms of water species.
The new model development includes the following features:

- Dust cycle module following the formulation used in SKIRON/Dust with 8 dust bins following lognormal distribution Zender et al. (2003), Kallos et al., (2005, 2007).
- Sea salt production mechanism with 2 size bins following Gong et al., (1999).
- Gas and aqueous phase chemistry (SAPRC mechanism as implemented in CAMx).
- Heterogeneous chemistry following ISOROPIA scheme and additional interactions with desert dust, sea salt and sulfates on a uniform environment.
- Impacts of aerosols and PMs on radiative transfer of the photochemically active bands.
- Visible and Infrared corrections due to aerosols and PMs.
- Treatment of CCN and GCCN as predictive quantities (4-D).
- All these new elements are directly coupled and executed together with the meteorological modules.
On 28 January 2003, a dust storm passed over the north east Mediterranean region.

On 29 JAN 2003 heavy rain and hail dispersed over the Middle East coastline and a few km inland.

Flood events and agricultural disasters were reported.

Airborne measurements of this episode were obtained during the Mediterranean Israeli Dust Experiment (MEIDEX)

RAMS6 with dust and sea salt modules

1st case: Natural particles are treated as passive tracers. User specified constant CCN #.

2nd case: Dust plume and sea-salt spray interact with clouds. CCN and GCCN prognostic (from dust and sea salt concentrations and size distribution.)
MODEL SETUP

RAMS6.0 with:

**DUST MODULE** (Zender at al., Marticorena and Bergameti)

8 *Bin lognormal dust particles distribution* - *Dust cycle*

**SEASALT MODULE** (Gong et al.)

2 *Bin lognormal salt particles distribution* - *Seasalt cycle*

DOMAIN SETUP

3 grids (36km-12km-4km), 31 vertical levels, 120 hours run

Initial and boundary conditions – NCEP 1deg GFS analysis data

**REFERENCE RUN (1st case)**

ICLOUD=5 (Constant # of CCN)

Dust and Salt particles do not interact with the rest of the model

**TEST RUN (2nd case)**

ICLOUD=7 (3-D prognostic CCN and GCCN field)

Particles serve as efficient cloud condensation nuclei (CCN).
On 28 Jan 2003 a cold cyclone moved from Crete through Cyprus accompanied by a cold front.

A second air mass transported dust particles from NE Africa over the sea towards the Israeli coast.
DUST CONCENTRATION at 1500UTC (all bins)

27JAN2003 1500 UTC

1071 m
6th model level

2087 m
9th model level

3440 m
12th model level

28JAN2003 1500 UTC

29JAN2003 1500 UTC
SEA SALT CONCENTRATIONS at 1500 UTC (both bins)

27JAN2003

97 m
2nd model level

530 m
4th model level

1071 m
6th model level

28JAN2003

29JAN2003
Case 1 - CONSTANT CCN (ICLOUD=5)

Case 2 - PROGNOSTIC CCN (ICLOUD=7)
HAIL PATTERN (3-hour accumulated)

Case 1 - CONSTANT CCN (ICLOUD=5)

Case 2 - PROGNOSTIC CCN (ICLOUD=7)
Total Particles have been measured at 15 locations along the aircraft flight (11:27–13:40 UTC 28JAN2003)

<table>
<thead>
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<th>Time in (LT)</th>
<th>Time in (UTC)</th>
<th>height (m)</th>
<th>Mean (Latitude)</th>
<th>Mean (Longitude)</th>
<th>Total concentration (cm⁻³)</th>
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<td>640.54</td>
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<td>32.12</td>
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<td>967.59</td>
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<td>31.94</td>
<td>33.98</td>
<td>680.34</td>
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<td>13:30</td>
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<td>32.35</td>
<td>34</td>
<td>922.83 below cloud</td>
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<td>13:36</td>
<td>1371.6</td>
<td>32.39</td>
<td>34.03</td>
<td>1082.56 in cloud</td>
</tr>
<tr>
<td>11:40</td>
<td>13:40</td>
<td>2286</td>
<td>32.32</td>
<td>34.09</td>
<td>323.15</td>
</tr>
</tbody>
</table>
Maximum particles concentration during the flight period (10:00 – 13:00 UTC) are ranging from 1000 #/cm³ near the ground to below 50#/#cm³ above 3 Km. These numbers compare well with the aircraft observations.
COARSE & FINE PARTICLES

