South East European Virtual Climate Change Center

Dust modeling
problems and uncertainties
impacts and case studies

Goran Pejanović
Assistant director
Republic Hydrometeorological Service of Serbia
(host of the SEEVCCC)

34% of the Earth's land surface is dry, home to two billion people exposed daily to the major sources of windblown dust circling the globe

WWW.SEEVCCC.RS

Importance of dust modeling - impacts

Mineral dust is recognized as major part of global aerosol mass, but with short residence time in the atmosphere (Kinne et al., 2006).

Including mineral dust transport and corresponding impacts in numerical models can improve accuracy of weather forecasts and climate simulations and also contribute to understand processes caused by mineral dust.

Impact on radiation budget:
Airborne dust changes Earth's radiation budget (modify incoming solar radiation and the outgoing infrared radiation) and consequently the atmospheric dynamics (Perez et al. 2006). Example: case study over Bodélé depression that radiative impact of high dust loadings resulted in a reduction in surface daytime maximum temperature around 7°C (Todd at al. 2007).

Impact on cloud ice nucleation:
Dust aerosol plays important role on climate and environment through its impact on the heterogeneous ice nucleation. Klein et al. (2010) found out that mineral dust is a dominant constituent in the ice nucleating process, observing coincidence of picks in ice nuclei numbers and dust concentration originating from a major Saharan dust intrusions into Europe.

Impact on ocean productivity:
Dust deposited over remote ocean regions after long-term atmospheric transport can be important nutrient for the marine life. Iron, phosphorus and silicates embedded in dust are considered as major potential micronutrients for the ecosystems in remote oceans. Singh et al. (2008) showed that dust deposition over Arabian Sea several days later causes chlorophyll blooming. Cooling of the ocean surface is also noticed along with higher ocean wind speeds during dust events, which can lead to favorable conditions for blooming.

Impact on health:
Airborne dust can significantly influence human health near and also far from source region. Middleton et al. (2008) observed an increased risk of hospitalization on dust storm days. Liu et al. (2009) estimated impacts of inter-continental transport of aerosols on premature mortality and found that nearly 380 thousands premature deaths per year globally associated with exposure to fine aerosols which dominant component is dust transported inter-continentally. Meningococcal (epidemic) meningitis in Sahel, one of the most serious diseases in Africa, has rapid start and high mortality and morbidity rate, and is highly correlated with dusty weather season. How dust eventually triggers the meningitis epidemics remains yet unclear.

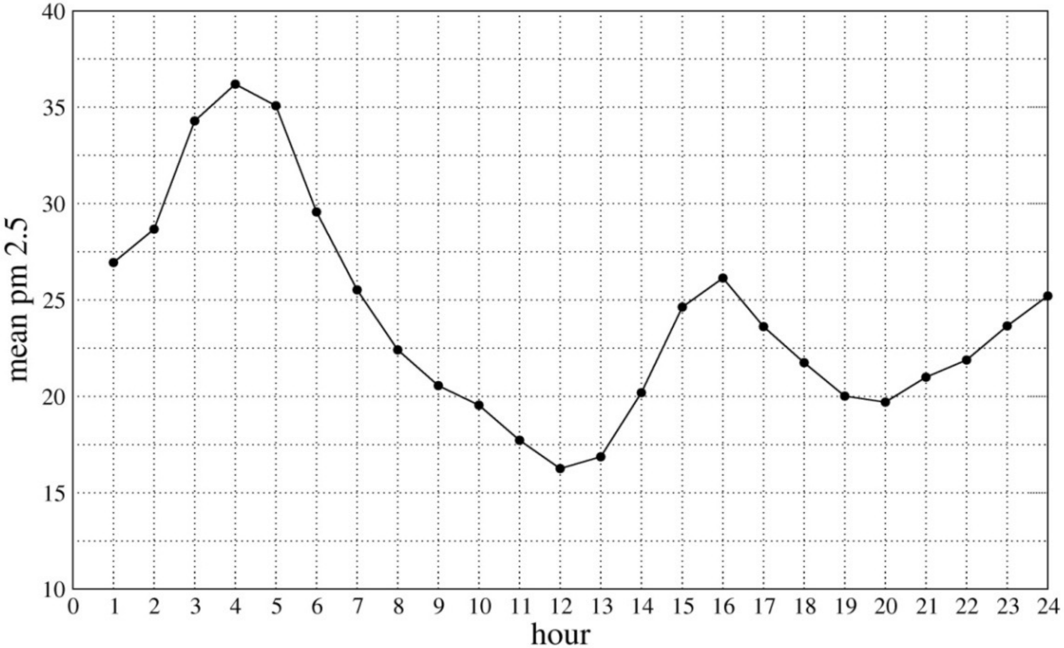
Behavior of air borne dust in its interaction with the environment is to a large extent determined by mineral composition of dust particles.

Problems in dust modeling and model verification - examples

Sources:
How to define properly dust source?
Necessary is to know land cover and soil texture. Source is region where ground is bare and contain soil particles available for uplift, which depends on soil moisture.
For large dust sources (deserts, such is Sahara) – not enough knowledge about soil texture. In recent years problem is tried to overcome with “preferential source” approach.
For areas with smaller scattered dust sources (South West America) problem is seasonal change of vegetation and needs regular update of land cover information.

Emission and deposition:
How to properly parameterize?
Models use different approaches for emission scheme.

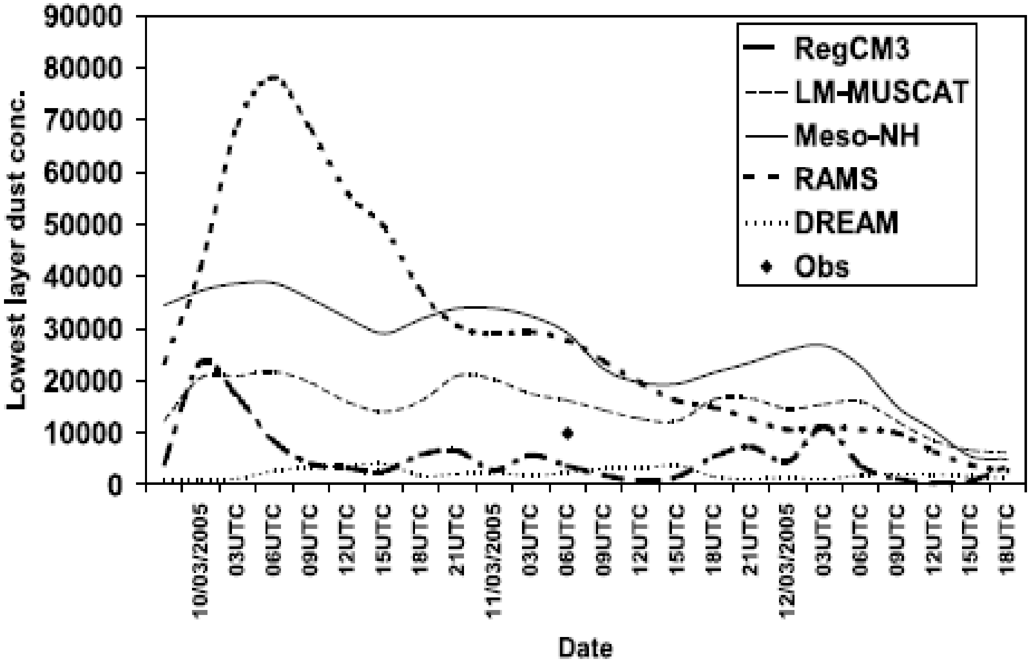
Verification and intercomparison of models:
Not enough measurements. If observations of pm are in urban areas, it is hard to exclude “man-made” pollution signal.
Models differ in dust related parameterisation schemes, definition of sources, number and size of dust particle nodes, which can influence intercomparison and reason for difference in results is hard to detect.



Problem with pm measurements:

Mean hourly values of PM2.5
in one of AIRNow stations in El Paso,
obtained from measured values
in period Dec 1st 2009 – Sep 30th 2010
(hour in UTC)

peeks coincide with traffic peeks



Time series of model simulated dust concentration in model lowest layer at Bodele depression, Chad

Todd et al., (2008) showed that five inter-compared dust models differed by an order of magnitude or more in their simulations of surface concentration.

Mask of dust sources

- provides a numerical model with an information on the location of potential dust sources, amount of dust available for uptake and size distribution of dust particles.

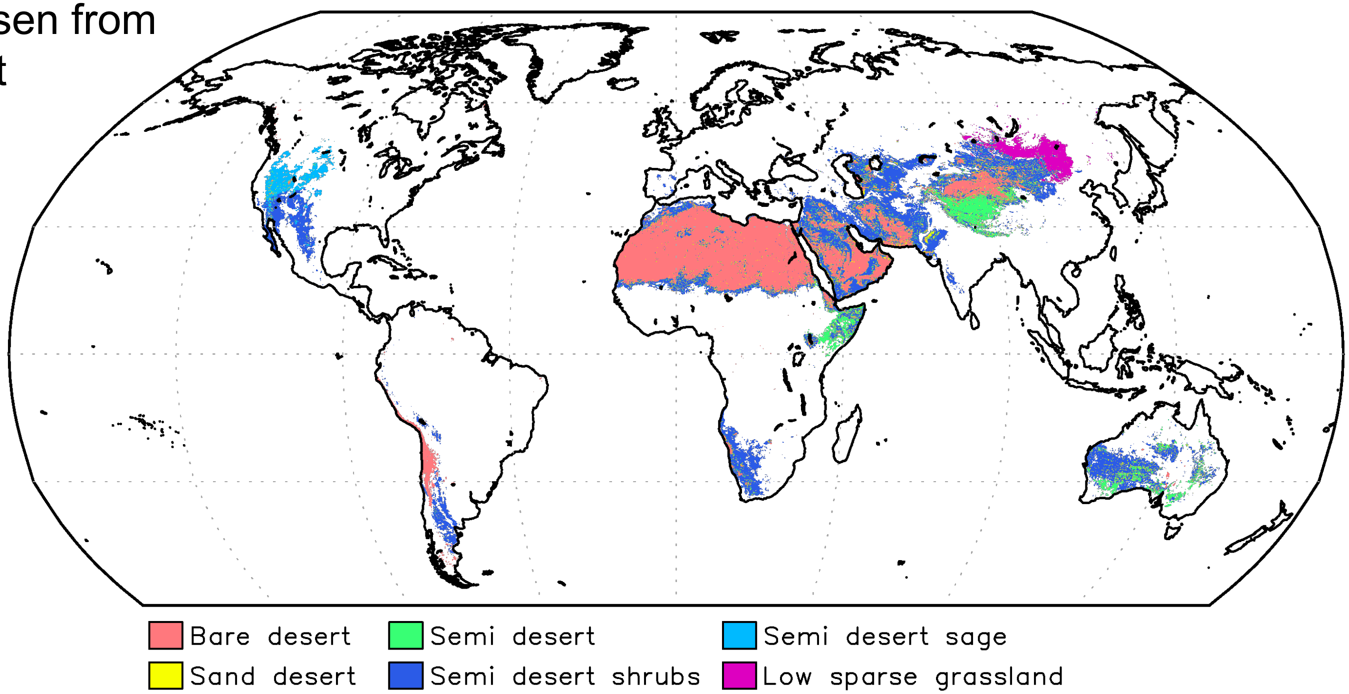
- process of making a dust sources mask differs from model to model and it contains a large amount of uncertainty

Land cover type based dust sources mask

- potentially dust productive land cover types are chosen from USGS land cover dataset

- chosen categories have different source efficiency

Land cover types used in DREAM



Preferential dust sources mask

- dust productive areas are mainly located in topographic lows, where during the history were located rivers and lakes, Ginoux et al. 2001

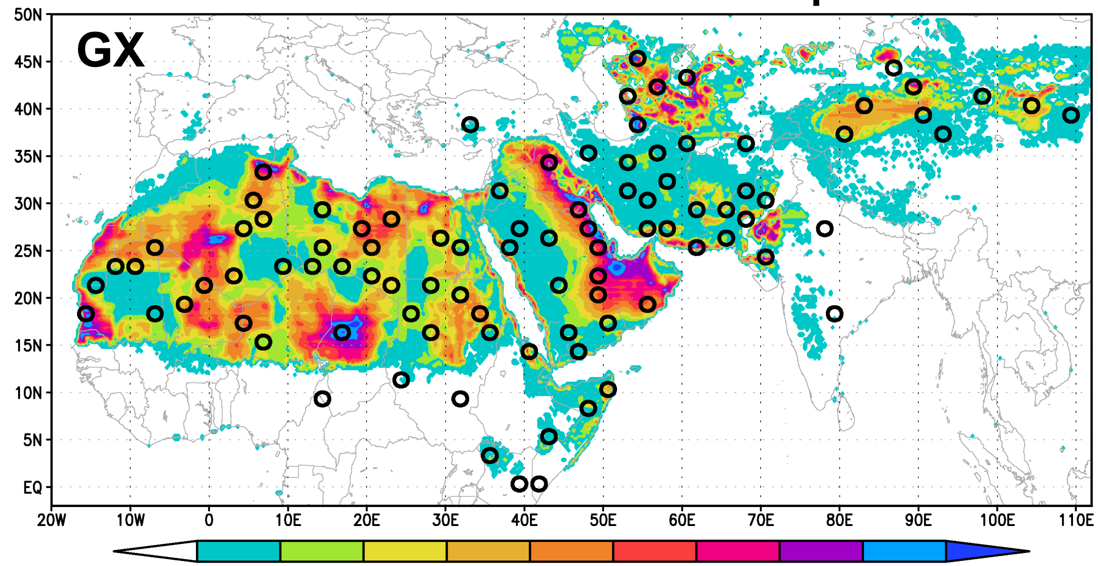
$$S = \left(\frac{z_x - z_i}{z_x - z_n} \right)^5$$

