Dust Impact on the Middle East Climate and the Red Sea: Observations, Modeling, and Validation

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1. Middle East Climate Mechanisms: **Dust is the main regional driver**
2. **Observations**: Aeronet, MPLNET, MICROTOPS, NASA balloon soundings, dust deposition and composition
3. Dust **Radiative Forcing**: surface cooling and atmospheric warming
4. Simulating Regional Climate Using **Global High-Resolution Model**
5. Simulating Regional Fine-Scale Processes Using **Regional WRF-Chem**
6. Closing **Dust Mass Balance** using **Dust Deposition Measurements**
7. Evaluating Dust Impact on the Red Sea Using **Coupled WRF and Regional Ocean Model (ROMS)**
8. Renewable Energy and **Dust Processes at "Nano" Scales**


Cairo
Kuwait
مدينة الكويت Al Kuwayt
Gulf of Aqaba
Persian Gulf
Arabian Gulf
Qushm Island
مدينة بريدة Buraydah
Ad Dammam
Manama
Bahrain
الدوحة Doha
Gulf of Oman
الرياض Ar Riyad
ابو ظبي Abu Dhabi
المدينة المنورة Al Madinah
مسقط
United Arab Emirates
Saudi Arabia
Ash Sharqiyah
Jeddah Port
Jeddah Port
Jiddah Saudi Arabia
Makkah
Oman
Red Sea
Eritrea
Yemen
Asmera
Sana'a
© 2010 Europa Technologies
© 2010 LeadDog Consulting
US Dept of State Geographer
© 2010 Google
Gulf of Aden
Djibouti
©2010 Google
20°50'42.24" N 45°35'43.68" E elev 737 m
Eye alt 2188.29 km

Flash Flood at KAUST in November 2009

Brown Booby at the Red Sea

Dust Storm Front Affecting the Saudi capital of Riyadh, Saudi Arabia, Tuesday, March 10, 2009

King Abdullah University of Science and Technology – founded in 2009

Dust Observations at the Red Sea coast

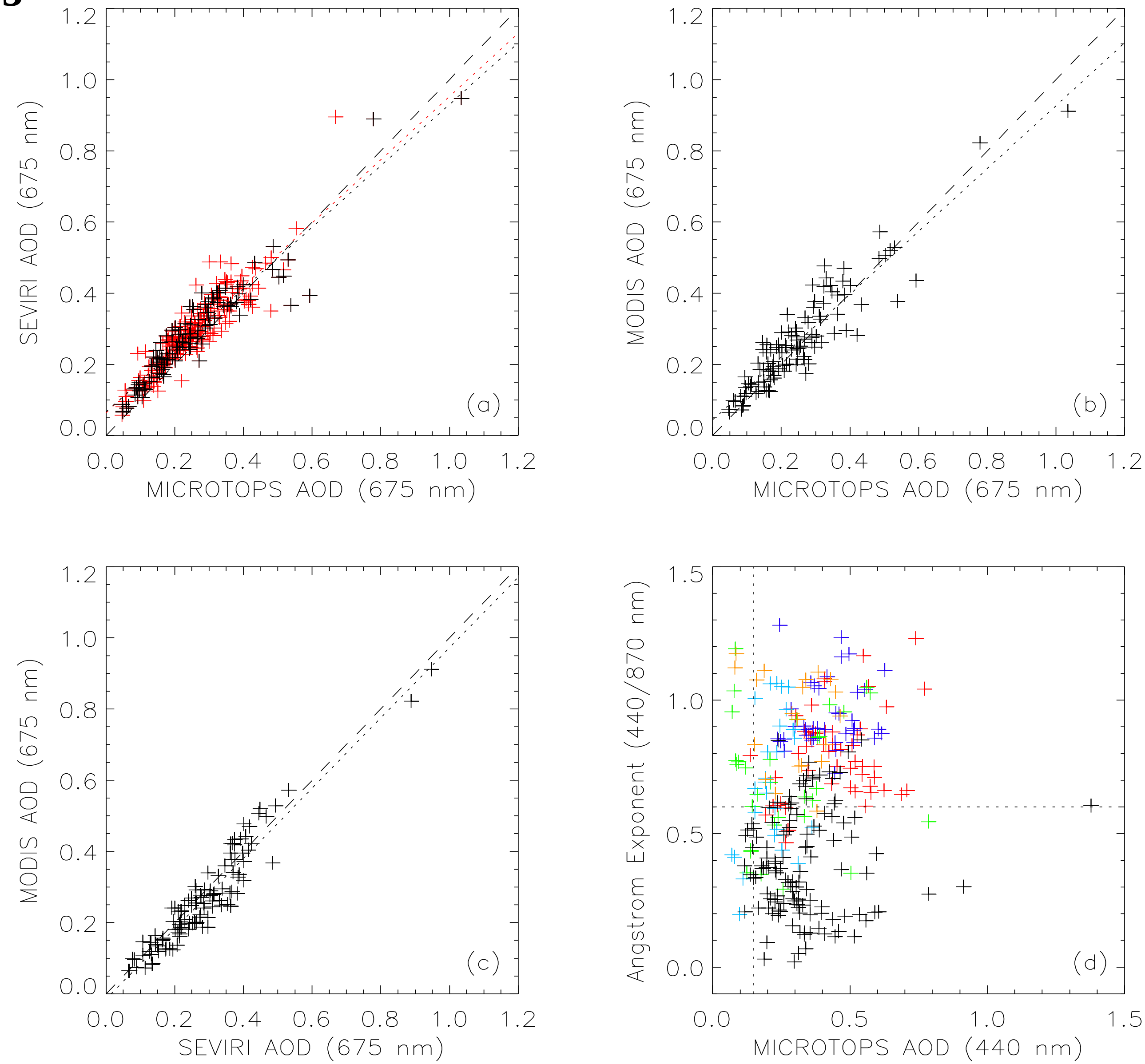
KAUST Campus Aeronet Site

DUST observations using hand-held sunphotometer

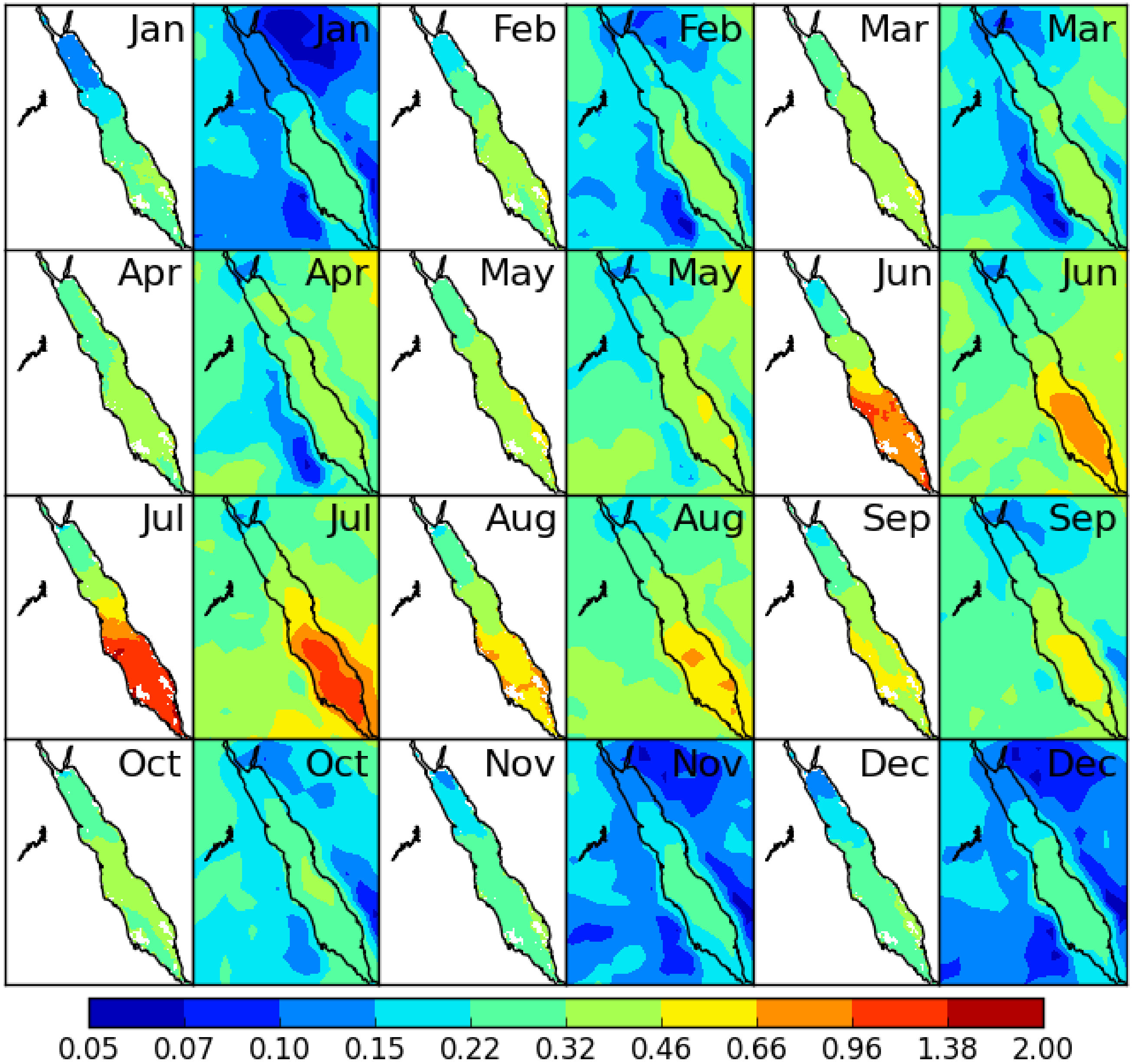
DUST Deposition Measurements

Micropulse Lidar

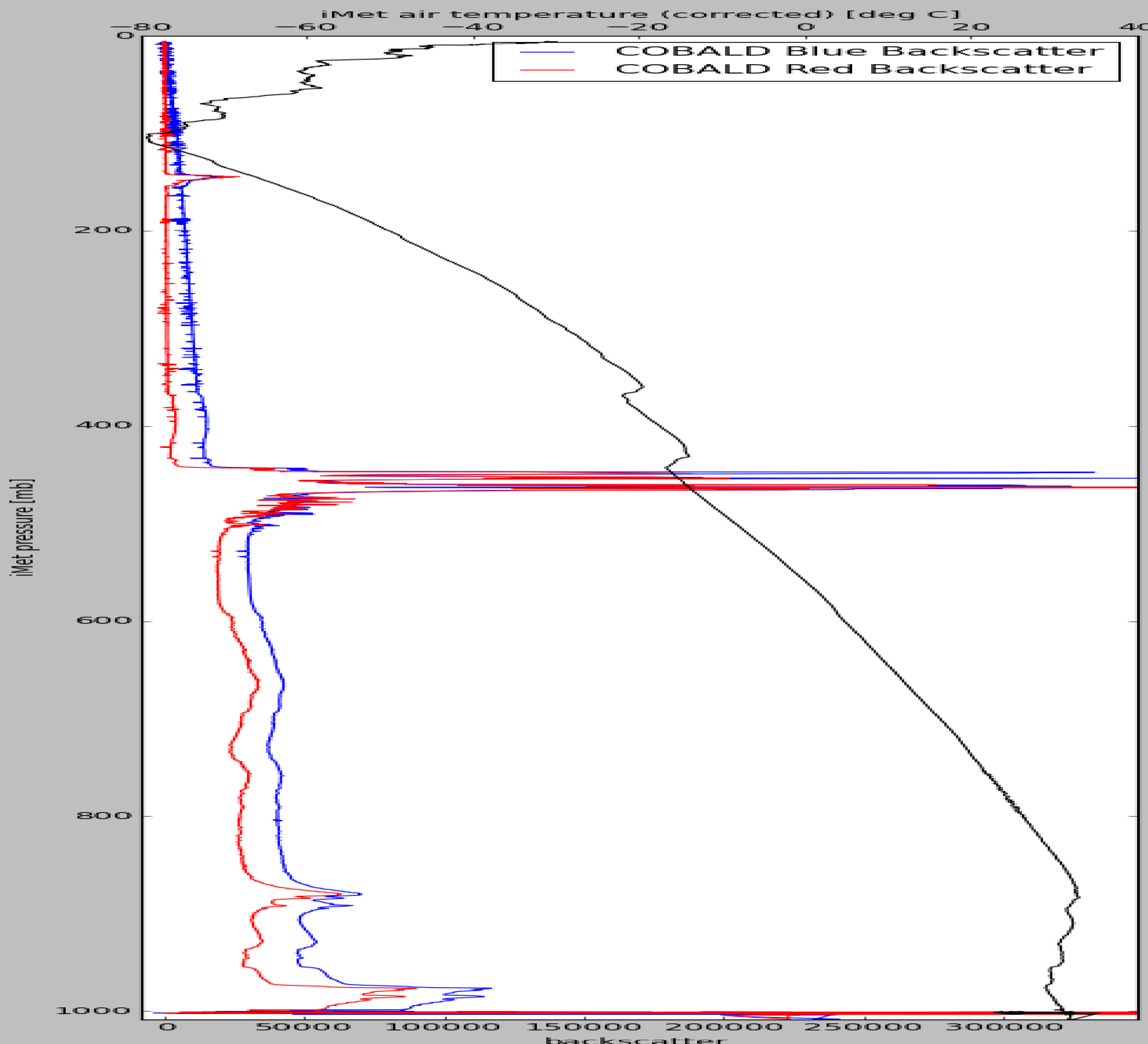
MODIS-SEVIRI-MICROTPS COMPARISON: **Brindley et al., JGR 2015**