- During the dust storm simulation the concentration profile for coarse particles (d>1 μm) ranged from 40 (#/cm³) near the ground to less than 5(#/cm³) above 2km.
- The simulated concentration for fine particles (d<1 μm) ranged from 1000 (#/cm³) near the ground to less than 100 above 3km.
- During the MEIDEX experiment an increase in fine particles concentration was measured between 2-3km because of the lack of enough bigger particles for coalescence. This feature was not reproduced accurately with the model.
2nd CASE: Aerosols serve as efficient CCN

- For simplicity we assume that all particles produced (dust and sea salt) are efficient CCN.
- However the CCN field will not retain the lognormal characteristics of aerosol size distribution.
- Dust and sea salt - born CCN will be added on the background value (CPARM 400) in order to enhance the effect of the dust storm in cloud processes.
- The rest of the RAMS microphysics scheme remains unchanged.
RAMS CCN VERTICAL DISTRIBUTION

Constant CCN field

CCN concentration (#/cm³)

Prognostic 3D CCN field

CCN concentration 28JAN2003 1700 UTC

CCN concentration 29JAN2003 0500 UTC

CCN concentration 29JAN2003 1600 UTC

CCN concentration 30JAN2003 0000 UTC
CLOUD CONCENTRATION VERTICAL CROSSECTION

Constant CCN field

Cloud concen. (#/cm³) 28JAN2003 16 UTC

Cloud concen. (#/cm³) 29JAN2003 11 UTC

prognostic CCN field

Cloud concen. (#/cm³) 28JAN2003 16 UTC

Cloud concen. (#/cm³) 29JAN2003 11 UTC
TOTAL CONDENSATES VERTICAL CROSSECTION

constant CCN field

Total condensates (#/cm³) 29JAN2003 12 UTC

Total condensates (#/cm³) 29JAN2003 15 UTC

Prognostic CCN field

Total condensates (#/cm³) 29JAN2003 12 UTC

Total condensates (#/cm³) 29JAN2003 15 UTC
ICE MIXING RATIO VERTICAL CROSSECTION

Constant CCN field

Ice mix ratio (gr/kgr) 28JAN2003 18 UTC

Ice mix ratio (gr/kgr) 28JAN2003 21 UTC

Prognostic CCN field

Ice mix ratio (gr/kgr) 28JAN2003 18 UTC

Ice mix ratio (gr/kgr) 28JAN2003 21 UTC
Significant delay on the updraft velocity maximum during cloud development and also increase in maximum value in 2nd mode run (yellow line)
### Feature

<table>
<thead>
<tr>
<th>Feature</th>
<th>Constant CCN field</th>
<th>All particles are effective CCN</th>
<th>All fine particles and 33% from the coarse are effective CCN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max updraft</td>
<td>9.27</td>
<td>10.26</td>
<td>10.63</td>
</tr>
<tr>
<td>Time and height</td>
<td>10:00 UTC at 4km</td>
<td>13:00 UTC at 4km</td>
<td>14:00 UTC at 4km</td>
</tr>
</tbody>
</table>
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 due to shading).

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.

There is a considerable amount of sulfate and nitrate transported from Europe to the ITCZ and then Central Atlantic.

The amount of third generation aerosols found in the lower and middle troposphere of the Central Atlantic is considerable.

Its role on hurricane formation needs further investigation.
ACKNOWLEDGEMENTS

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