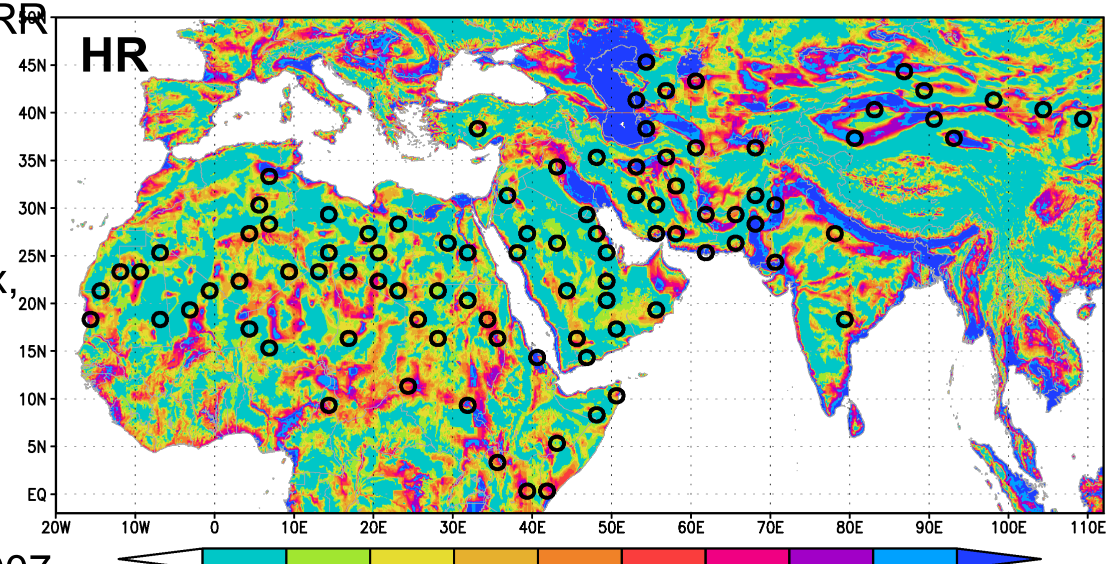
Ginoux (**GX**):
low resolution, 10x10 degrees box,
S function + bare surface from AVHRR (1x1 degrees)

High resolution (**HR**):
1km resolution, 2.5x2.5 degrees box,
S function only

○ dust hotspots – points with maximum TOMS values, Engelstaedter and Wasington, 2007

N. Africa – Europe - SW Asia





Dust sources mask based on MODIS dat

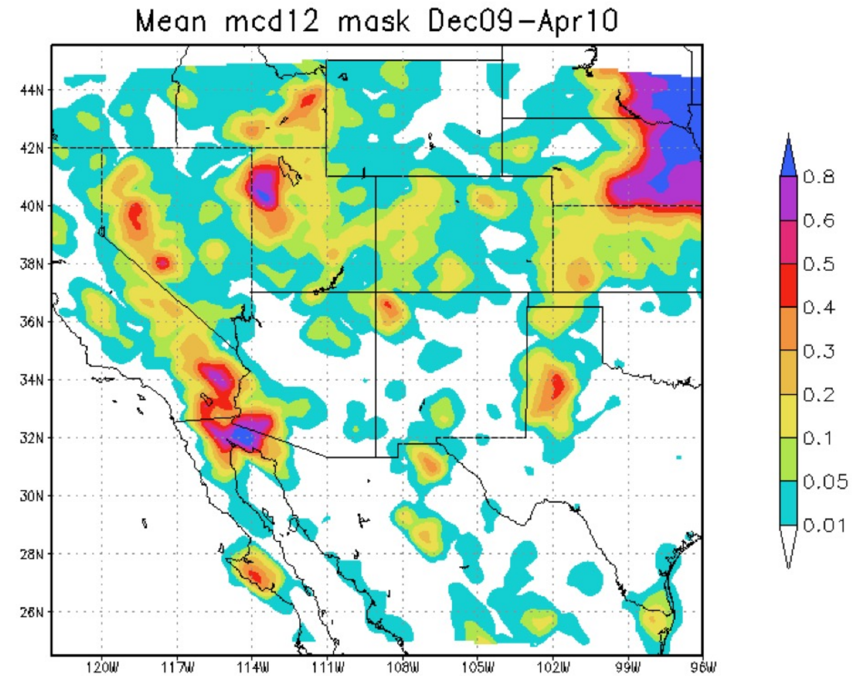
(experience from NASA/EMPHASYS project)

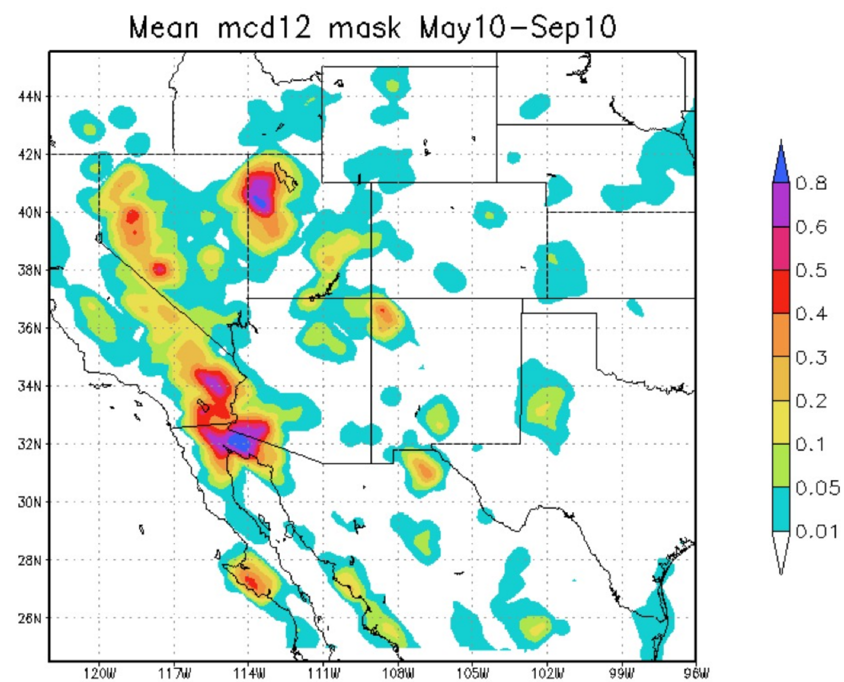
-bare soil from MCD12Q1 annual land cover data from MODIS Aqua and Terra

- seasonal dust sources from agricultural regions should also be included when there are no crops; this could be a very important dust source on local level

- combine bare soil from MCD12Q1 with NDVI data from MODIS Terra

- NDVI data are available for 16-days long periods; updated dust sources mask every 16 days





DREAM (Dust Regional Atmospheric Model) workflow

Dust model is coupled with atmospheric model (Eta, NMM,…)

Preprocessing:
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

Kernel of dust modeling – to solve equation:

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

horizontal advection

vertical advection

horizontal turbulent mixing

vertical turbulent mixing

source

sink

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

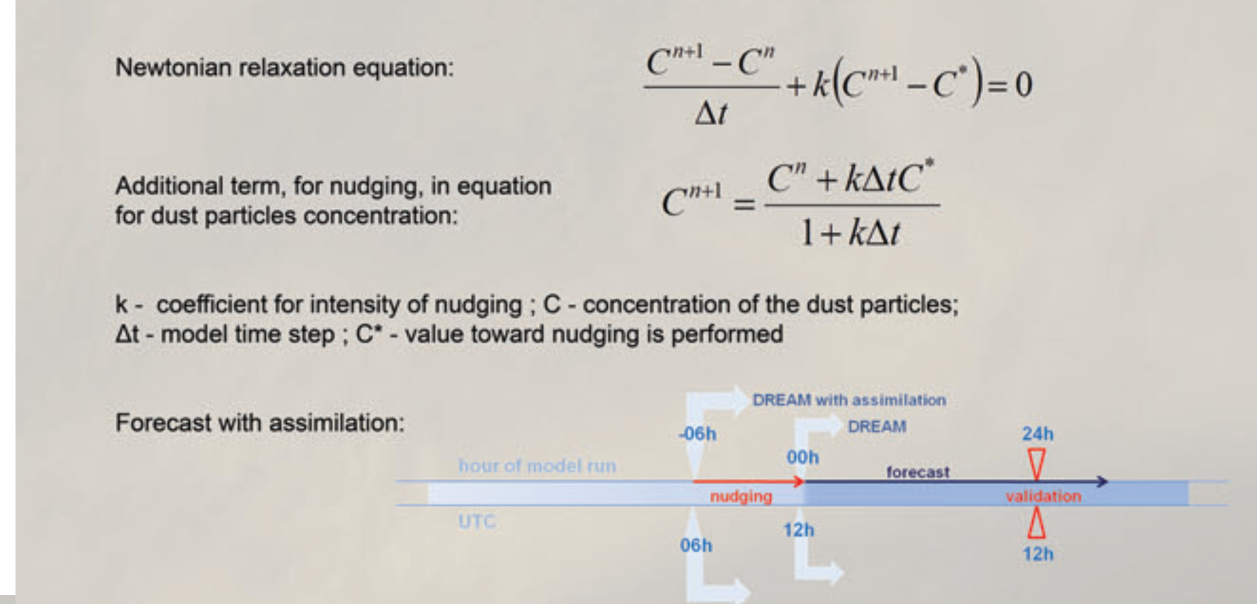
loss through dry (gravitational settling) and wet (washed down by precipitation) deposition

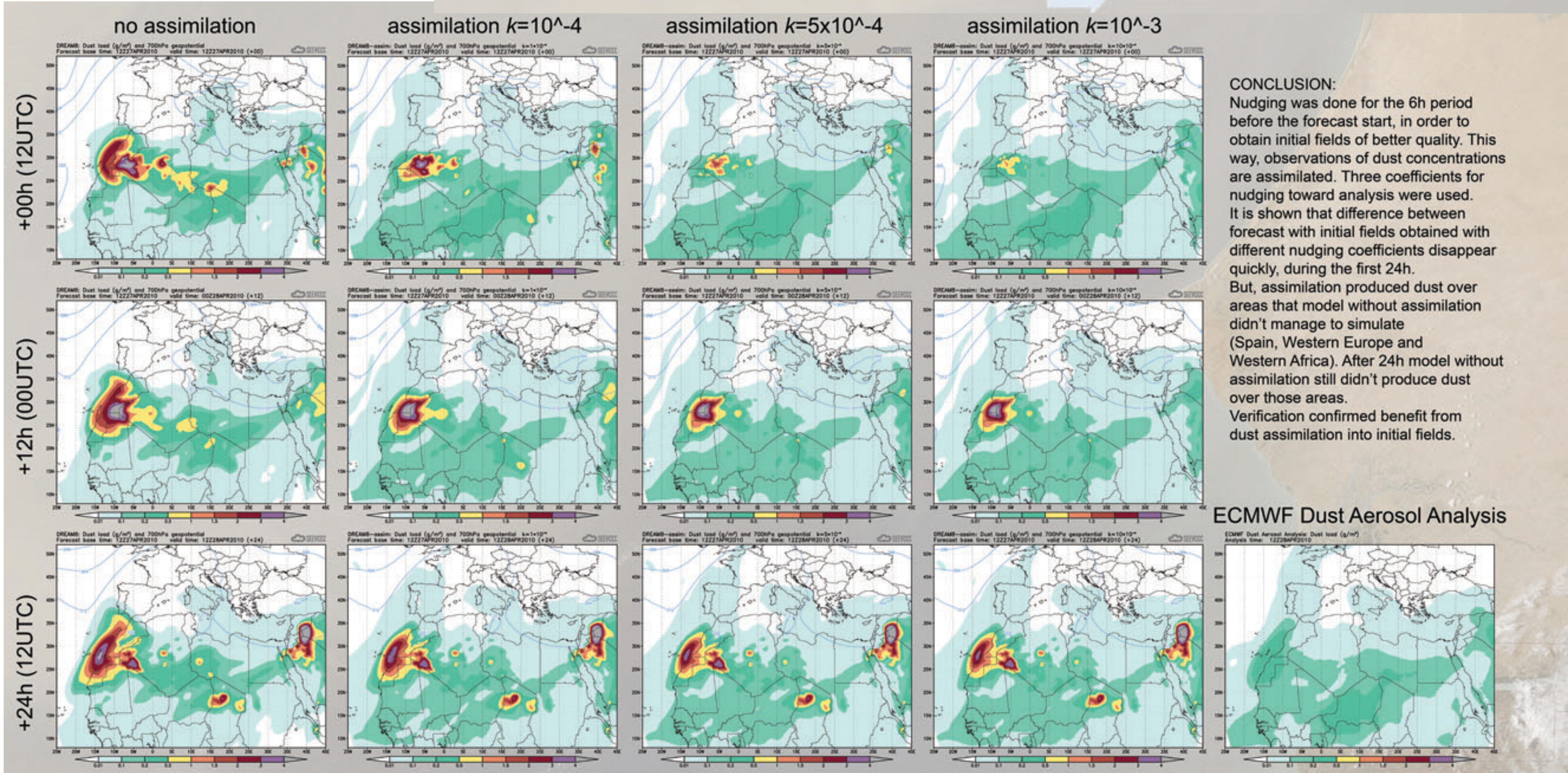
(Nickovic et al., 2001)

Assimilation of satellite information on mineral dust

ECMWF dust aerosol analysis assimilated in initial field.

http://www.seevccc.rs/test/wp-content/uploads/2010/04/assimilation.jpg





Dust related products in SEEVCCC

Daily products:

- DREAM8: forecast starting from 00 UTC for 72h ahead using
  DREAM model with 8 dust particles size bins;
  domain: Euro- Mediterranean and North Africa; resolution: 1/3 degrees
- DREAM8assim: forecast starting from 00 UTC for 72h ahead using
  DREAM model with 8 dust size bins:
  ECMWF dust analysis from previous day is incorporated within
  the initial field of dust concentration
  domain: Euro- Mediterranean and North Africa; resolution: 1/3 degrees

http://www.seevccc.rs/?p=8

- DREAM8asia: forecast starting from 00 UTC for 72h ahead using
  DREAM model with 8 dust particles size bins;
  domain: Southwestern Asia; resolution: 1/3 degrees

http://www.seevccc.rs/SW_ASIA/

Products for special purposes:

- FENNEC project: during FENNEC field campaign SEEVCCC provides with
  DREAM8 72h forecasts twice per day, starting at 00 and 12 UTC
  domain: Northwestern Africa and Mediterranean; resolution: 1/6 degrees