SEVIRI and MODIS AOD over the Red Sea: **Brindley et al., JGR 2015**

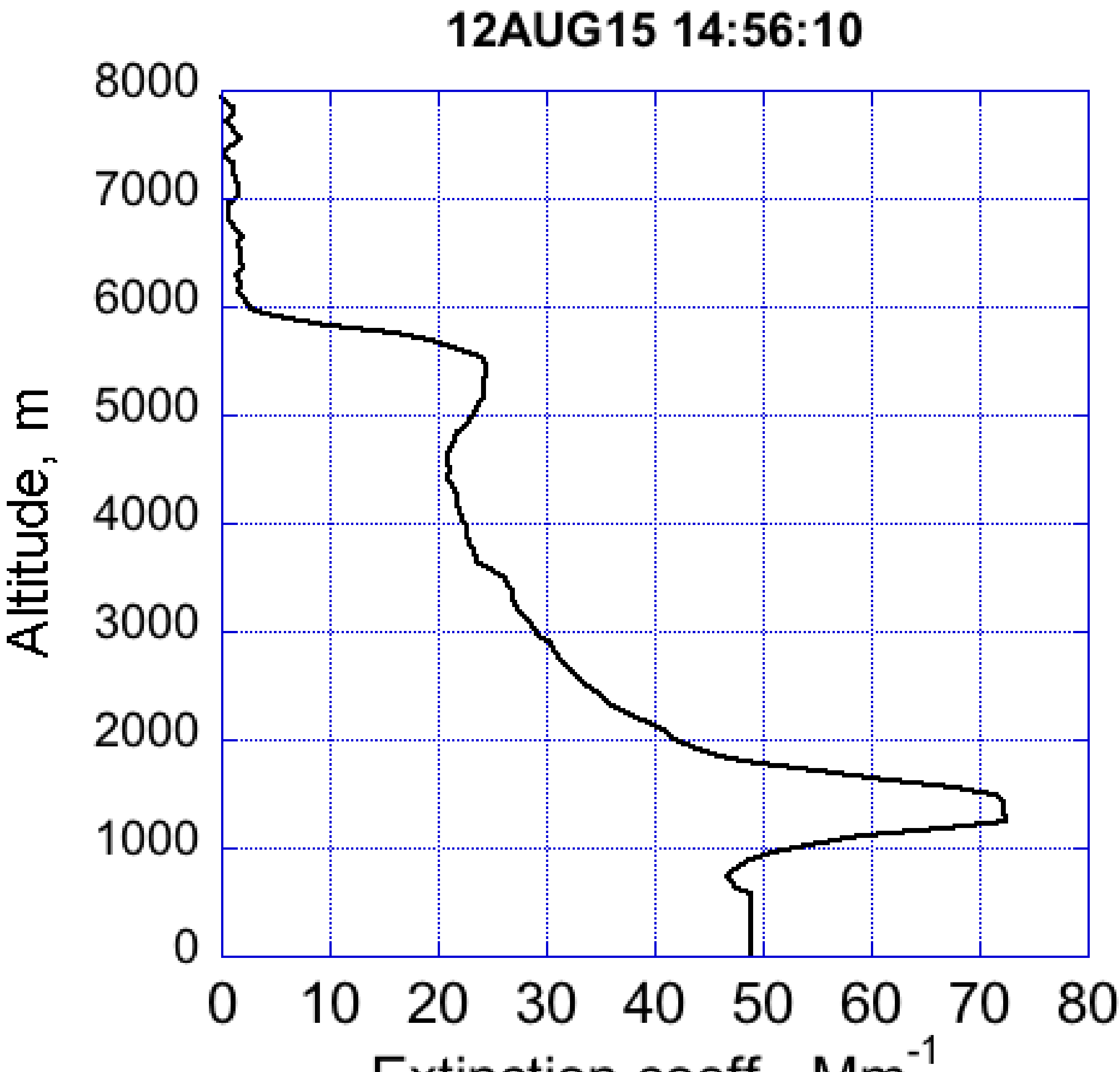


NASA Langley Balloon campaign (BATAL) in August 2015

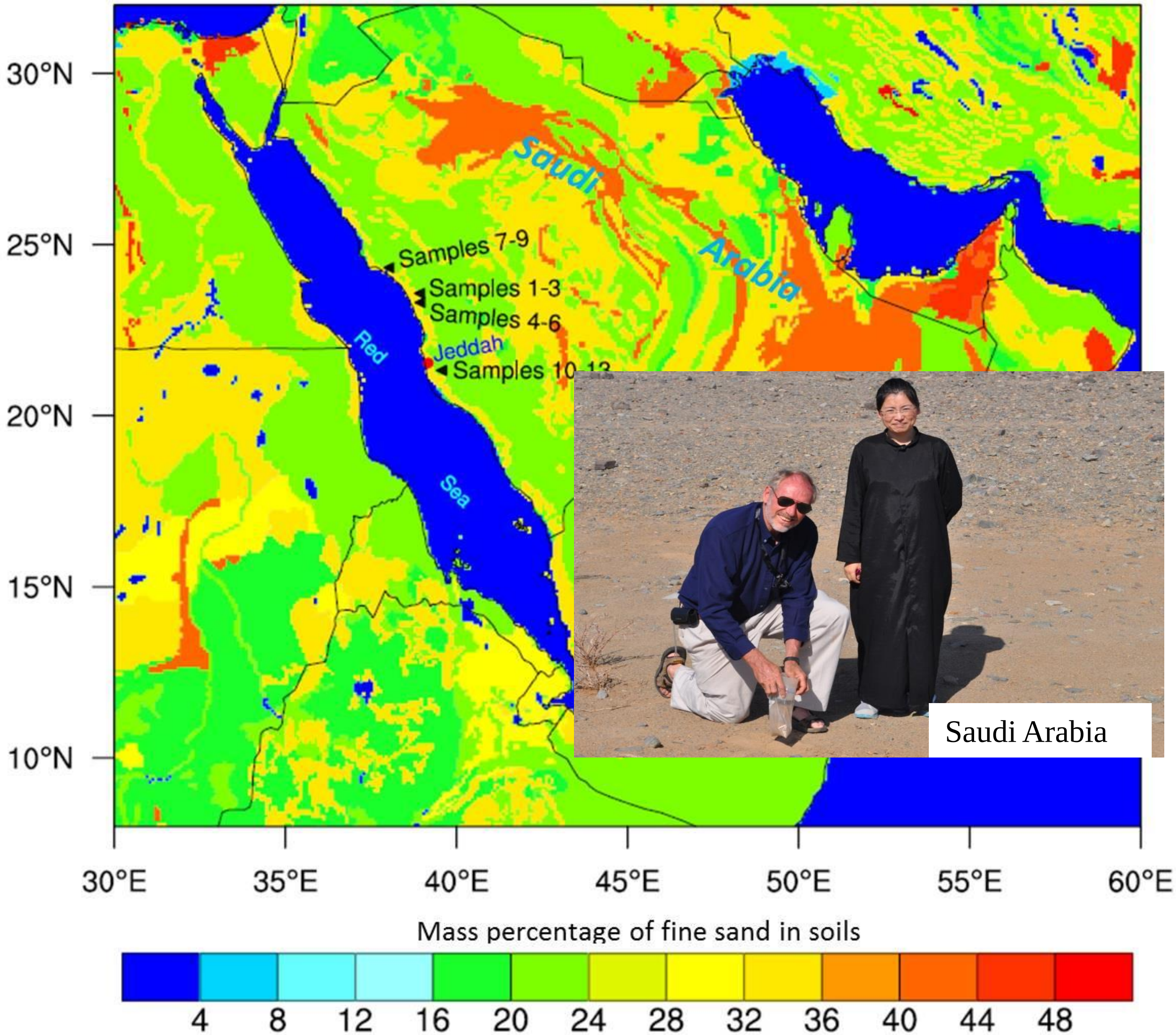


iMet air temperature (corrected) [deg C]
−80
−60
−40
−20
0
20
40
COBALD Blue Backscatter
COBALD Red Backscatter
iMet pressure [mb]
0
200
400
600
800
1000
0
50000
100000
150000
200000
250000
300000
backscatter