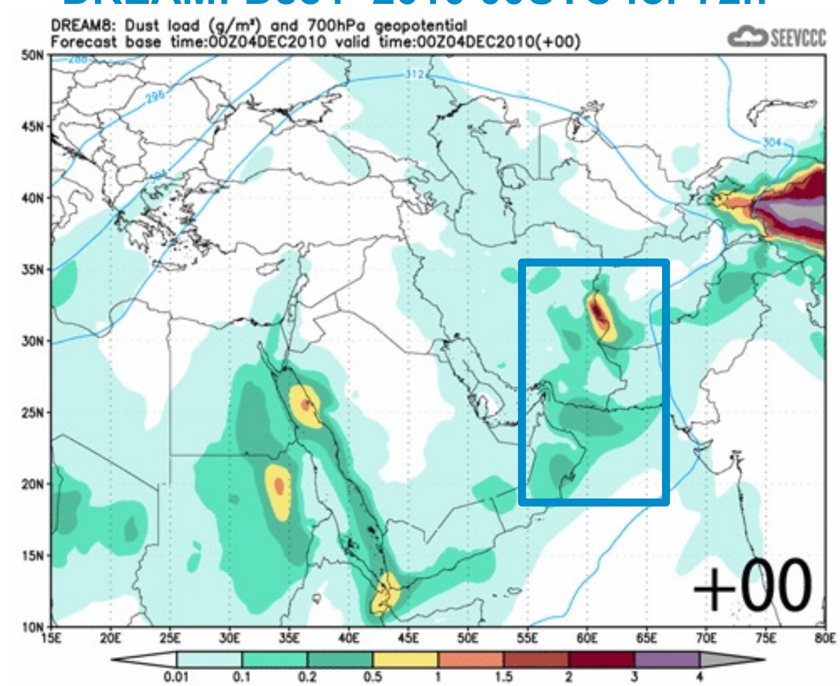
http://www.seevccc.rs/FENNEC/

Example of SW- ASIA domain dust forecast: Dust storm December 4th -5th 2010

NASA Earth Observatory:

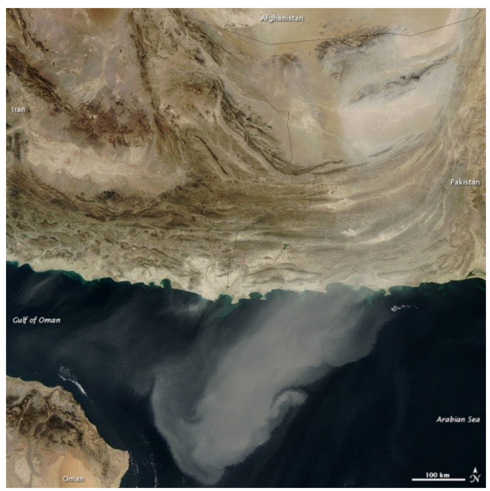
- A dust storm spanned hundreds of kilometers over the borders between Iran, Afghanistan and Pakistan on December 4, 2010. This dust storm appears to arise from the dry lake region along the Iran-Afghanistan border, and may pick up more dust over the Afghanistan-Pakistan border
- On December 5, 2010, the plume was over the Arabian Sea, headed for the southeastern tip of the Arabian Peninsula.

DREAM: Dec4th2010 00UTC for 72h



MODIS: Dec 4th 2010

MODIS: Dec 5th 2010



High resolution dust modeling

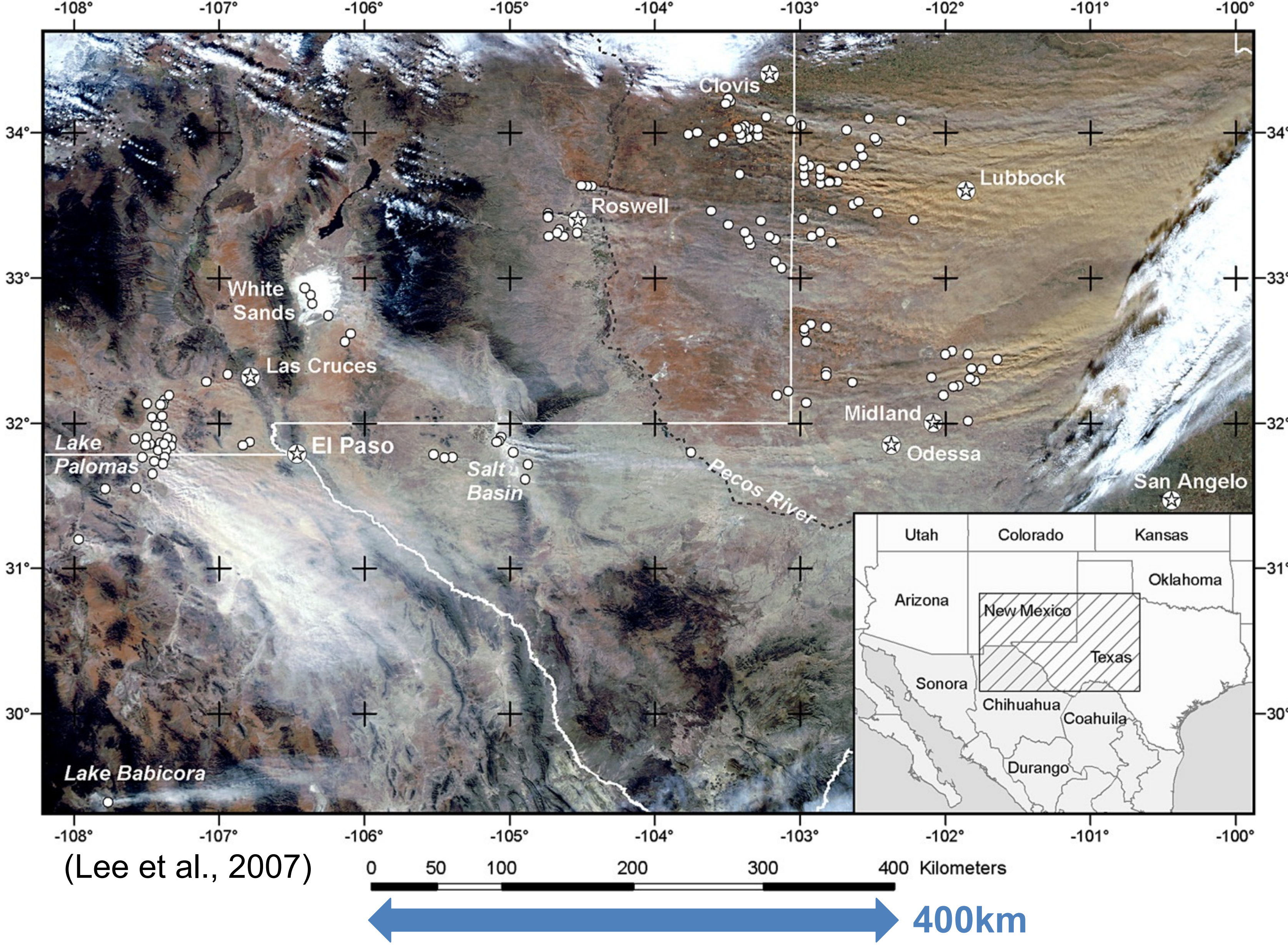
In case of short time and intense dust events high resolution (bellow 10km) of model simulations is necessary.

Example:

South middle and west USA
– territory with a lot of small strong dust sources, seasonally dependant.

During summer season, under NAM monsoon conditions, strong winds followed by dust storms are common. Dust outbursts are local, short lived but with extremely high dust concentrations. These events are called “haboobs”.

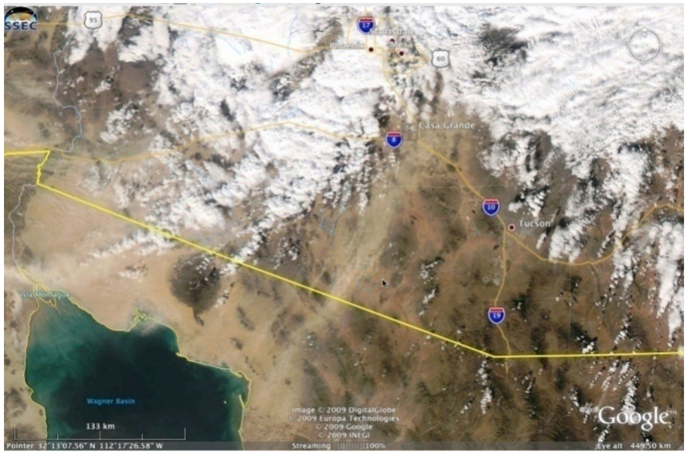
High resolution is necessary because of local character of the event and for models to be able to capture small dust sources.

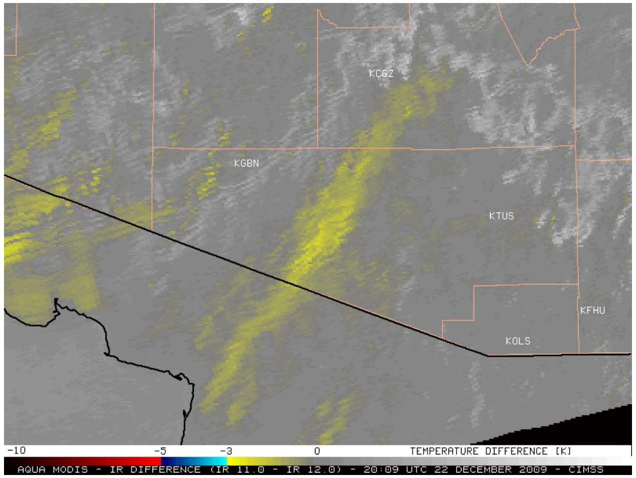


(Lee et al., 2007)

Dust hot spots in Texas, New Mexico detected from NASA/MODIS images.

Case: Arizona - December 22nd 2009 (from NASA/EMPHASYS report)

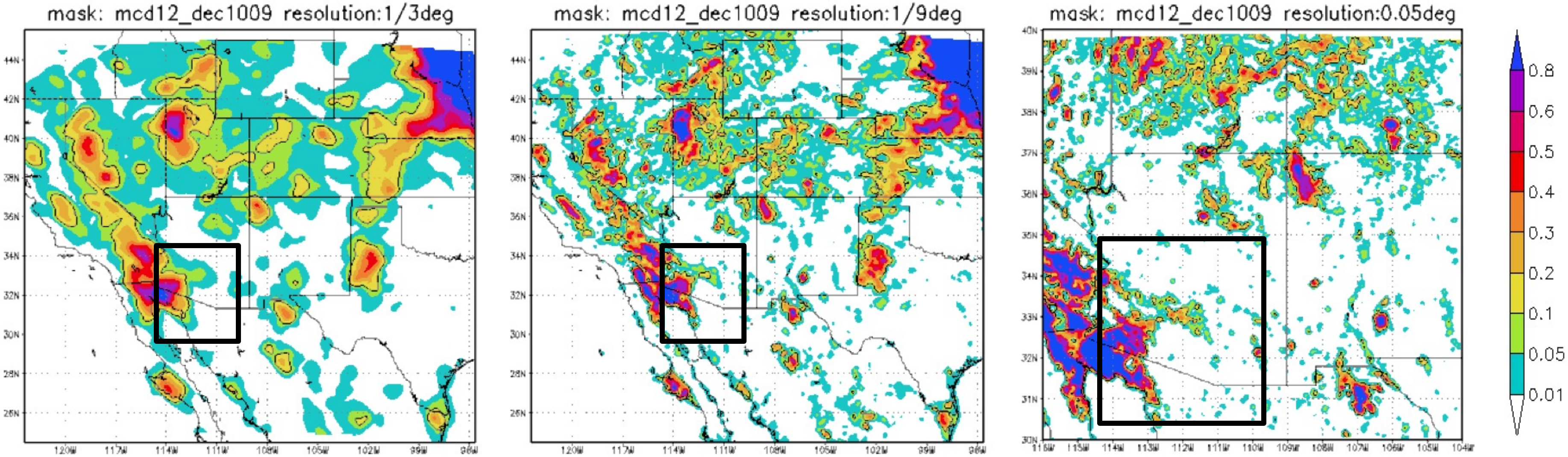




Satellite images for December 22nd 2009 (~20hUTC), Terra MODIS (left) and Aqua MODIS IR difference (right)

Model resolutions: 50km, 17km, 7.5km

Dust mask: Mcd annual + NDVI for period of simulation (data from Modis & Aqua)



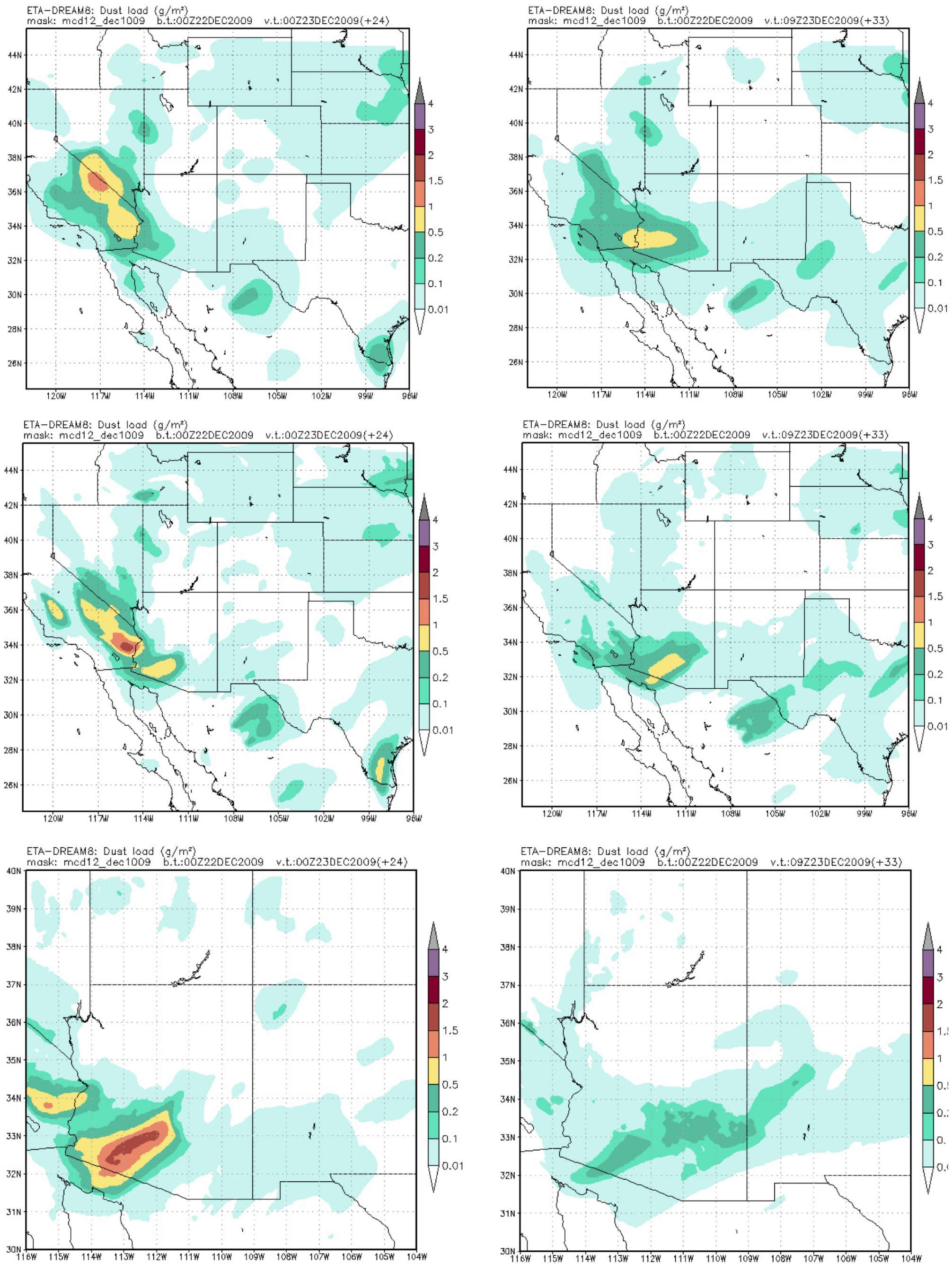
December 22nd 2009 00UTC +24h

December 22nd 2009 00UTC +33h

D8MCD 50km

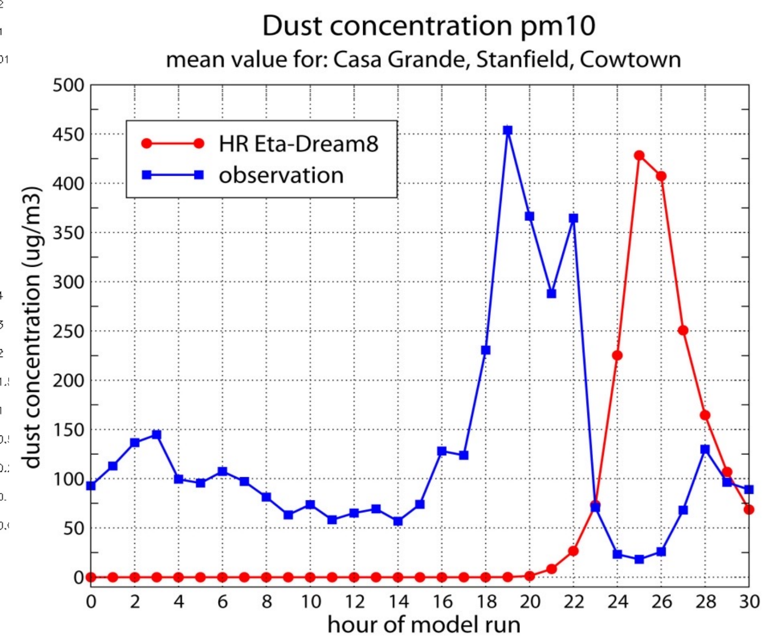
D8MCD 17km

D8MCD 7.5km



Model:
DREAM with ETA atmospheric driver

Results show:
With increasing model resolution
timing is better,
dust sources in mask are stronger,
produce larger dust uptake,
closer to reality.



Case: Arizona, Phoenix – July 5th 2011

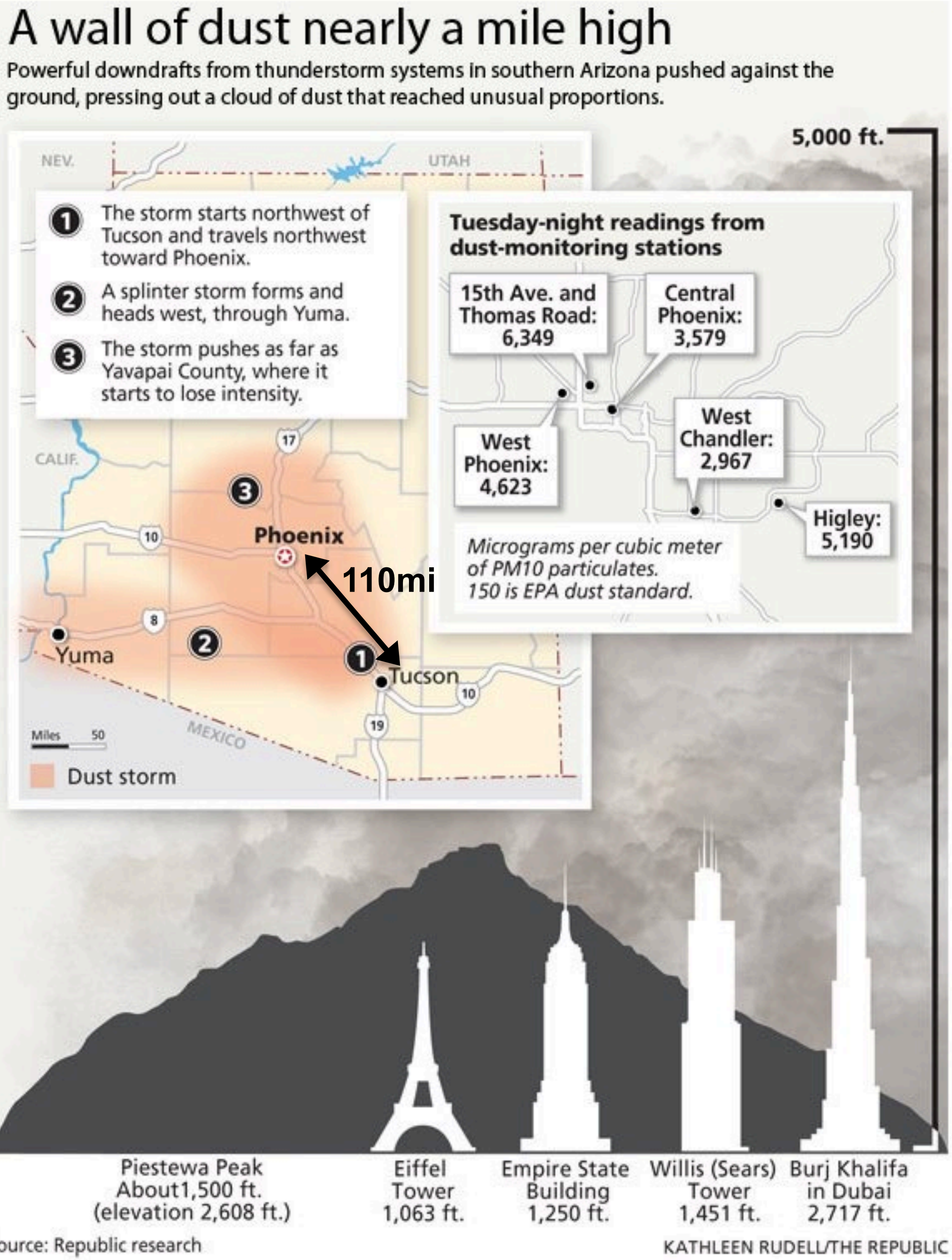
According to National Weather Service Forecast Office:

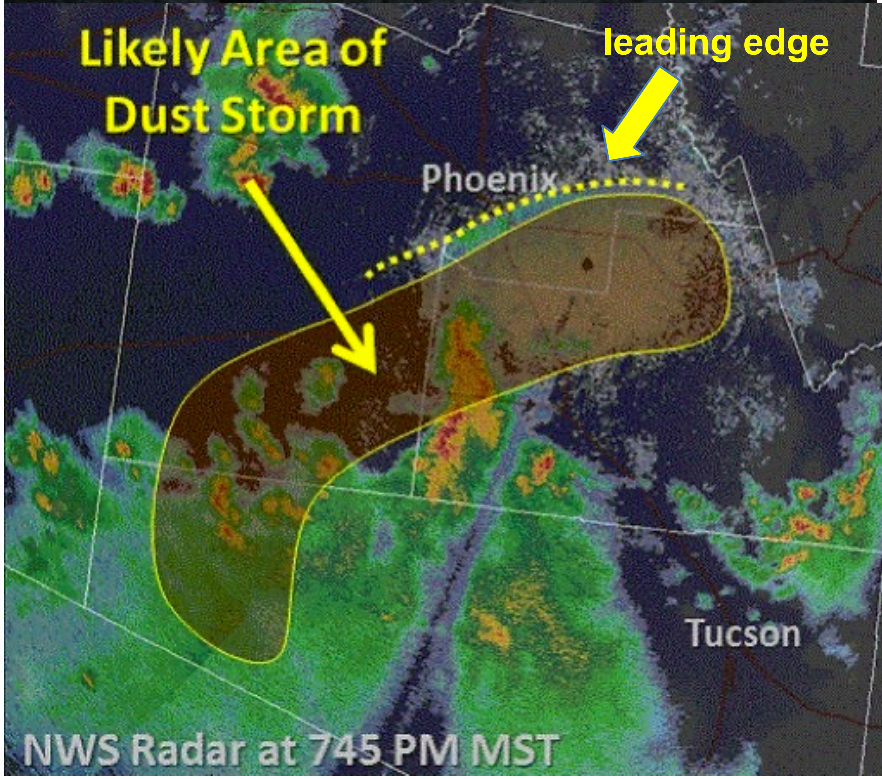
dust storm was estimated to reach a peak height of at least 5000ft (1500m);
areal coverage on the leading edge stretching nearly 100 miles (160 km);
storm traveled at least a 250km and in the evening hours reduced visibility in Phoenix to zero;

at about 7 PM MST (2 UTC) dust storm hit the far southeast part of Phoenix and continued further through entire city area during next two hours;

Cause for such event is development of severe thunderstorms in south of Arizona that produced downburst winds and elevation difference between Tuscon and Phoenix area (+460m). Strong outflow winds continued toward north over very dry area, with precipitation less than 50% of normal since the end of the last summer.

Dust storms developed in this way are also called haboobs.

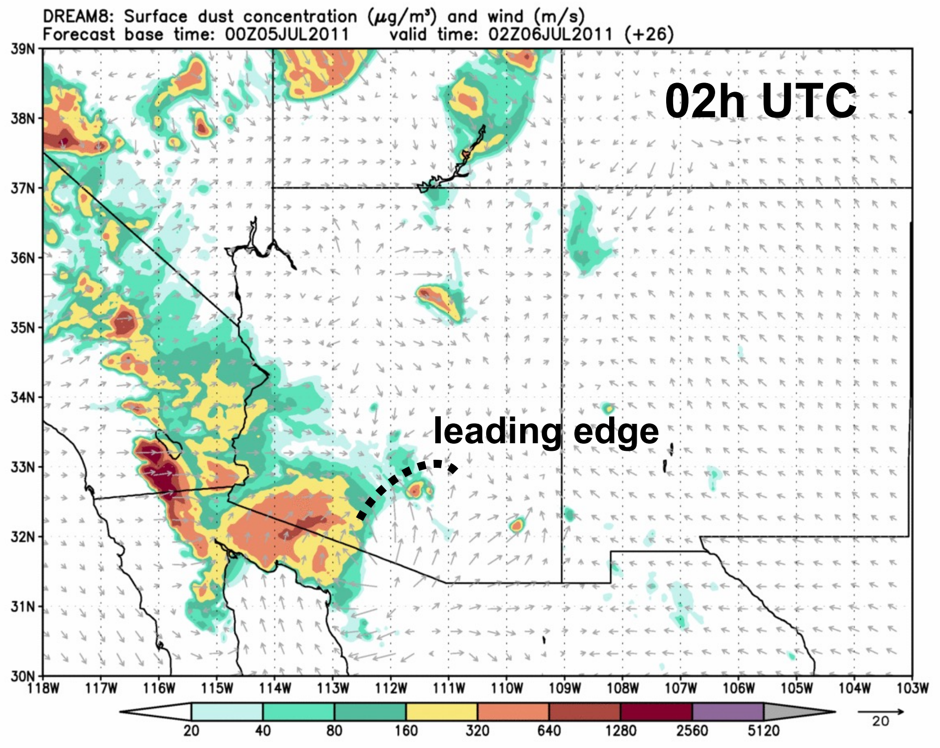

A wall of dust nearly a mile high
Powerful downdrafts from thunderstorm systems in southern Arizona pushed against the ground, pressing out a cloud of dust that reached unusual proportions.
5,000 ft.
NEV.
UTAH
CALIF.
MEXICO
1 The storm starts northwest of Tucson and travels northwest toward Phoenix.
2 A splinter storm forms and heads west, through Yuma.
3 The storm pushes as far as Yavapai County, where it starts to lose intensity.
Phoenix
Yuma
Tucson
110mi
Miles 50
Dust storm
Tuesday-night readings from dust-monitoring stations
15th Ave. and Thomas Road: 6,349
Central Phoenix: 3,579
West Phoenix: 4,623
West Chandler: 2,967
Higley: 5,190
Micrograms per cubic meter of PM10 particulates. 150 is EPA dust standard.
Piestewa Peak About1,500 ft. (elevation 2,608 ft.)
Eiffel Tower 1,063 ft.
Empire State Building 1,250 ft.
Willis (Sears) Tower 1,451 ft.
Burj Khalifa in Dubai 2,717 ft.
Source: Republic research
KATHLEEN RUDELL/THE REPUBLIC