GRASP Retrieval of MPL Backscattering Profile

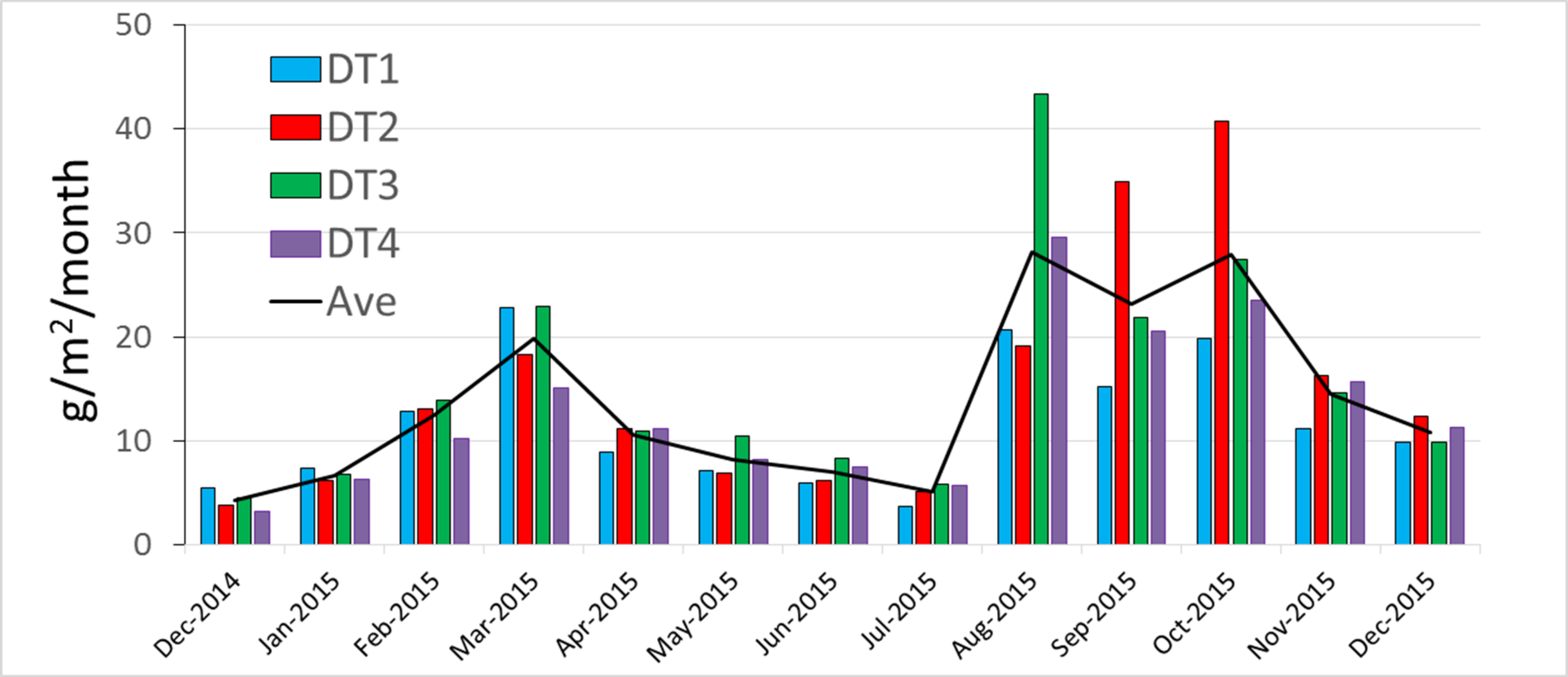


Grab Sampling along the Coast of the Red Sea
Praksh et al., ACP, 2016



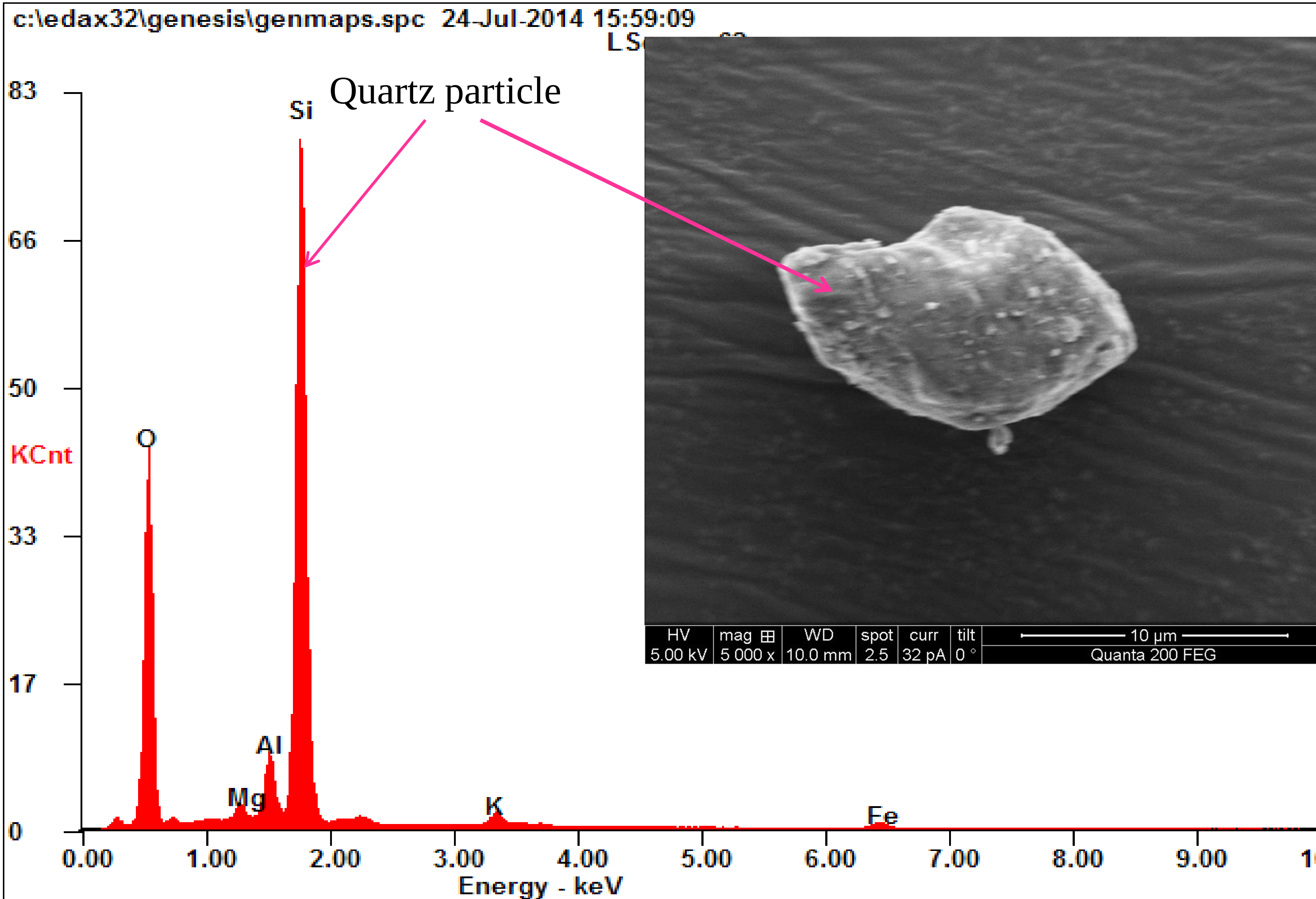
Deposition Site at the Red Sea Island

KAUST – Deposition Rates for Frisbee Samplers at Four Campus Sites (DT1-residential, DT2-CMOR, DT3-NEO, DT4-NEO4)
Engelbrecht et al., ACPD, 2017

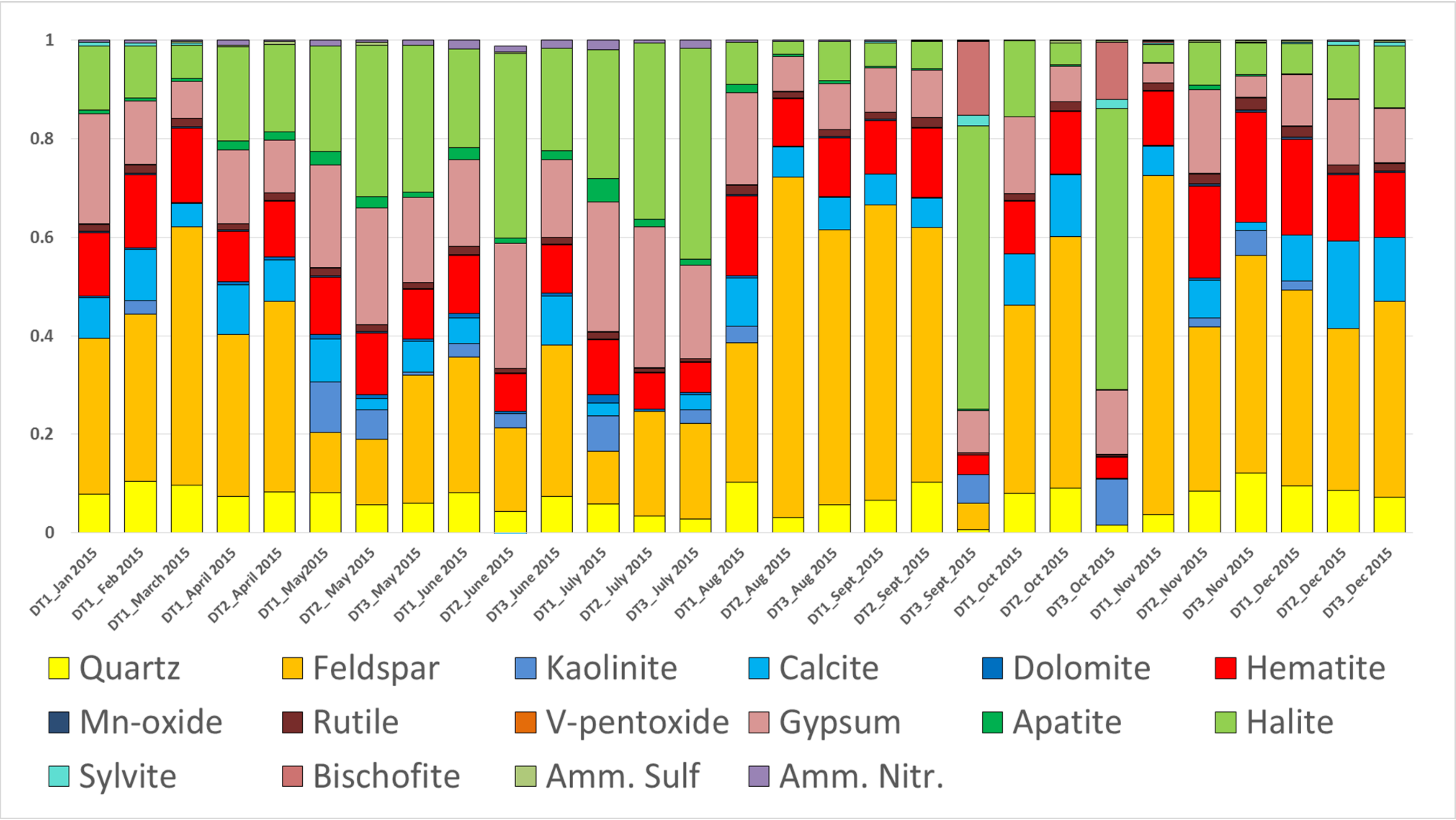


KAUST

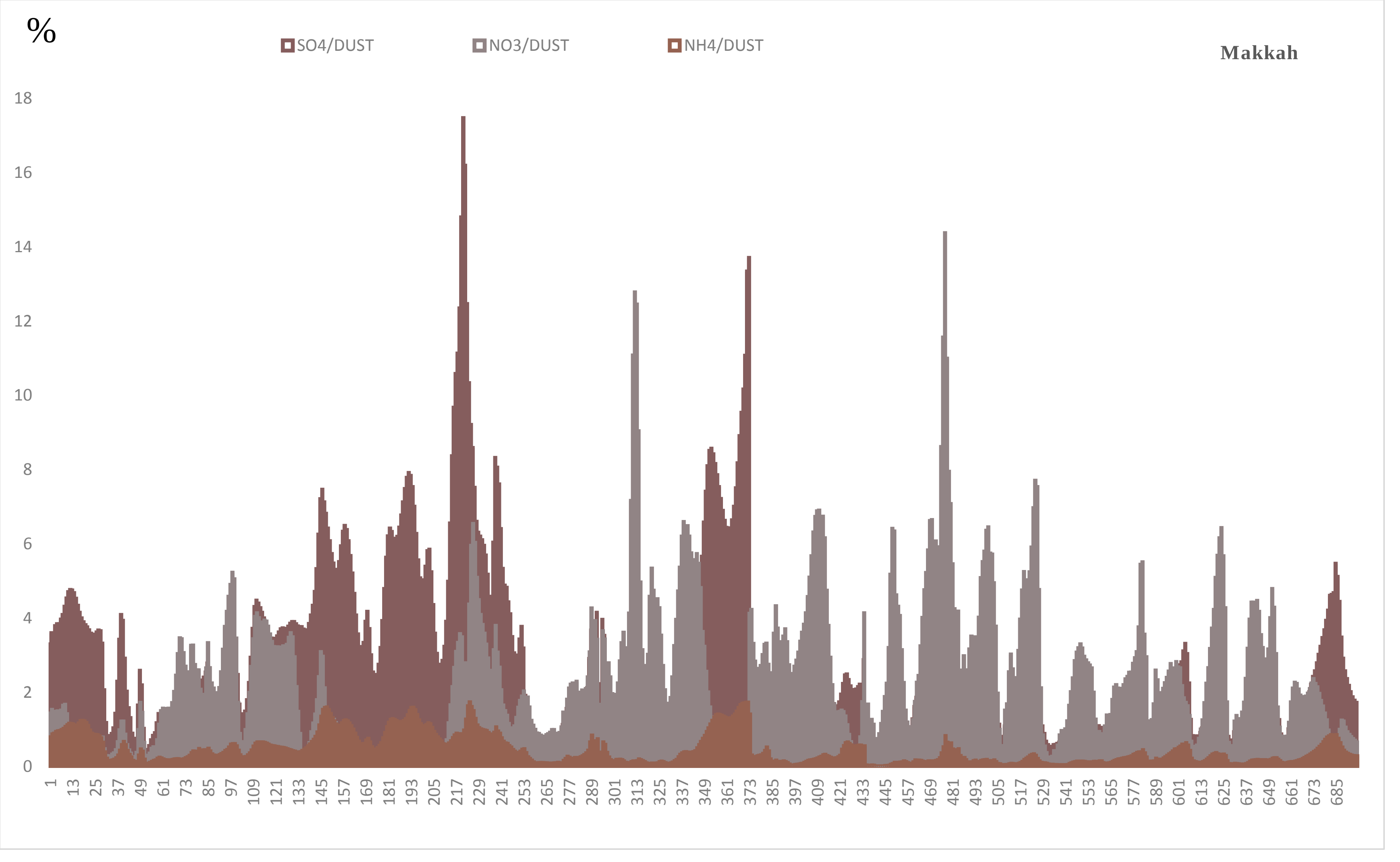
SEM Analysis of Dust Particles (Engelbrecht et al., ACPD, 2017)



Mineralogy of monthly deposition samples (Engelbrecht et al., ACPD, 2017)



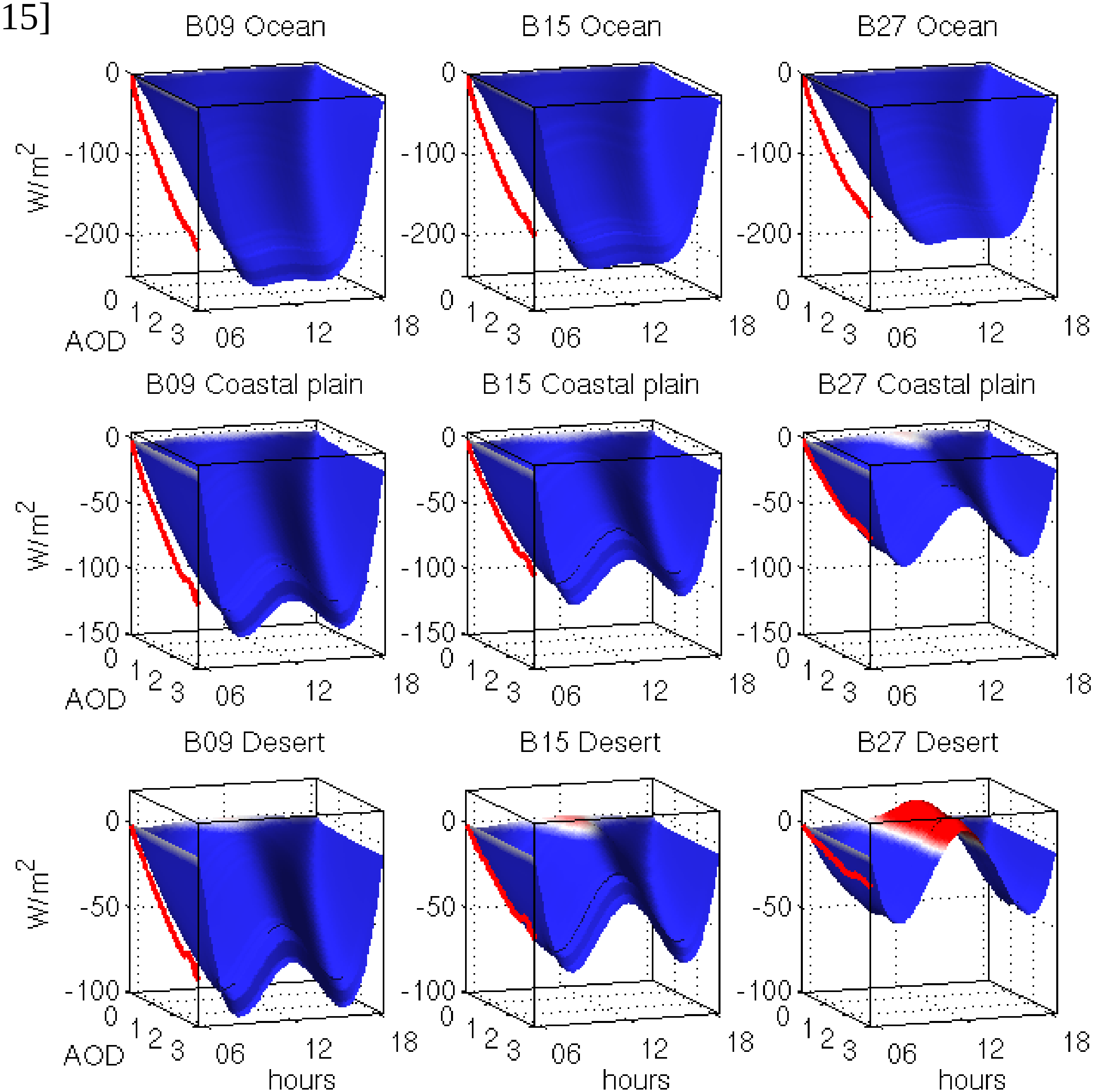
AIR Quality
Secondary Aerosol/Dust ratio (%) in Saudi Urban Centers