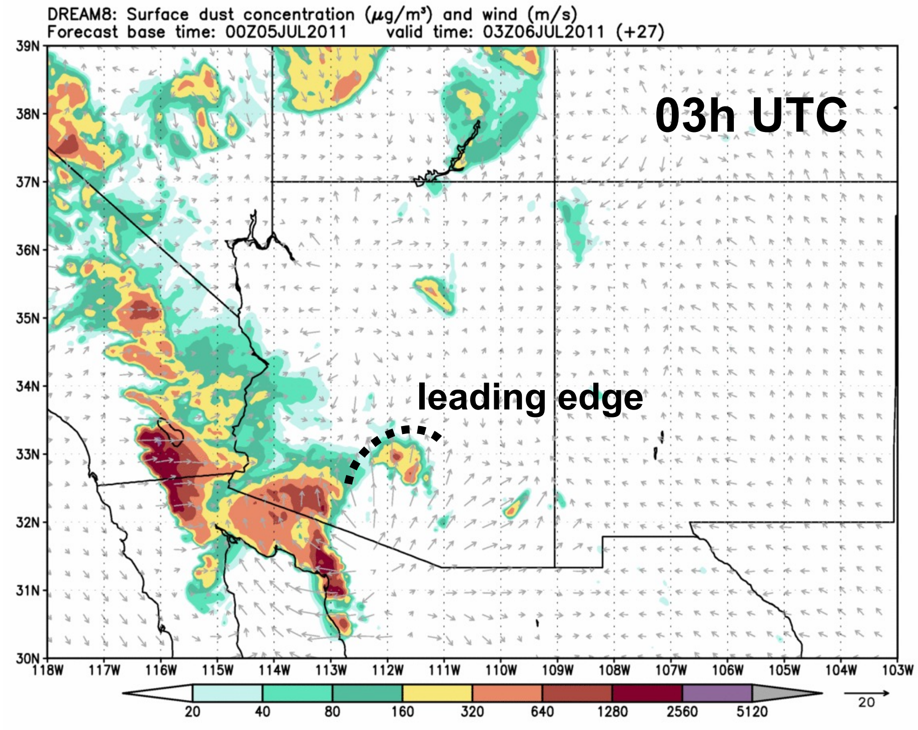

Likely Area of Dust Storm
leading edge
Phoenix
Tucson
NWS Radar at 745 PM MST

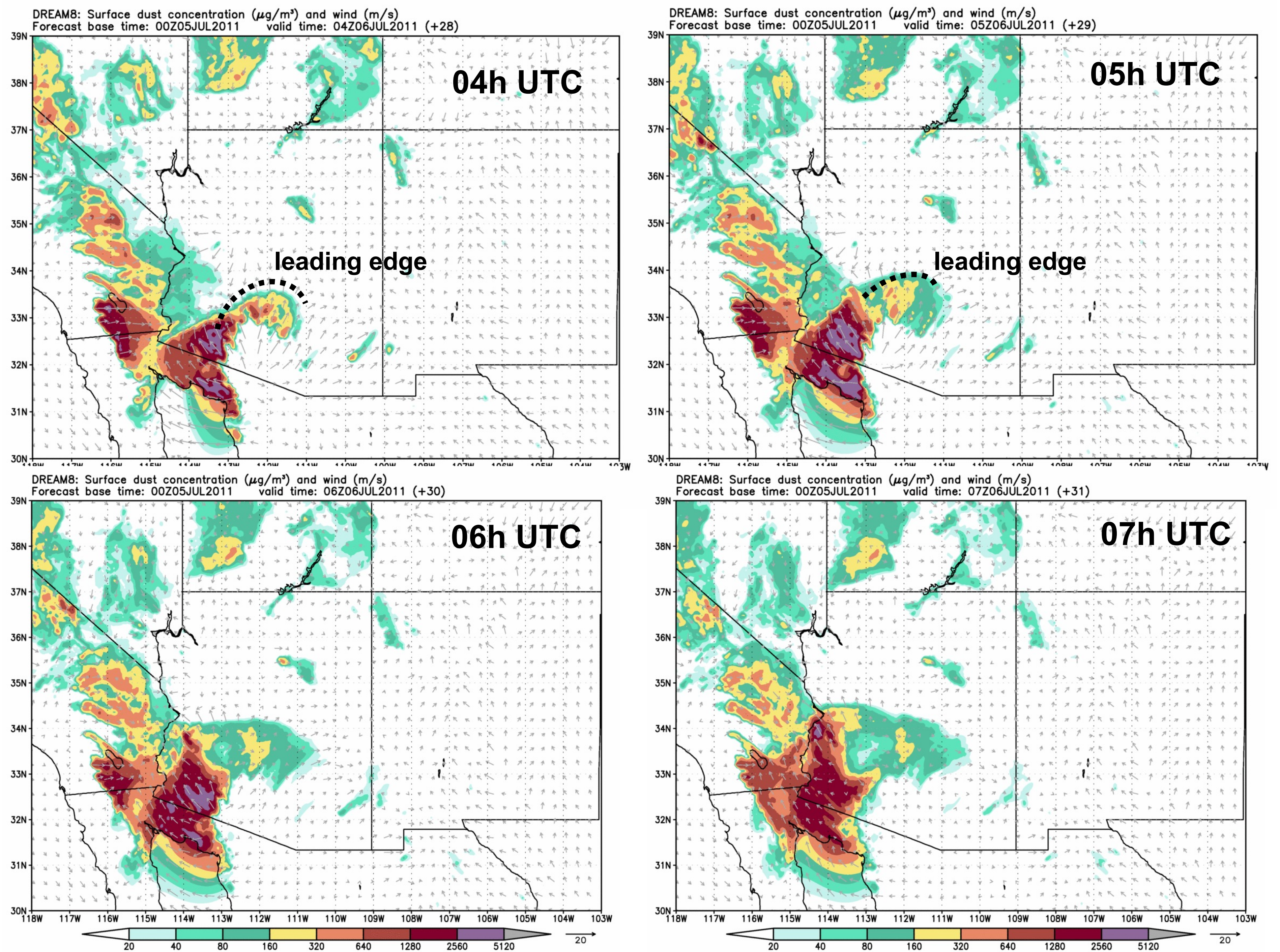
Simulations specification:

model: DREAM with NMM as atmospheric driver;
simulation: start at July 5th 2011 00UTC +48h
resolution: 6km and 3.5 km
mask: mcd12_jun0110

Results for 6km resolution run



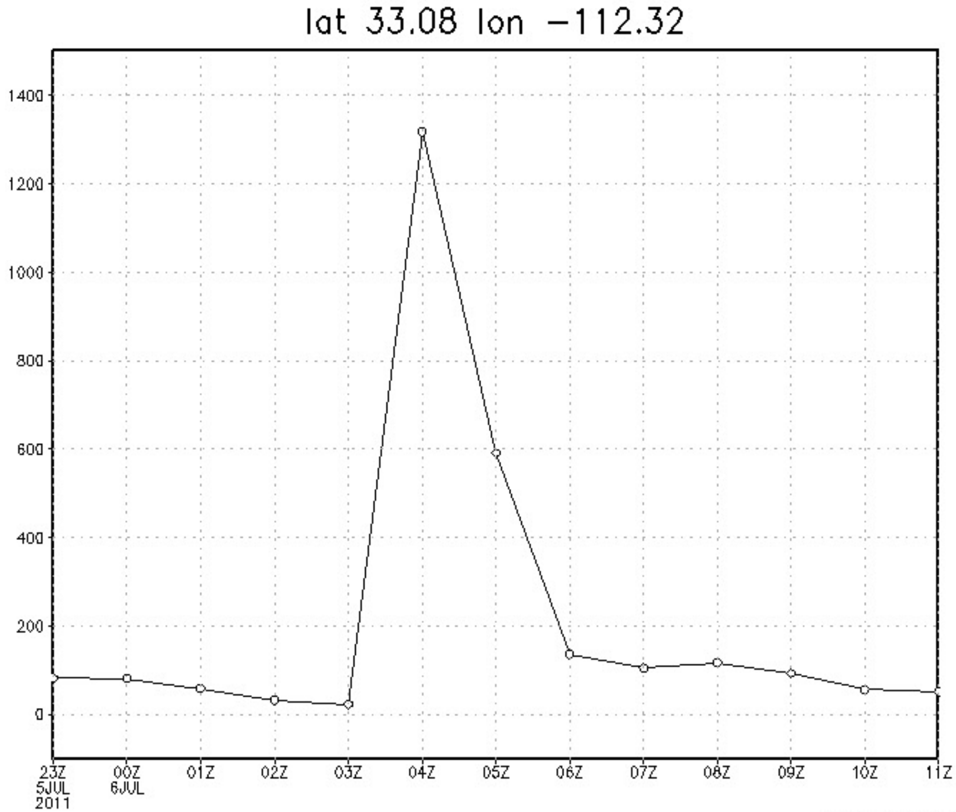


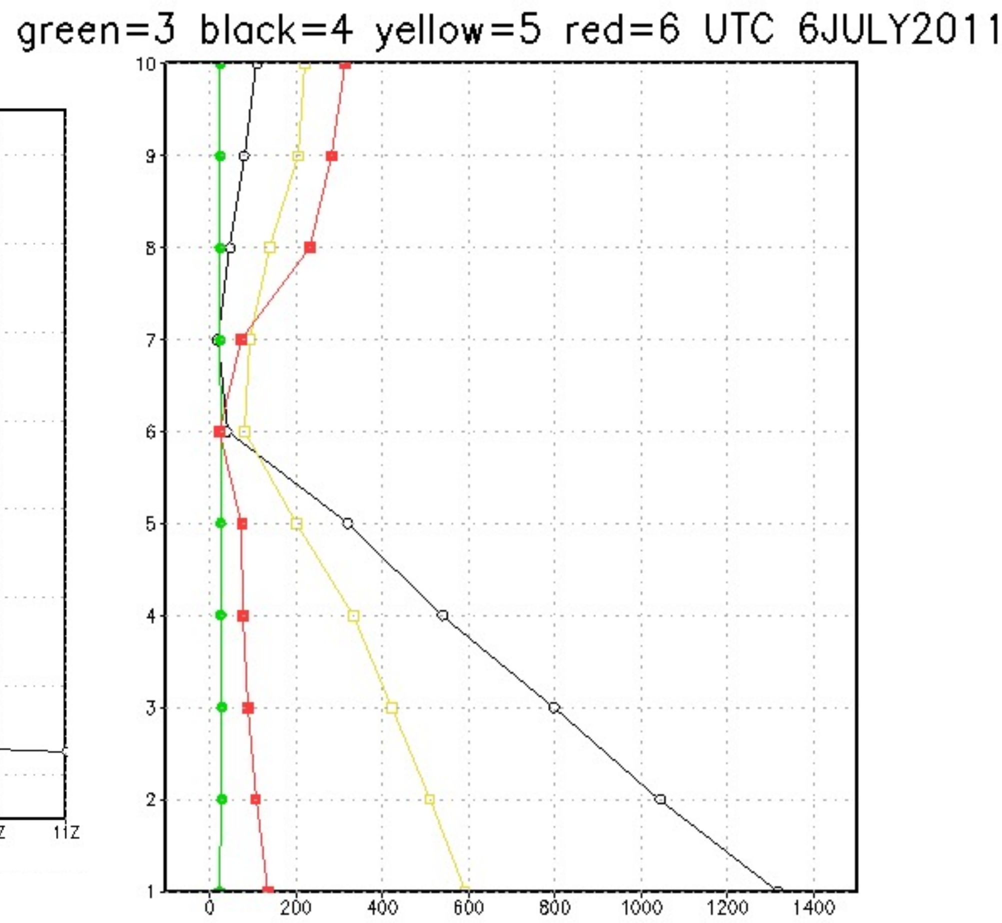

DREAM8: Surface dust concentration (µg/m³) and wind (m/s)
Forecast base time: 00Z05JUL2011 valid time: 04Z06JUL2011 (+28)
04h UTC
leading edge
DREAM8: Surface dust concentration (µg/m³) and wind (m/s)
Forecast base time: 00Z05JUL2011 valid time: 05Z06JUL2011 (+29)
05h UTC
leading edge
DREAM8: Surface dust concentration (µg/m³) and wind (m/s)
Forecast base time: 00Z05JUL2011 valid time: 06Z06JUL2011 (+30)
06h UTC
DREAM8: Surface dust concentration (µg/m³) and wind (m/s)
Forecast base time: 00Z05JUL2011 valid time: 07Z06JUL2011 (+31)
07h UTC
39N 38N 37N 36N 35N 34N 33N 32N 31N 30N
118W 117W 116W 115W 114W 113W 112W 111W 110W 109W 108W 107W 106W 105W 104W 103W
20 40 80 160 320 640 1280 2560 5120
20

Cross-sections and profiles for point N33.08 W112.32
(point with max. dust concentration)

In point with max surface dust concentration:
-> maximum at 4 UTC

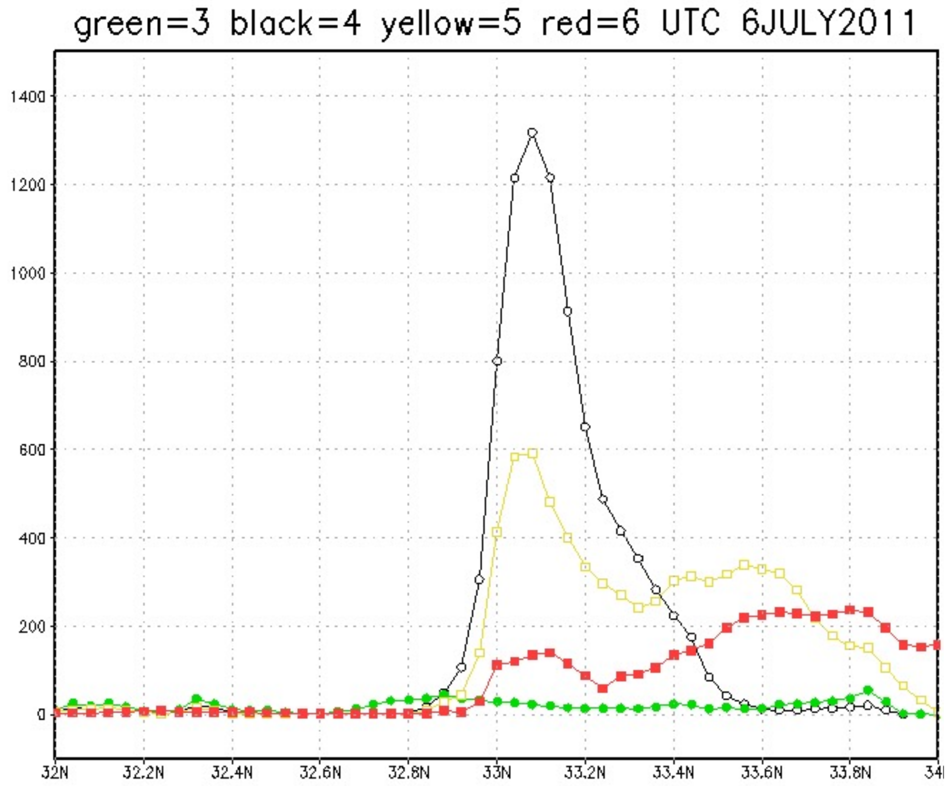
vertical profile of dust concentration
in first 10 model levels:



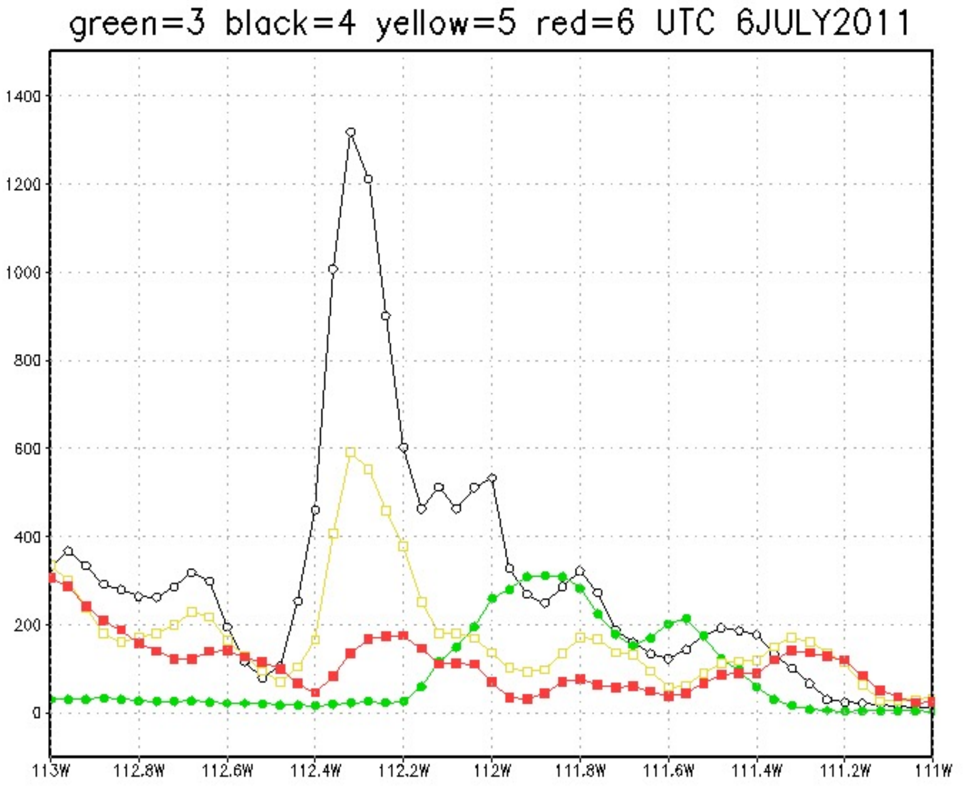


Example of cross-sections: over selected point

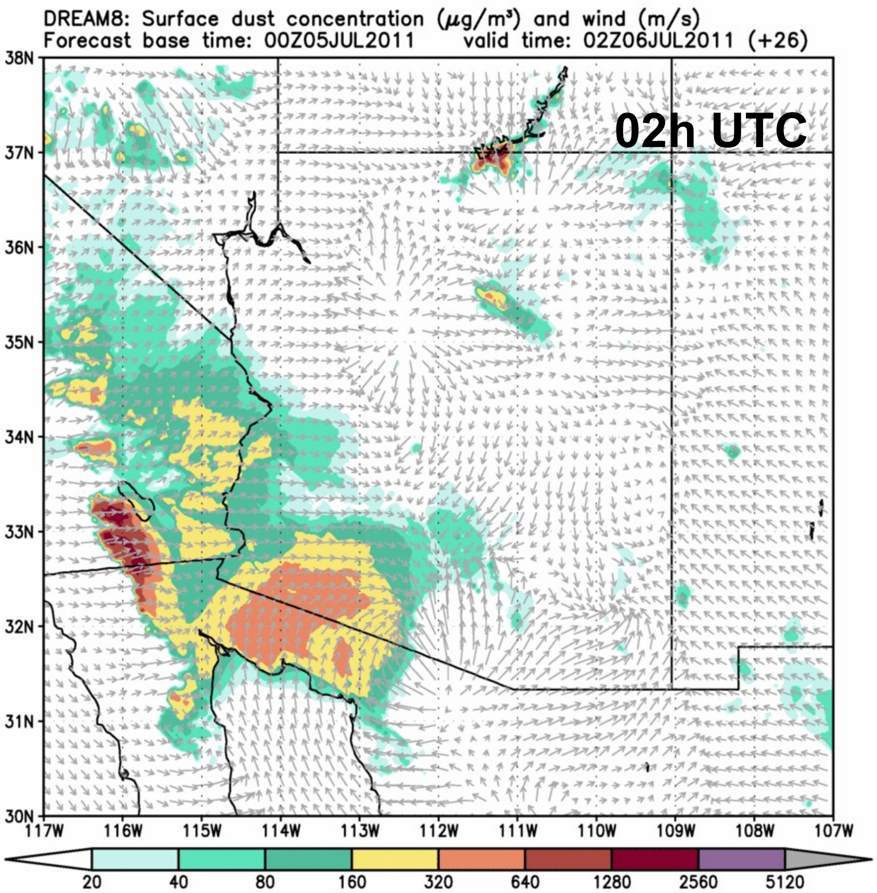
Cross-section along lon W112.32:

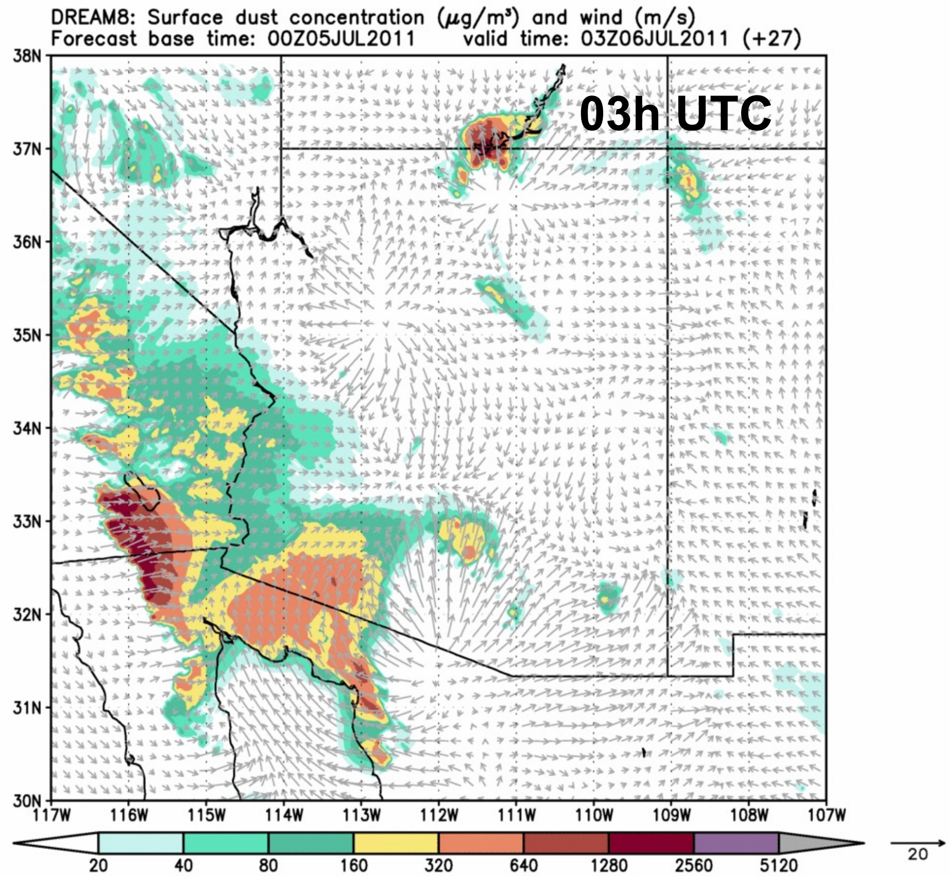


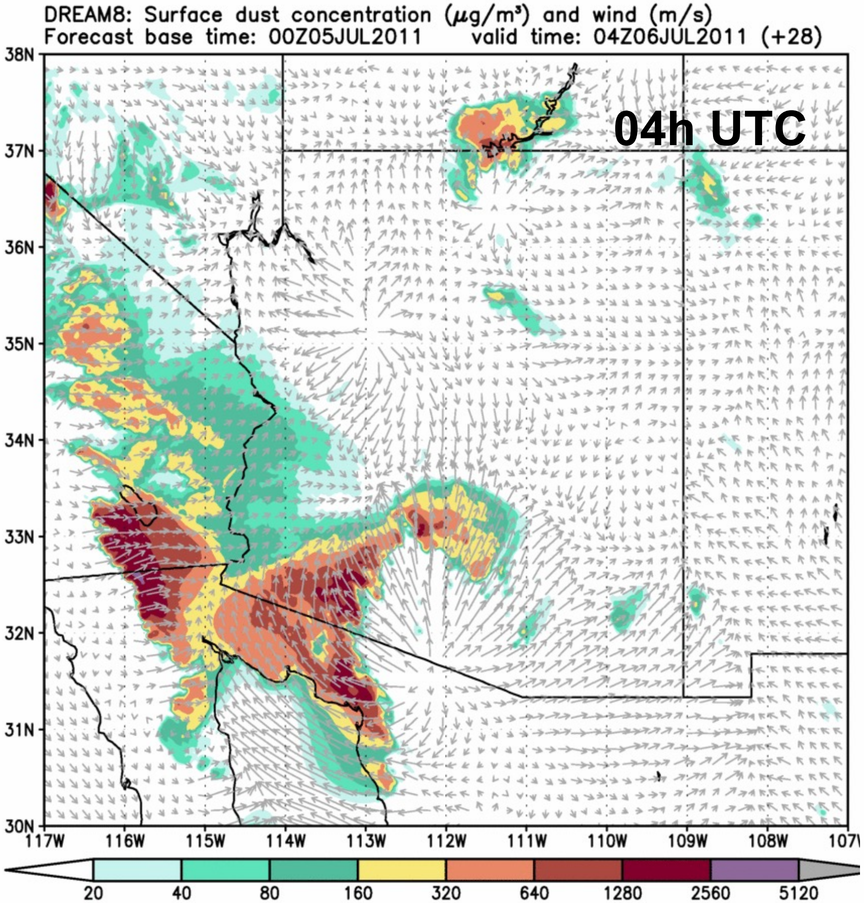
Cross-section along lat N33.08:

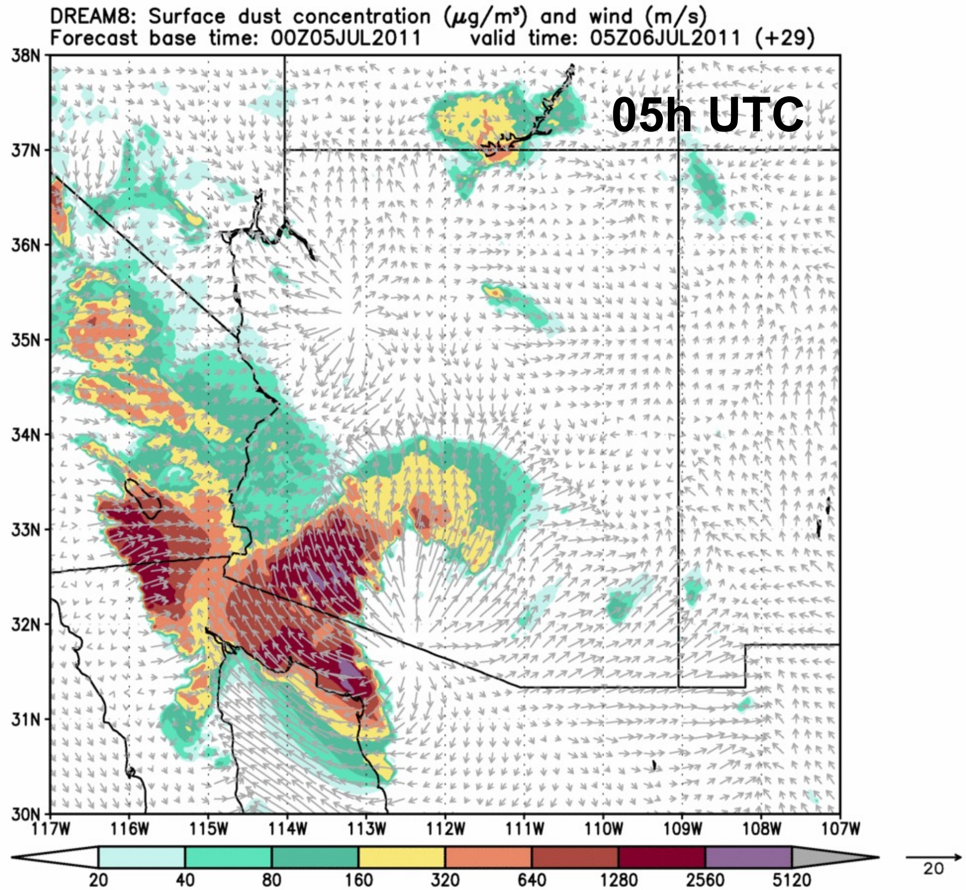


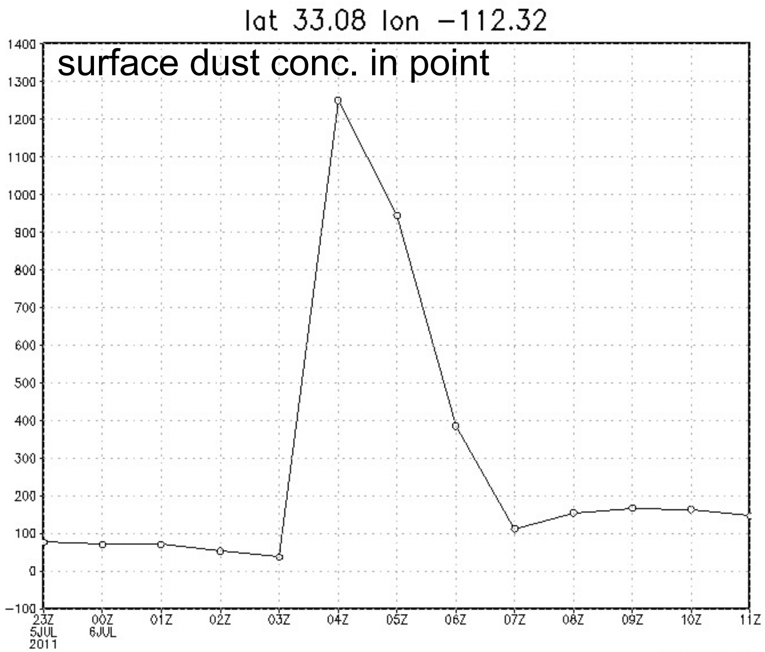
Results for 3km resolution run

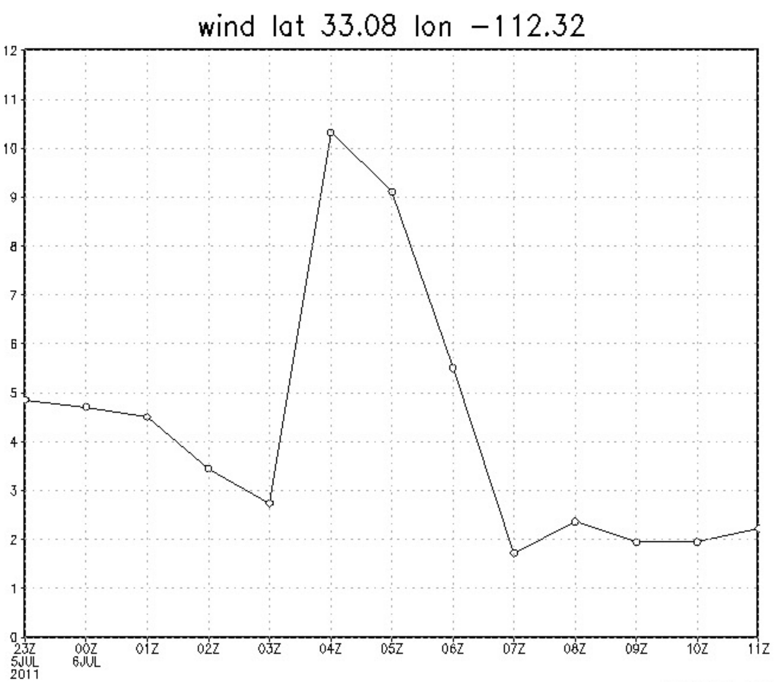


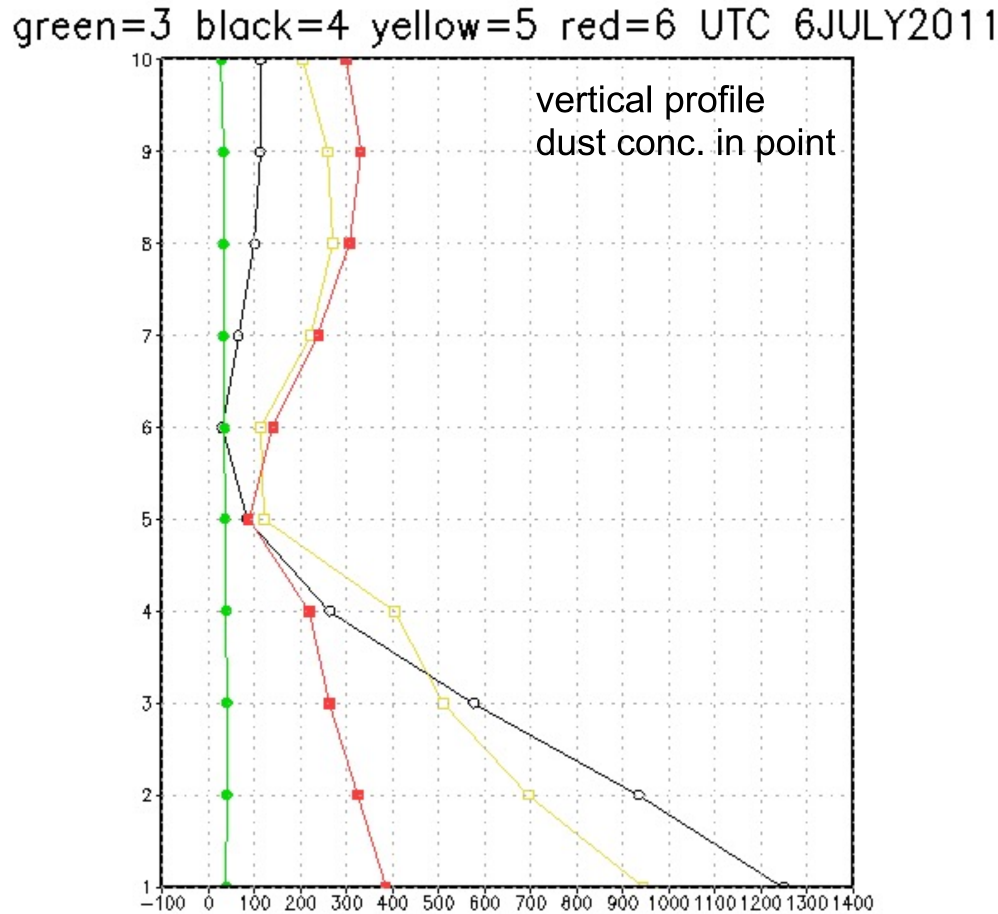



DREAM8: Surface dust concentration (μg/m³) and wind (m/s)
Forecast base time: 00Z05JUL2011 valid time: 04Z06JUL2011 (+28)
04h UTC
38N
37N
36N
35N
34N
33N
32N
31N
30N
117W
116W
115W
114W
113W
112W
111W
110W
109W
108W
107W
20
40
80
160
320
640
1280
2560
5120


DREAM8: Surface dust concentration (μg/m³) and wind (m/s)
Forecast base time: 00Z05JUL2011 valid time: 05Z06JUL2011 (+29)
05h UTC
38N
37N
36N
35N
34N
33N
32N
31N
30N
117W
116W
115W
114W
113W
112W
111W
110W
109W
108W
107W
20
40
80
160
320
640
1280
2560
5120
20


lat 33.08 lon −112.32
surface dust conc. in point
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
−100
23Z 5JUL 2011
00Z 6JUL
01Z
02Z
03Z
04Z
05Z
06Z
07Z
08Z
09Z
10Z
11Z


wind lat 33.08 lon −112.32
12
11
10
9
8
7
6
5
4
3
2
1
0
23Z 5JUL 2011
00Z 6JUL
01Z
02Z
03Z
04Z
05Z
06Z
07Z
08Z
09Z
10Z
11Z


green=3 black=4 yellow=5 red=6 UTC 6JULY2011
vertical profile
dust conc. in point
10
9
8
7
6
5
4
3
2
1
−100
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400

Mineral composition of arid soils

- dust is composed of minerals that differ in physical and chemical characteristics
- each mineral has different impact on environment, atmospheric radiation, ice nucleation
- important impacts on: human health, ocean bio-productivity, cloud formation

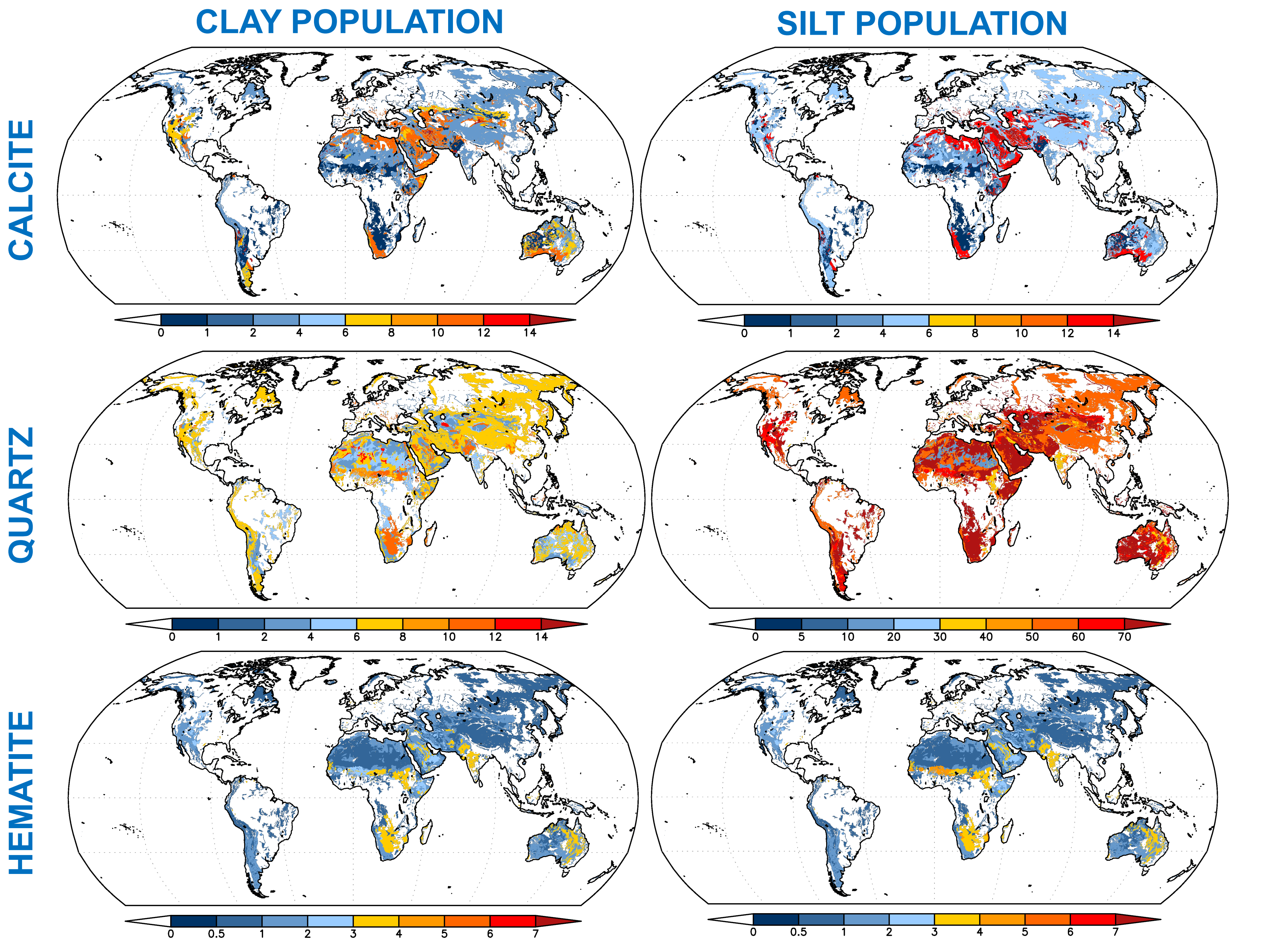
GMINER30: High-resolution global dataset on surface mineralogy in arid areas

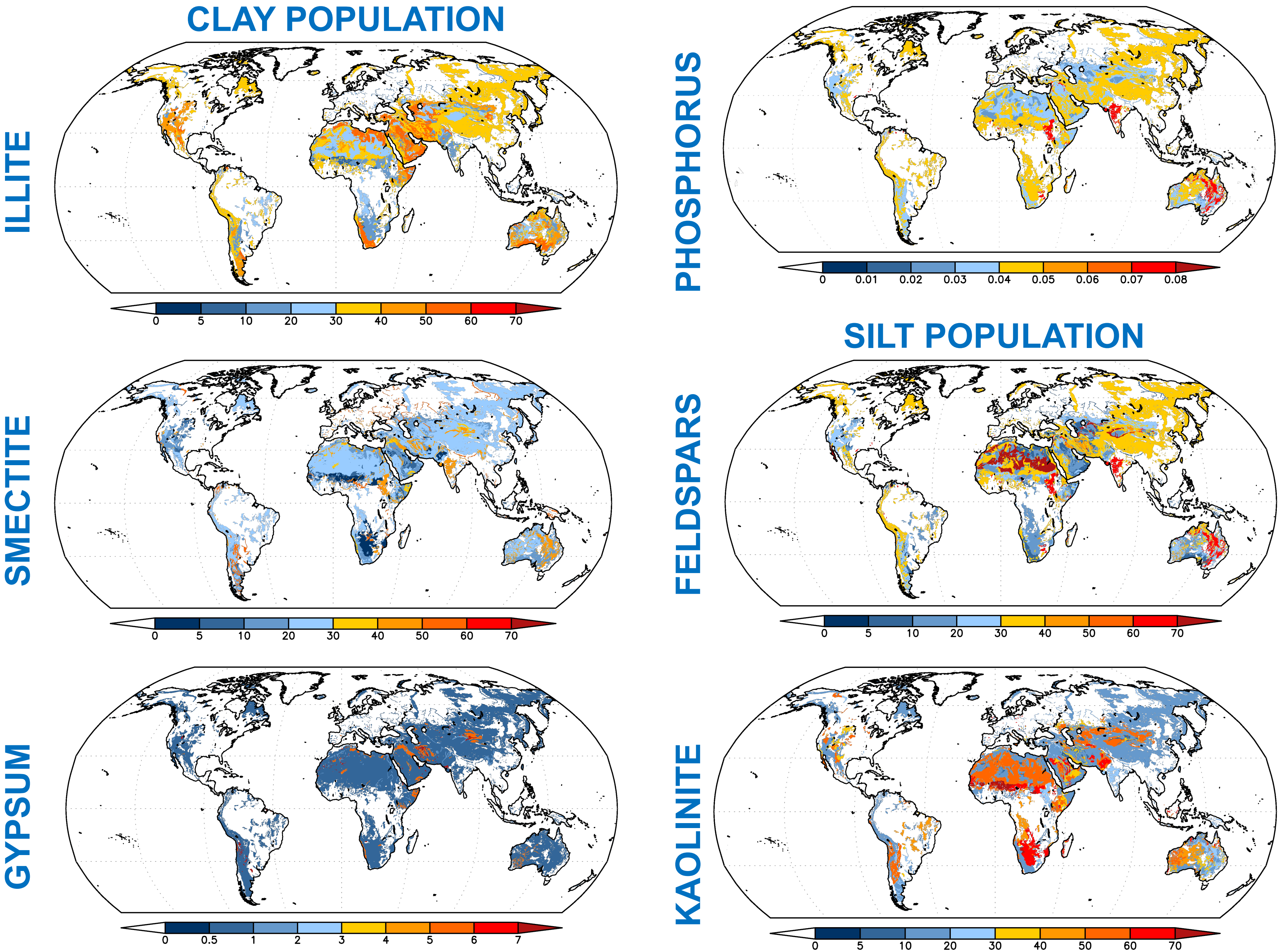
- data on mineral fraction for 9 most common minerals in arid regions
- based on Claquin et al., 1999, but improved
- minerals are sorted by size in clay and silt populations

silt	clay	silt & clay
feldspar	illite	calcite
gypsium	kaolinite	hematite
	smectite	quartz