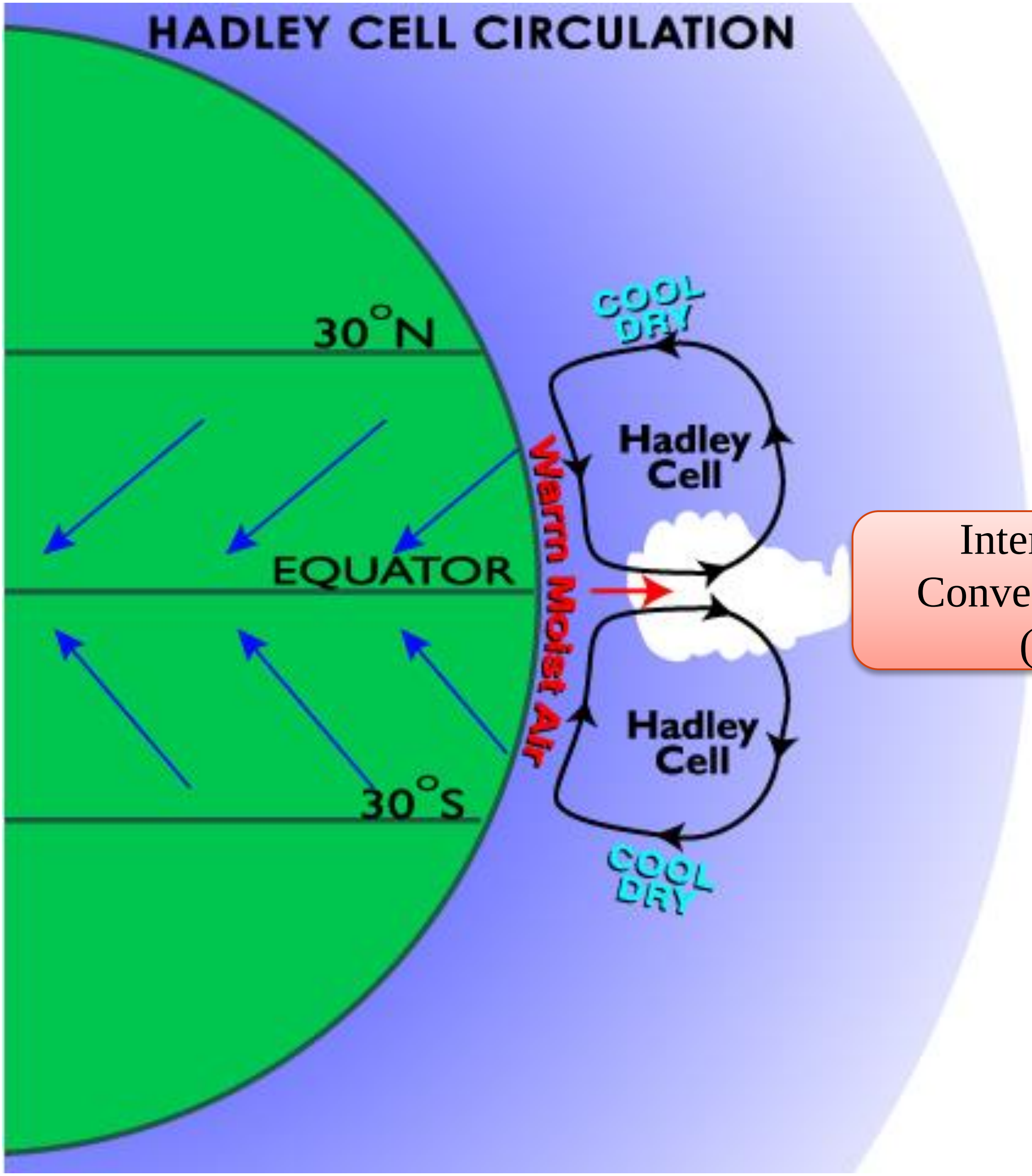


Time (days)

[Osipov et al., ACP 2015]

DIURNAL CYCLE of AEROSOL TOA RADIATVE FORCING over DIFFERENT SURFACES as a FUNCTION of AOD





Inter-trorpical Convergence Zone (ITCZ)

Global Climate Model with 25-km grid spacing

Continuity equation

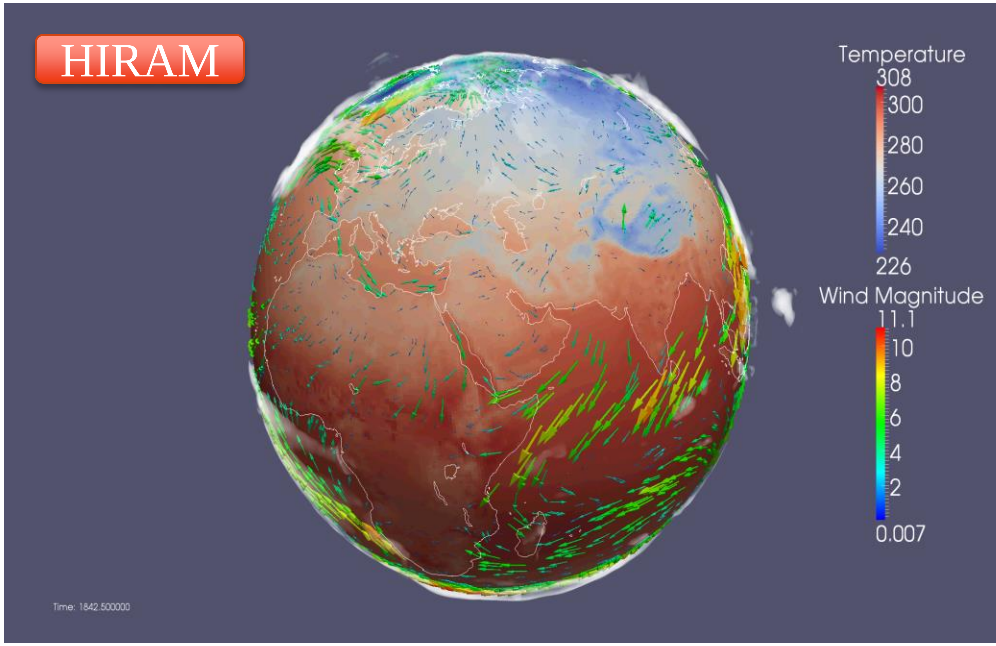
$$\frac{d\rho}{dt} = -\rho\, div\vec{V};$$

Momentum equation

$$\frac{d\vec{V}}{dt} = -2\omega\,\vec{k}\times\vec{V} - \frac{1}{\rho} gradP + \vec{g} + \vec{F};$$

Energy equation

$$Cp\frac{dT}{dt} = Q + \frac{1}{\rho}\frac{dP}{dt};$$



Radiative Transport

$$\frac{\partial I\nu}{\partial s} = -\chi_\nu \rho\,[I\nu - J\nu];$$

Spatial domain

$$0<\lambda<2\pi; \quad -\pi/2<\varphi<\pi/2; \quad z_s<z<z_{top}$$

Water vapor transport

$$\frac{dq}{dt} = S(q);$$

Boundary conditions

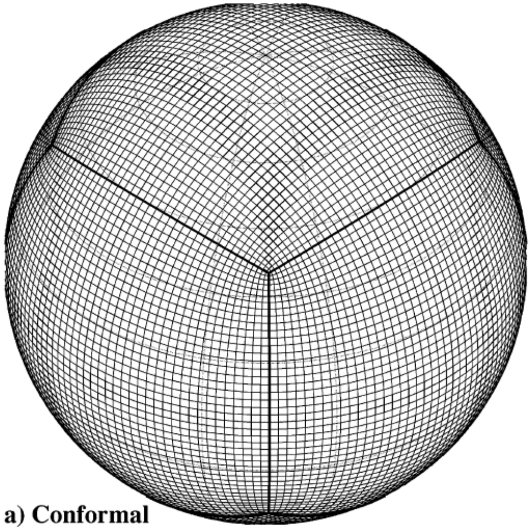
$$z = z_s: \quad v_n = 0; \quad F^{\uparrow} = Fs$$