+ phosphorus

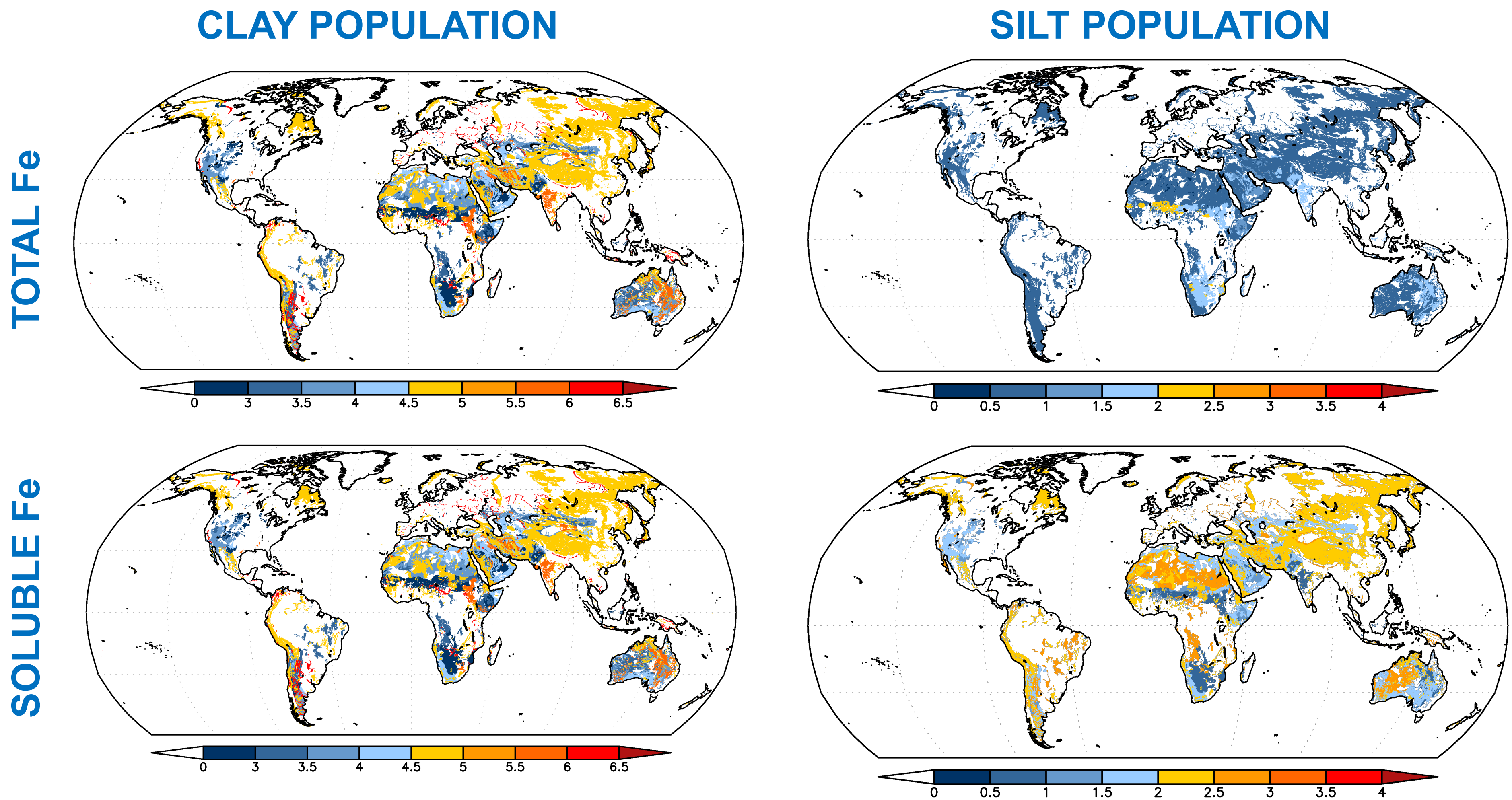
- dataset is global on 30 arc-seconds resolution (~ 1 km)
- available for download at: http://www.seevccc.rs/GMINER30/


CLAY POPULATION
SILT POPULATION
CALCITE
QUARTZ
HEMATITE
0 1 2 4 6 8 10 12 14
0 1 2 4 6 8 10 12 14
0 1 2 4 6 8 10 12 14
0 5 10 20 30 40 50 60 70
0 0.5 1 2 3 4 5 6 7
0 0.5 1 2 3 4 5 6 7


CLAY POPULATION
ILLITE
0 5 10 20 30 40 50 60 70
SMECTITE
0 5 10 20 30 40 50 60 70
GYPSUM
0 0.5 1 2 3 4 5 6 7
PHOSPHORUS
0 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08
SILT POPULATION
FELDSPARS
0 5 10 20 30 40 50 60 70
KAOLINITE
0 5 10 20 30 40 50 60 70

- using mineralogy data we calculated fraction of total and soluble Fe in clay and silt

-information on Fe percentage combine with land cover data provides information on how much Fe is available to uptake DREAM-IRON



Atmospheric iron transport modeling

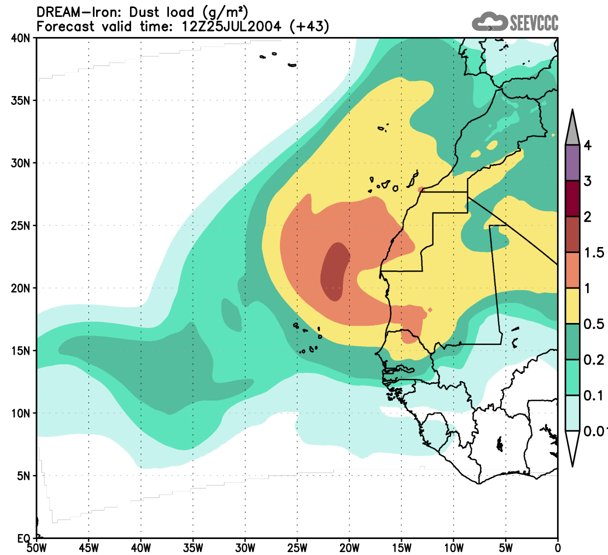
Example of mineral database application

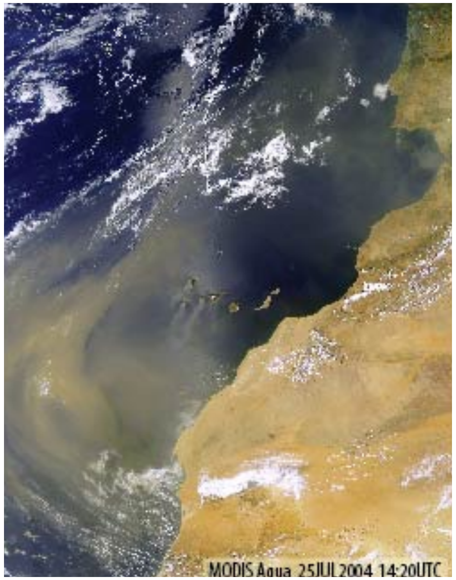
CASE STUDY

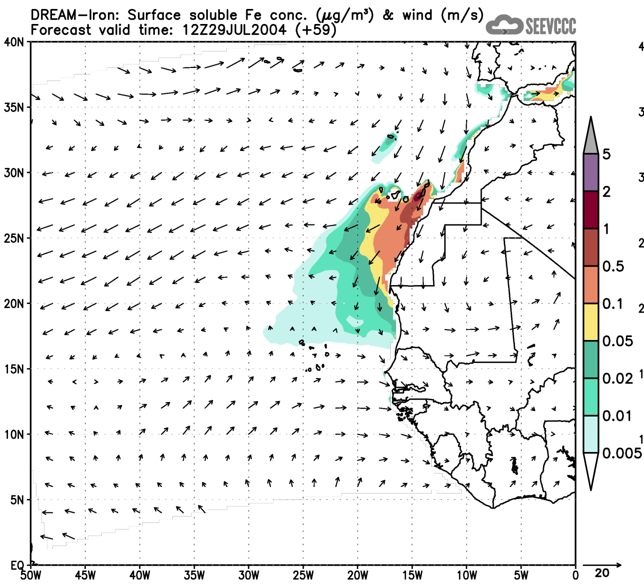
Dust storm induced chlorophyll bloom near Canary Islands, July 2004

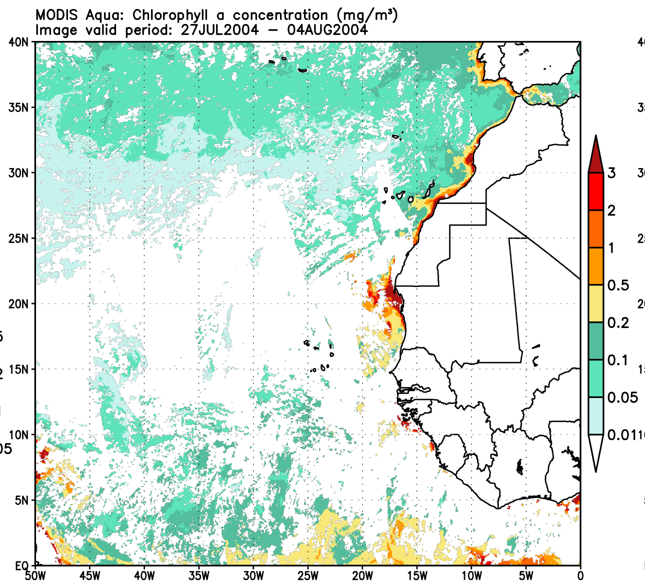
During July and August 2004, numerous dust storms occurred in northwestern part of Africa during which Saharan dust was blown towards the Atlantic ocean. Mineral rich dust aerosol was deposited mainly along the northwest African shelf, supplying the ocean with nutrient necessary for phytoplankton growth.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

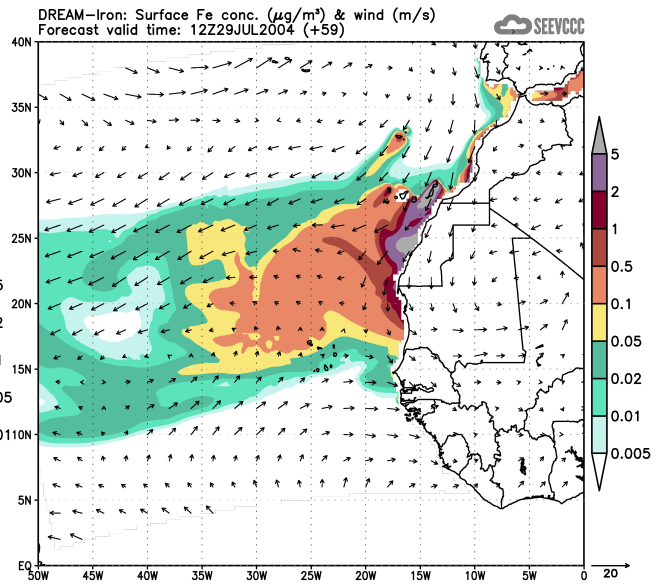
According to the iron hypothesis (Martin, 1994), the deposition of iron, along with dust aerosol, might increase biological productivity of the ocean and might enhance chlorophyll concentration. Therefore, we simulated this event using DREAM-Iron. The integration covers the period between 15th and 31st 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.











References

Claquin, T., Schulz, M., and Balkanski, Y.: Modeling the mineralogy of atmospheric dust sources, *J. Geophys. Res.*, 104(D18), 22243-22256, 1999

Engelstaedter, S. and Washington, R.: Temporal controls on global dust emissions: The role of surface gustiness, *Geophys. Res. Lett.*, 34, L15805, doi:10.1029/2007GL029971, 2007

Kinne, S. et al. : An AeroCom initial assessment – optical properties in aerosol component modules of global models, Atmos. Chem. Phys., 6, 1815-1834, doi:10.5194/acp-6-1815-2006, 2006

Klein, H., Nickovic, S., Haunold, W., Bundke, U., Nillius, B., Ebert, M., Weinbruch, S., Schuetz, L., Levin, Z., Barrie, L. A., and Bingemer, H.: Saharan dust and ice nuclei over Central Europe, Atmos. Chem. Phys., 10, 10211-10221, doi:10.5194/acp-10-10211-2010, 2010

Lee, J.A., T.E. Gill, K.R. Mulligan, M.D. Acosta, A.E. Perez 2009, Land use/land cover and point sources of the 15 December 2003 dust storm in southwestern North America. Geomorphology 105.18–27

Liu, J, **DL Mauzerall**, LW Horowitz. Evaluating Inter-continental transport of fine aerosols: (2) Global Health Impacts, *Atmospheric Environment,* doi:10.1016/j.atmosenv.2009.05.032, 2009

Middleton N, Yiallouros P, Kleanthous S, Kolokotroni O, Schwartz J, Dockery DW, et al. 2008. A 10-year time-series analysis of respiratory and cardiovascular morbidity in Nicosia, Cyprus: the effect of short-term changes in air pollution and dust storms. Environ Health 7:39.doi:10.1186/1476-069X-7-39

Nickovic, S., G. Kallos, A. Papadopoulos, and O. Kakaliagou (2001), A model for prediction of desert dust cycle in the atmosphere, J. Geophys. Res., 106(D16), 18113-18129

Pérez, C., S. Nickovic, G. Pejanovic, J. M. Baldasano, and E. Özsoy (2006), Interactive dust-radiation modeling: A step to improve weather forecasts, *J. Geophys. Res.*, *111*, D16206, doi:10.1029/2005JD006717

Prospero, J. M., Ginoux, P., Torres, O., Nicholson, S. E., and Gill, T. E.: Environmental characterization of global sources of atmospheric soil dust identified with the NIMBUS 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product, *Rev. Geophys.*, 40(1), 1002, doi:10.1029/2000RG000095, 2002

Singh, R. P., A. K. Prasad, V. K. Kayetha, and M. Kafatos (2008), Enhancement of oceanic parameters associated with dust storms using satellite data, *J. Geophys. Res.*, *113*, C11008, doi:10.1029/2008JC004815

Todd, M. C., R. Washington, J. V. Martins, O. Dubovik, G. Lizcano, S. M'Bainayel, and S. Engelstaedter (2007), Mineral dust emission from the Bodélé Depression, northern Chad, during BoDEx 2005, *J. Geophys. Res.*, *112*, D06207, doi:10.1029/2006JD007170

Todd, M. C., et al. (2008), Quantifying uncertainty in estimates of mineral dust flux: An intercomparison of model performance over the Bodélé Depression, northern Chad, *J. Geophys. Res.*, *113*, D24107, doi:10.1029/2008JD010476