$$z = z_{top}:$$

Equation of state

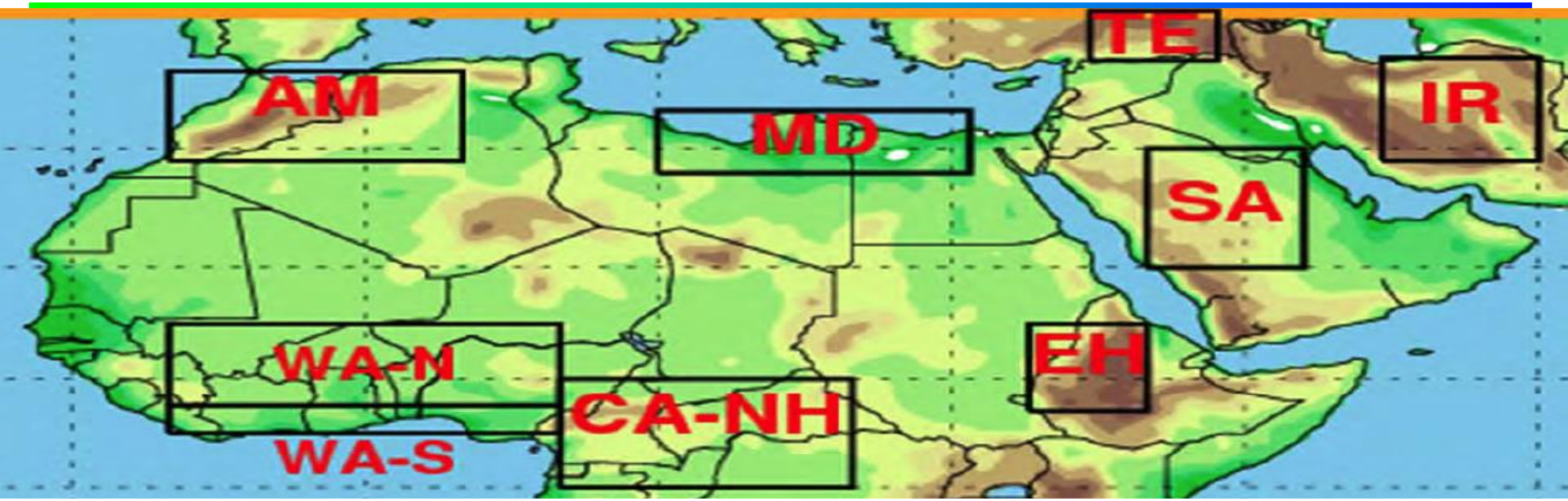
$$P = \rho RT;$$

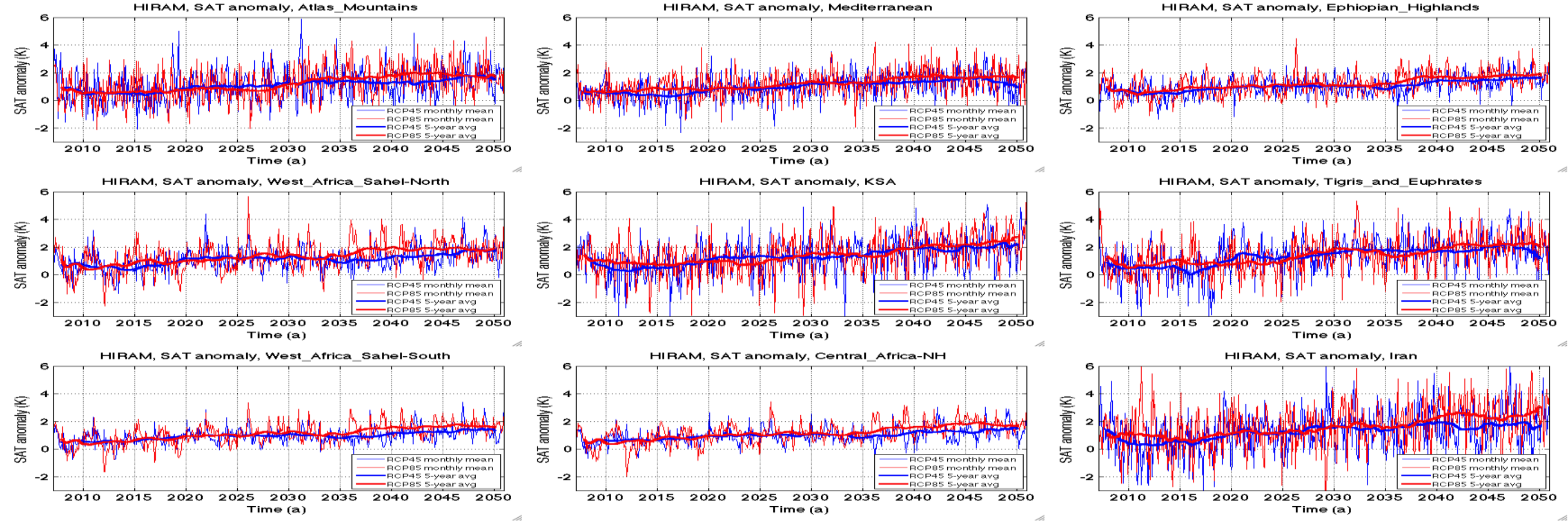
$$w = \frac{\partial z_{top}}{\partial t} + u\frac{\partial z_{top}}{(a\cos\varphi)\partial\lambda} + v\frac{\partial z_{top}}{a\partial\varphi}; \quad F^{\downarrow} = S_0\cos\varsigma$$



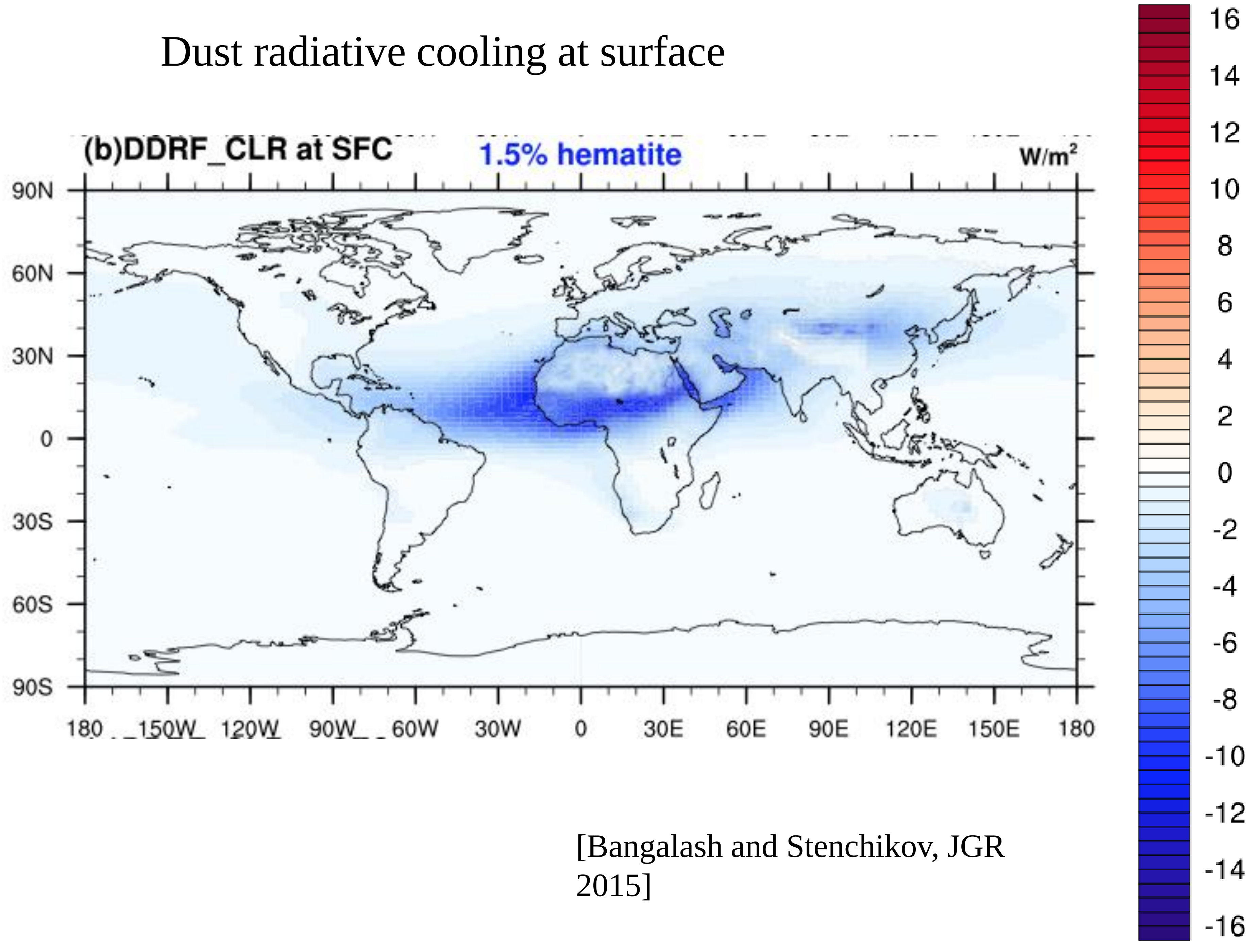
a) Conformal

United Nations Economic and Social Commission for Western Asia (ESCWA) coordinated Assessment of the Impact of Climate Change on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR)



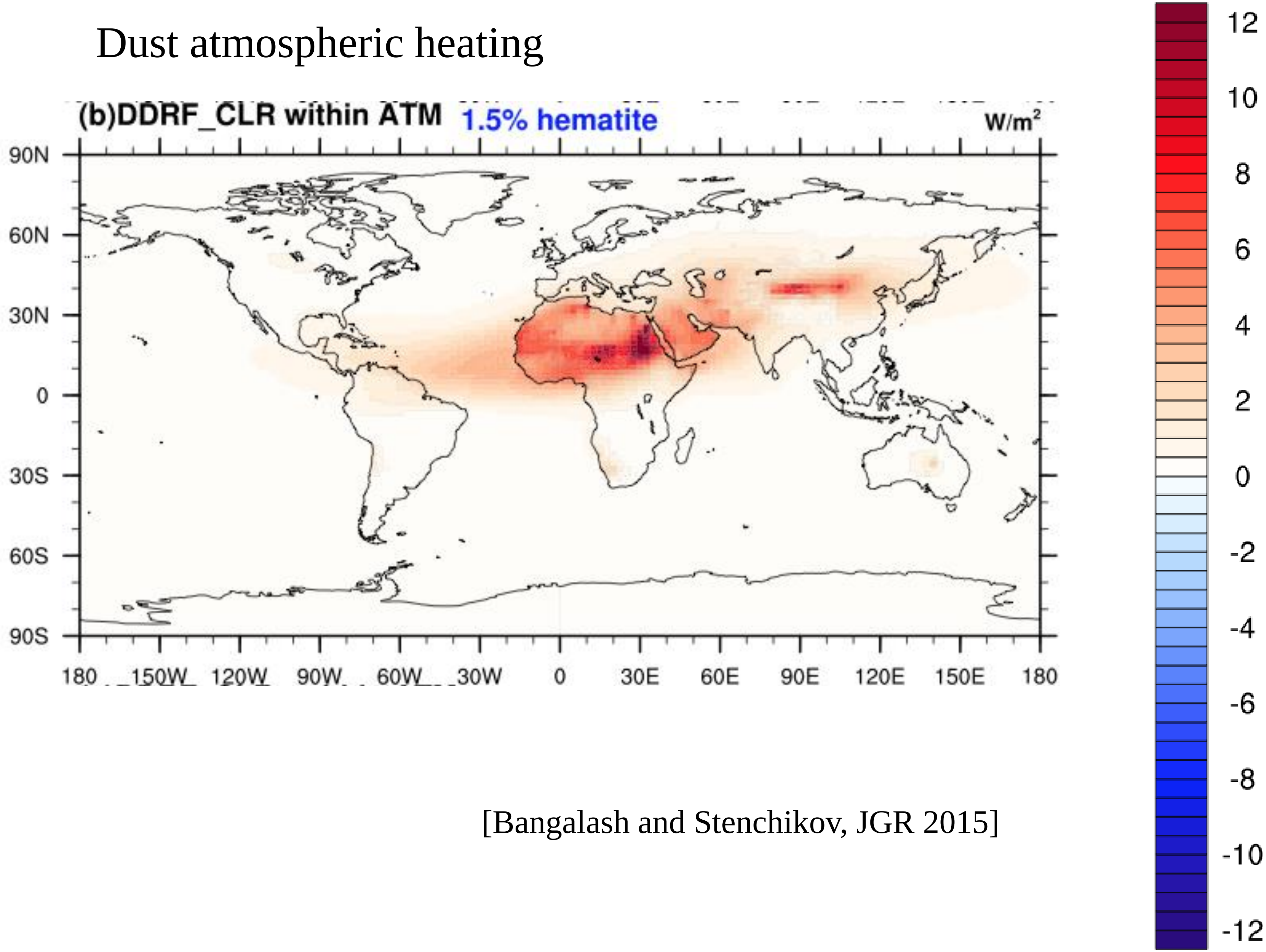


Dust radiative cooling at surface

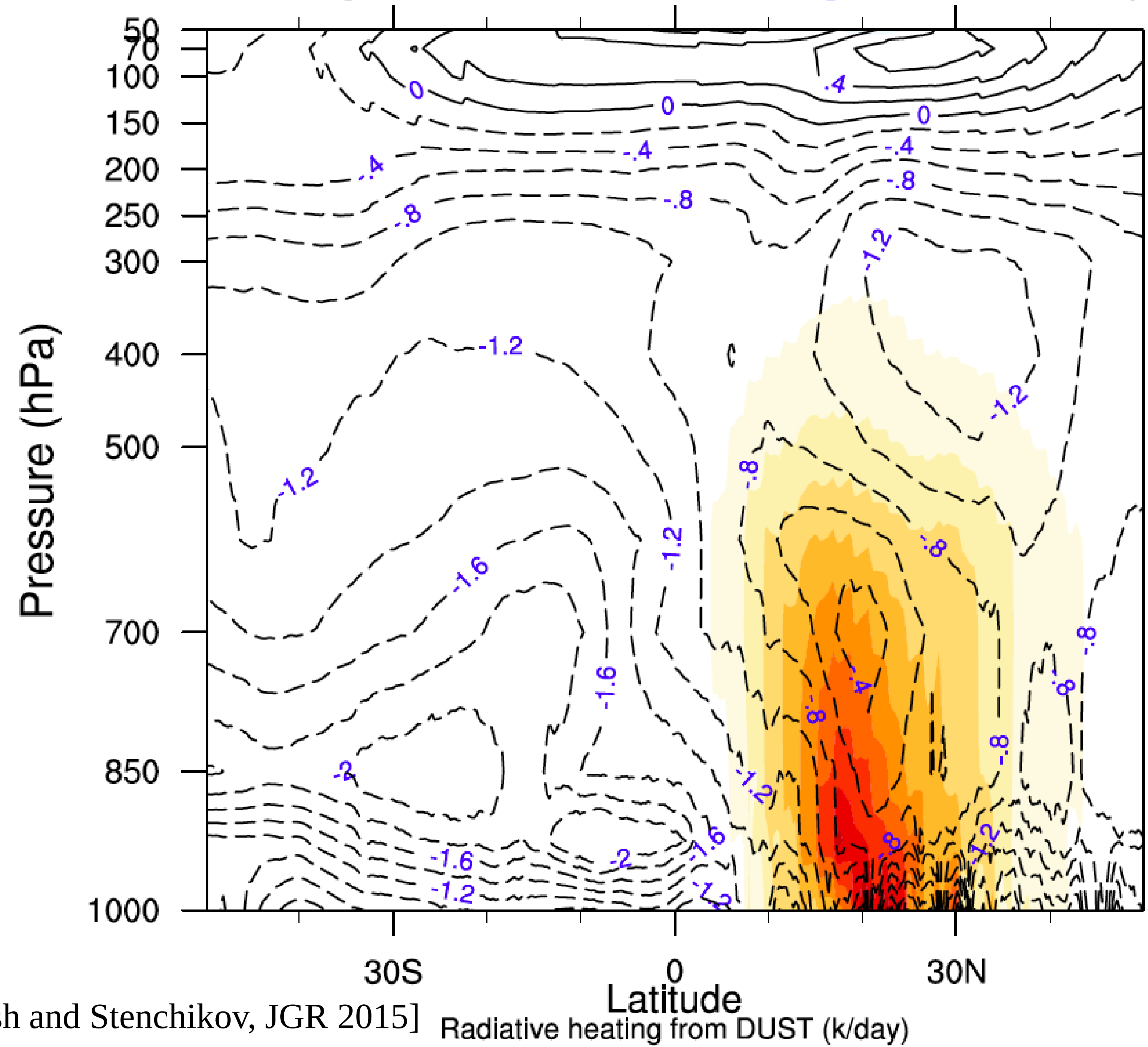


[Bangalash and Stenchikov, JGR 2015]

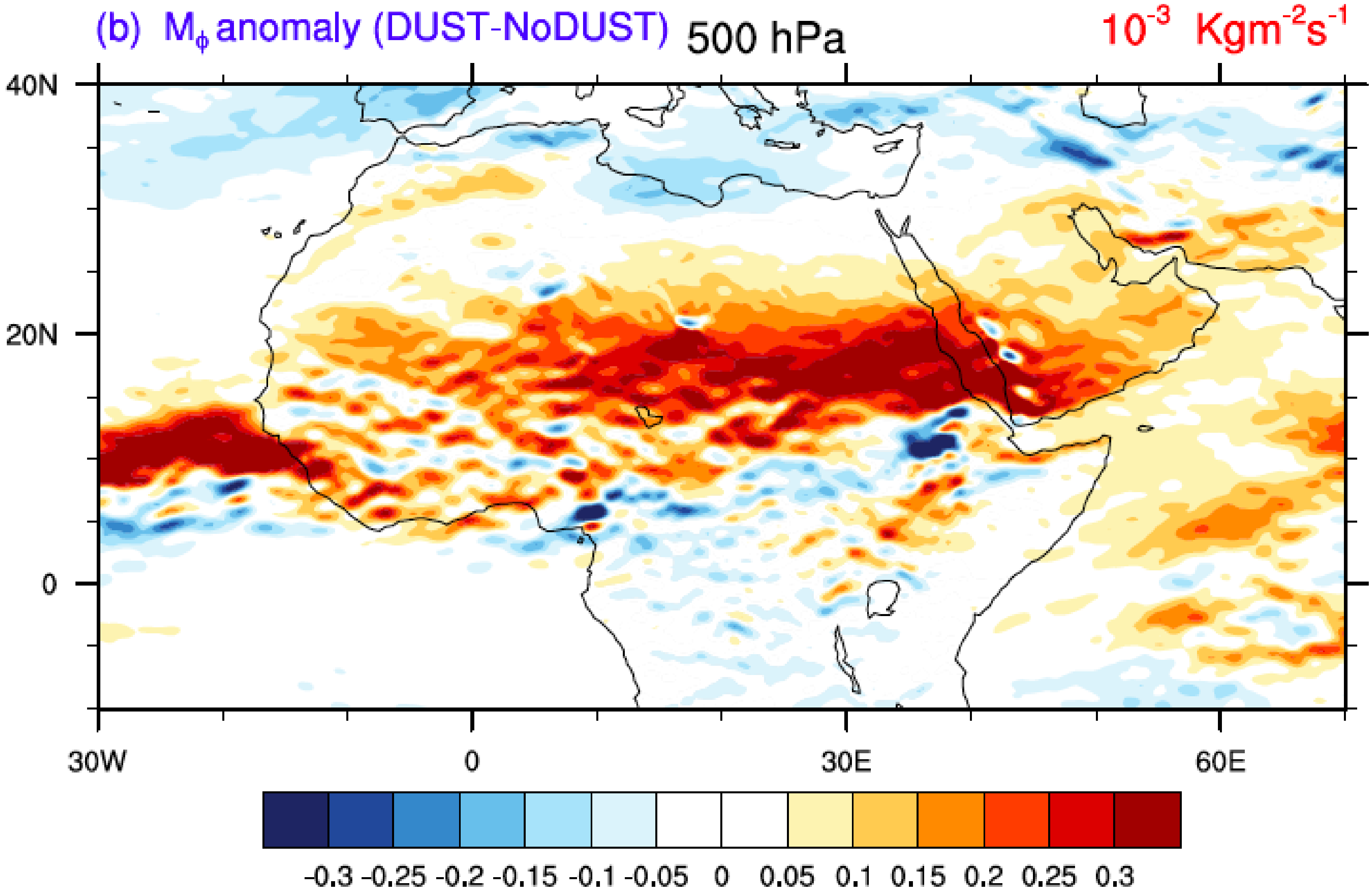
Dust atmospheric heating



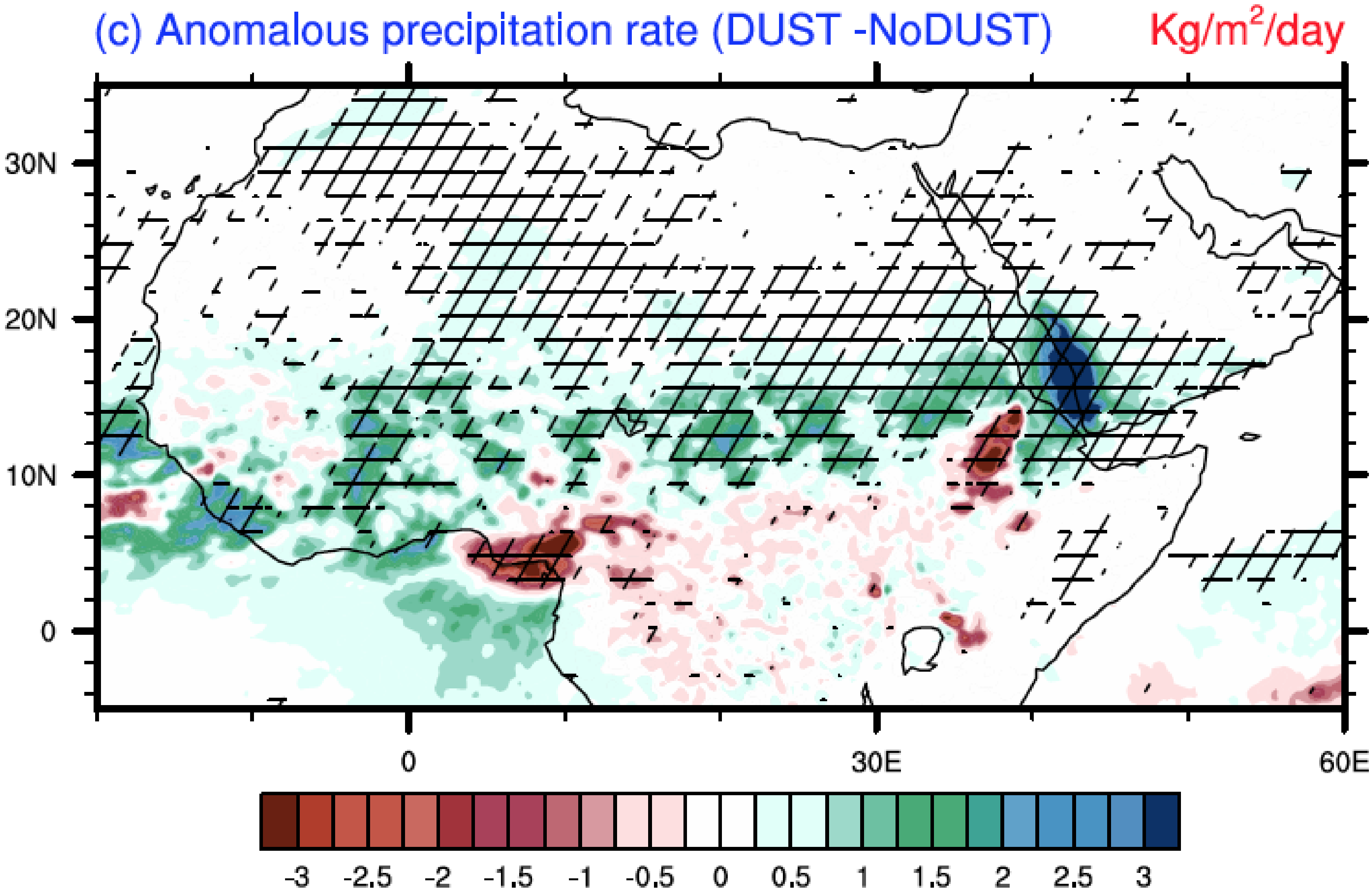
[Bangalash and Stenchikov, JGR 2015]



[Bangalash and Stenchikov, JGR 2015]

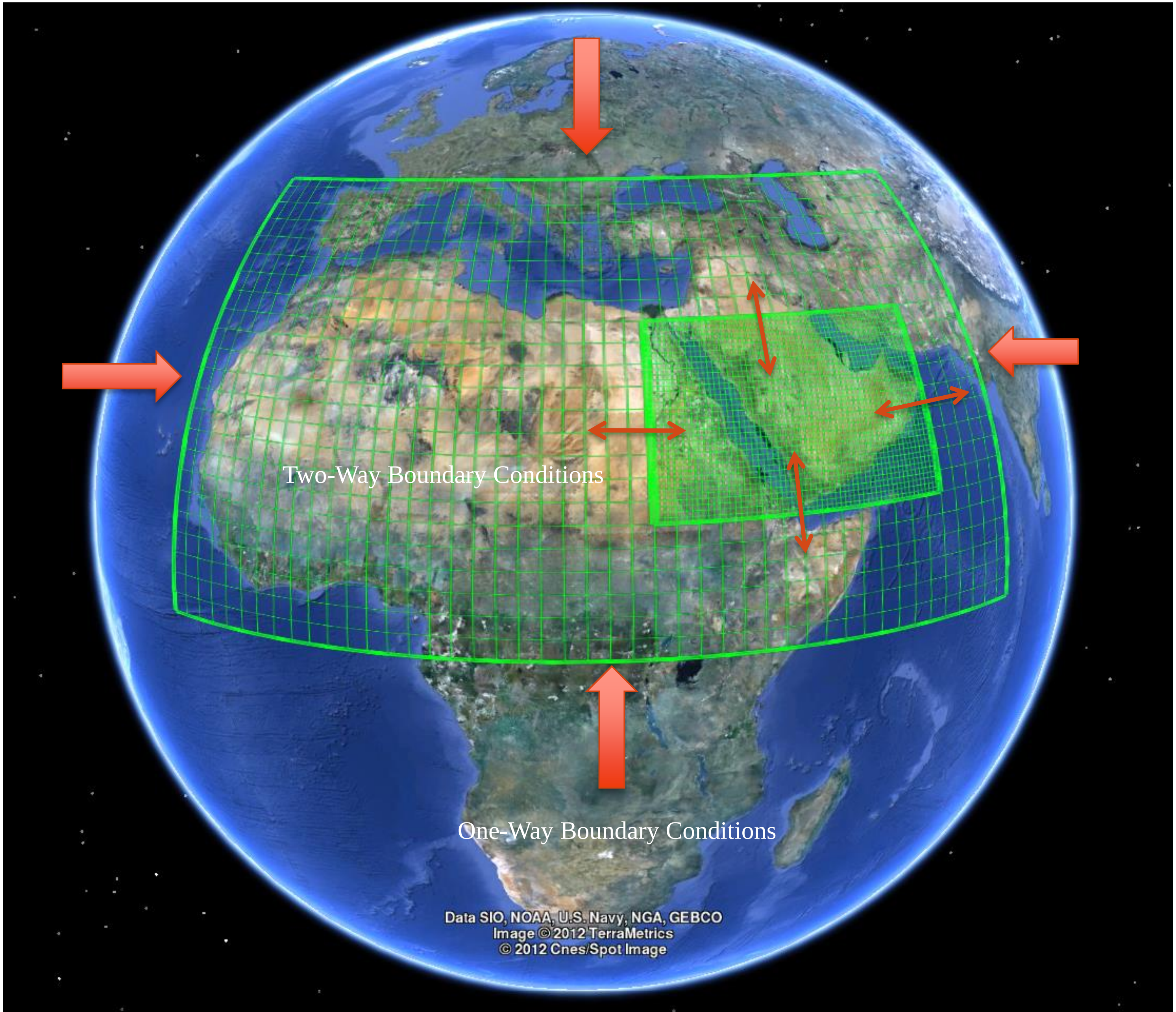


[Bangalash and Stenchikov, JGR 2015]

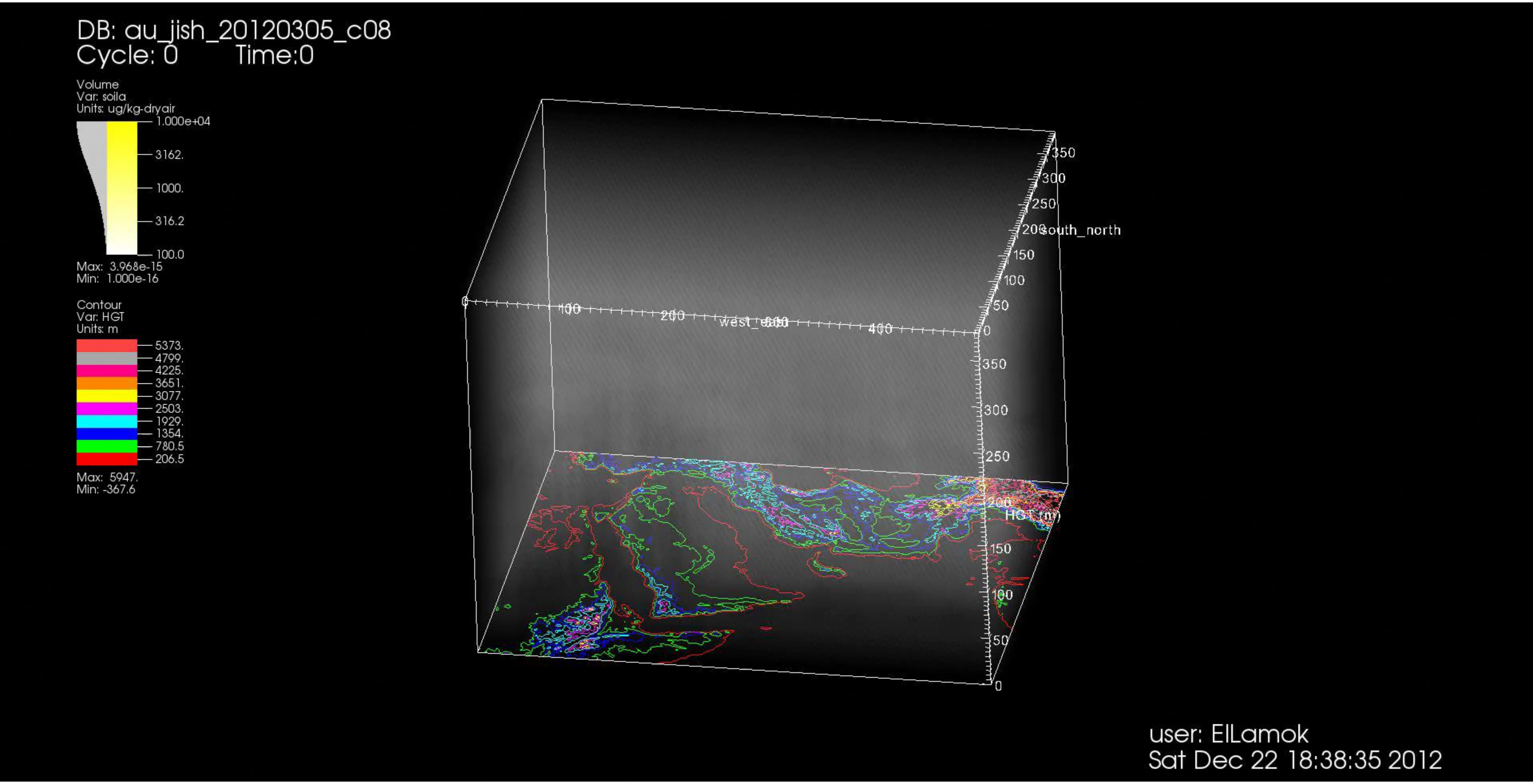


[Bangalash and Stenchikov, JGR 2015]

Process Oriented Regional Model WRF-Chem



DUST STORM SIMULATION



Aerosol optical depth calibration

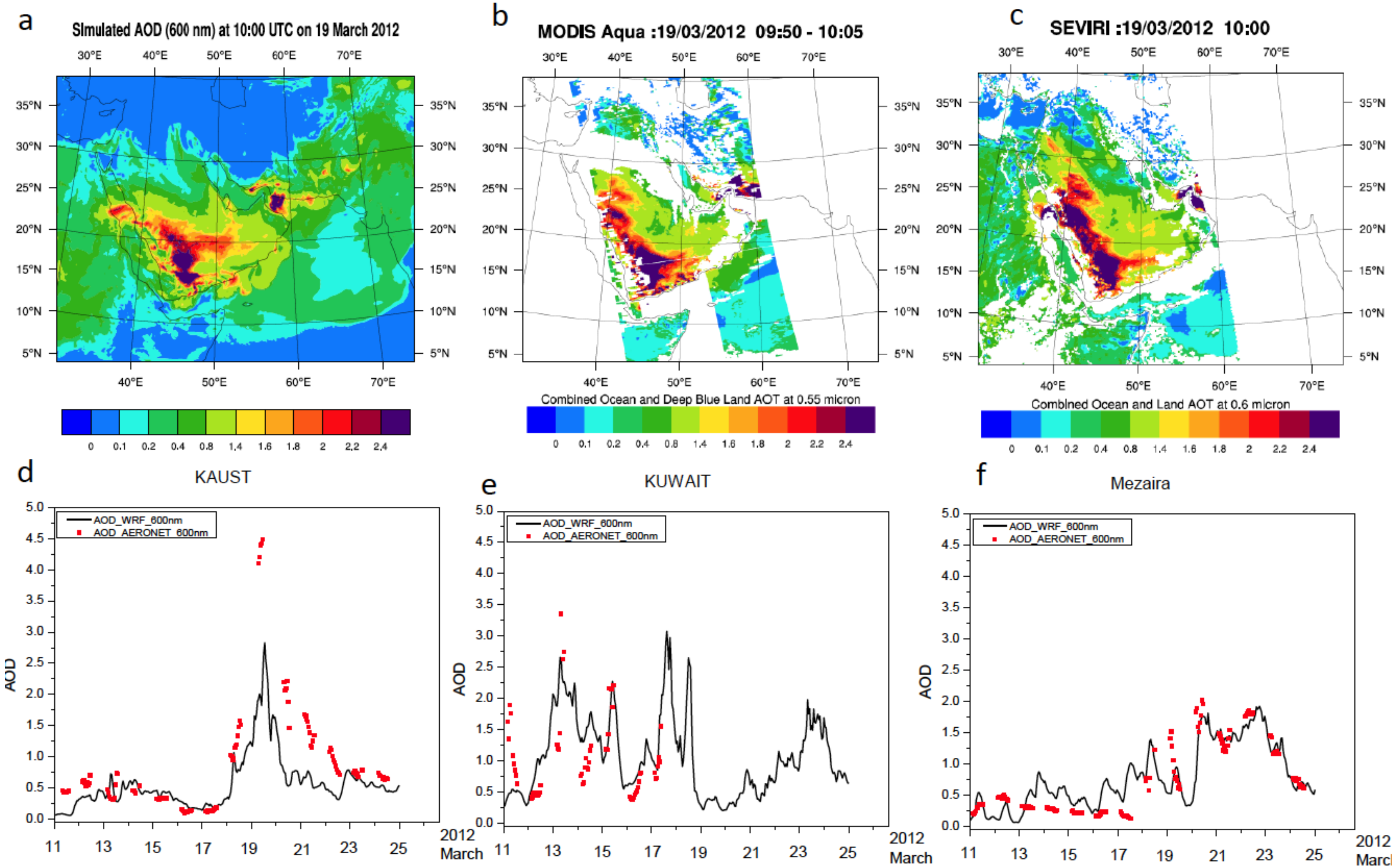
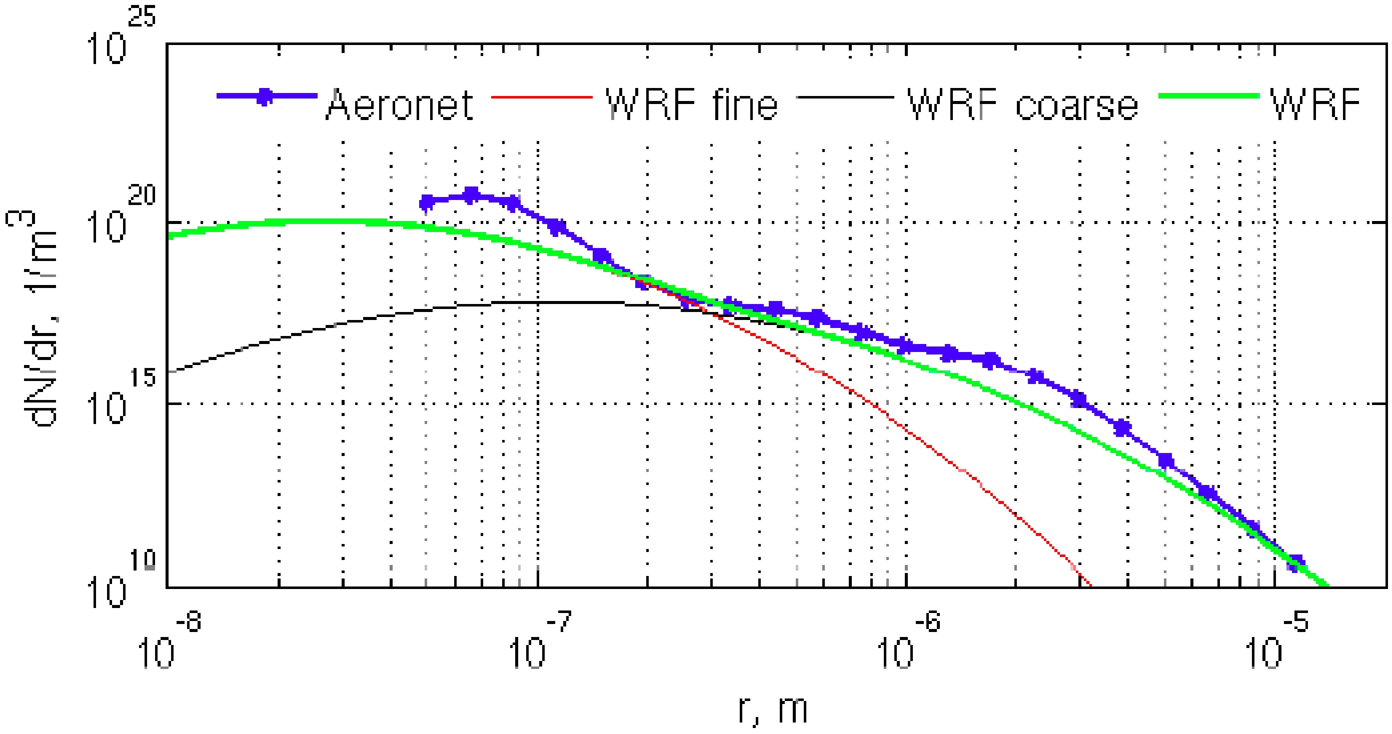


Figure 10. (a) Simulated spatial distribution of AOD (600 nm) at 1000 UTC 19 March (b) AOD obtained from MODIS (standard ocean and Deep blue products) at 0950-1005 UTC March 19 (c) AOD obtained from SIVIRI(Product description) at 1000 UTC March 19 (d) Time series of simulated AOD (600 nm) and AERONET Sun photometer AOD(red dots) for KAUST Campus (22.30º N 39.10º E) (e) Same as 9d, but for Kuwait University (29.32º N, 47.97º E) and (g) Same as 9d, but for Mezaira (23.14º N, 53.77º E).

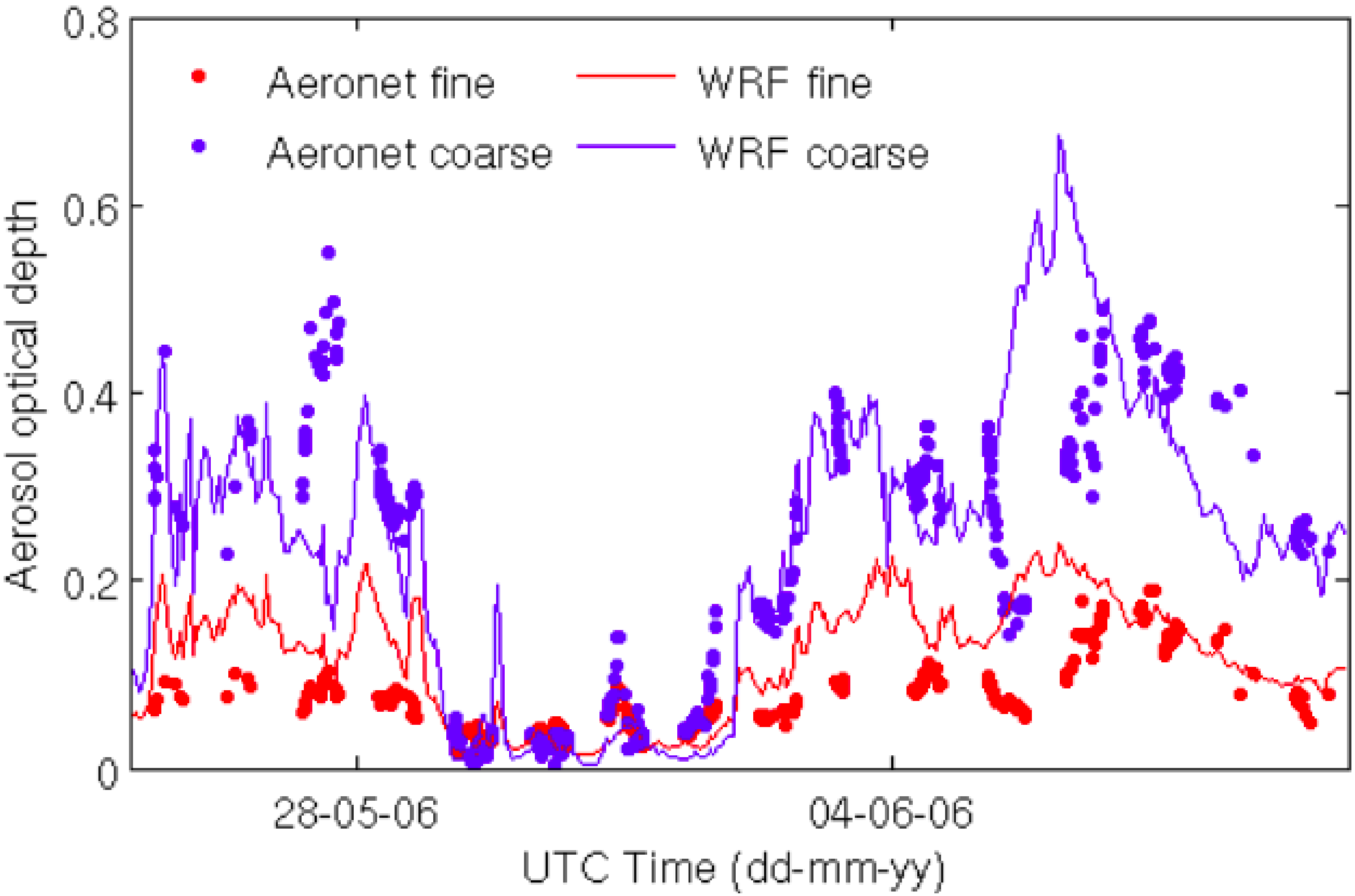
[Prakash et al., ACP 2015]

Aerosol size distribution



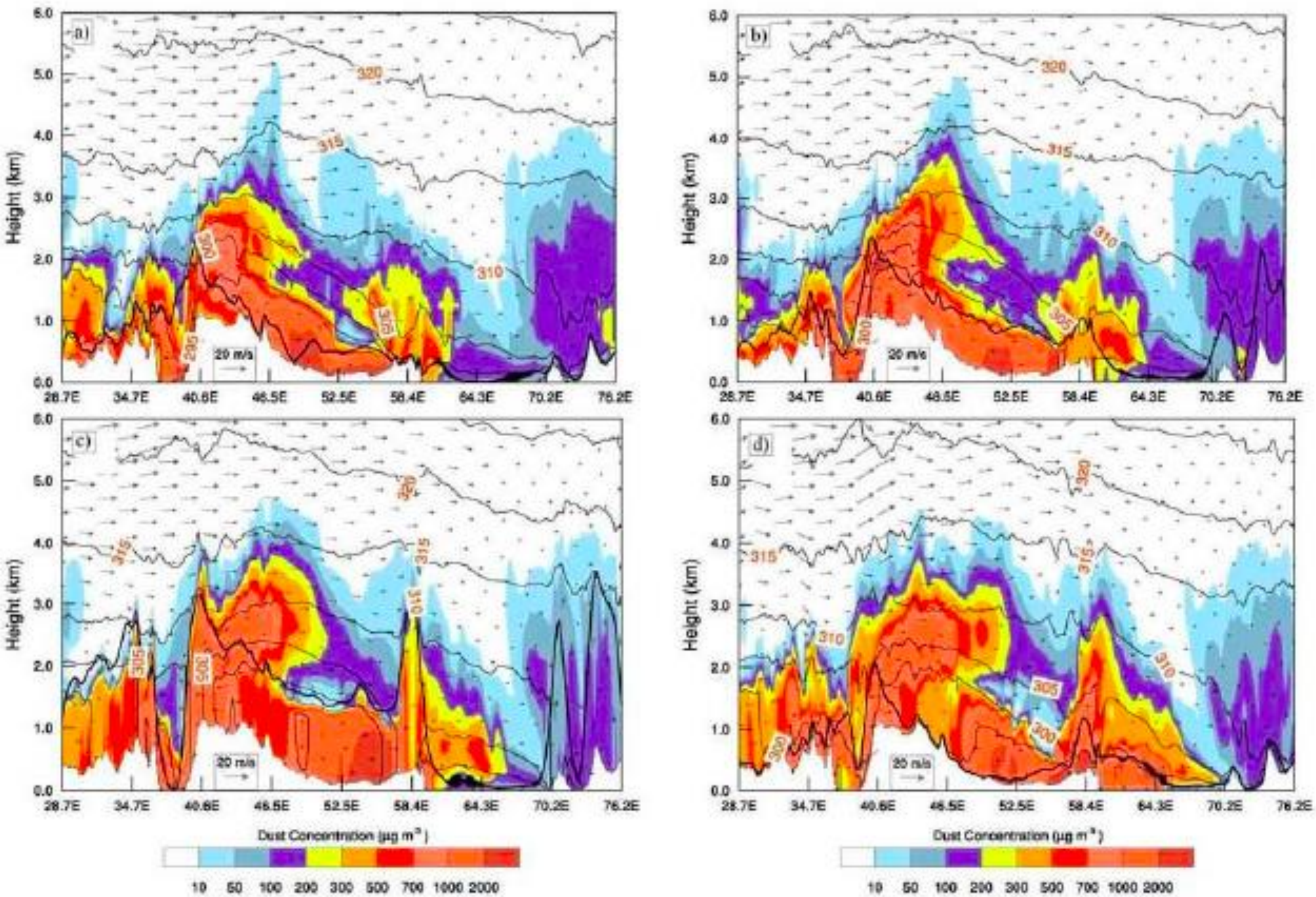
[Khan et al., Tellus-B, 2015]

Fine and Coarse aerosol modes



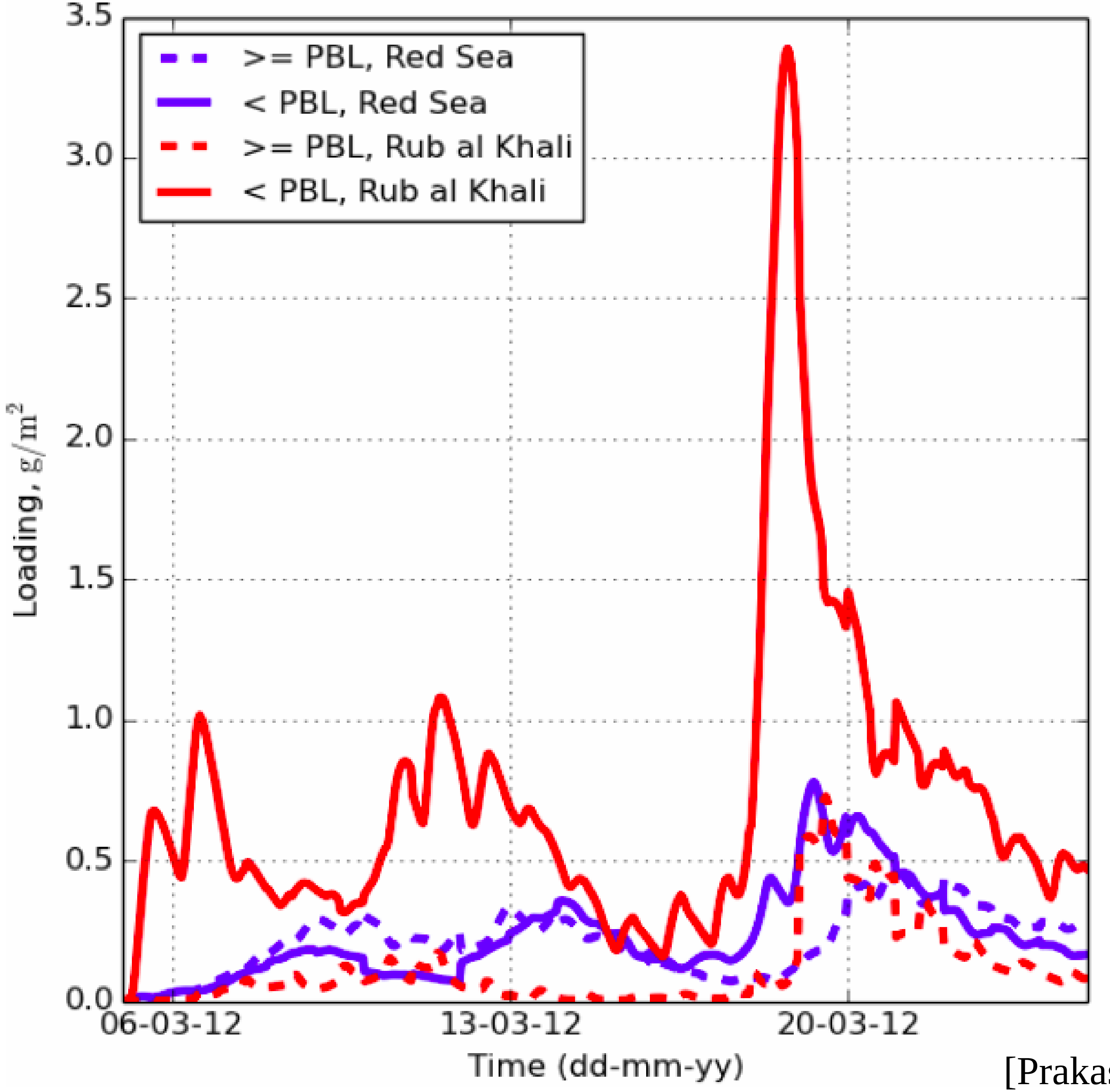
[Khan et al., Tellus-B, 2015]

Mechanisms of Aerosol Mixing into the Free Troposphere



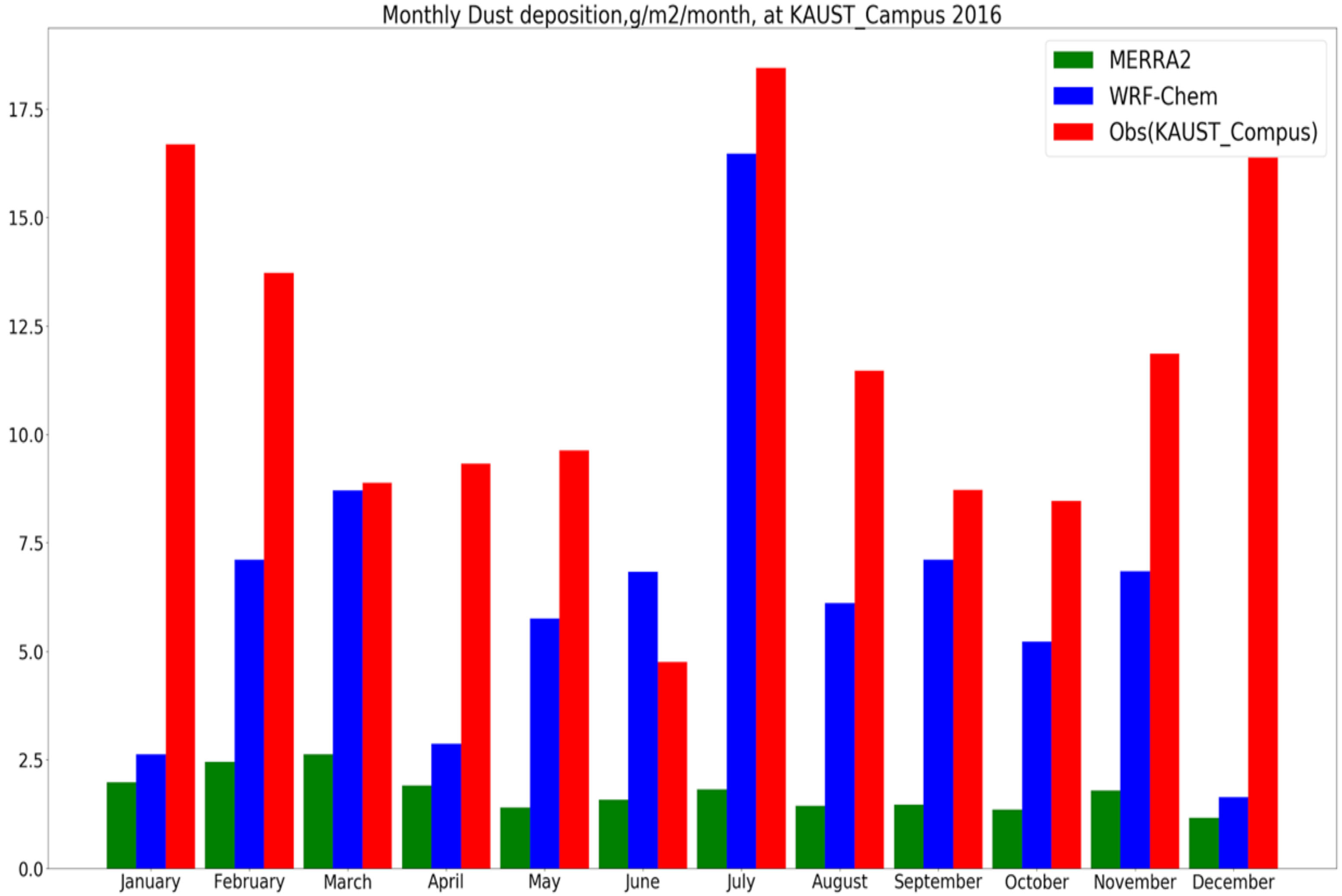
[Prakash et al., ACP 2015]

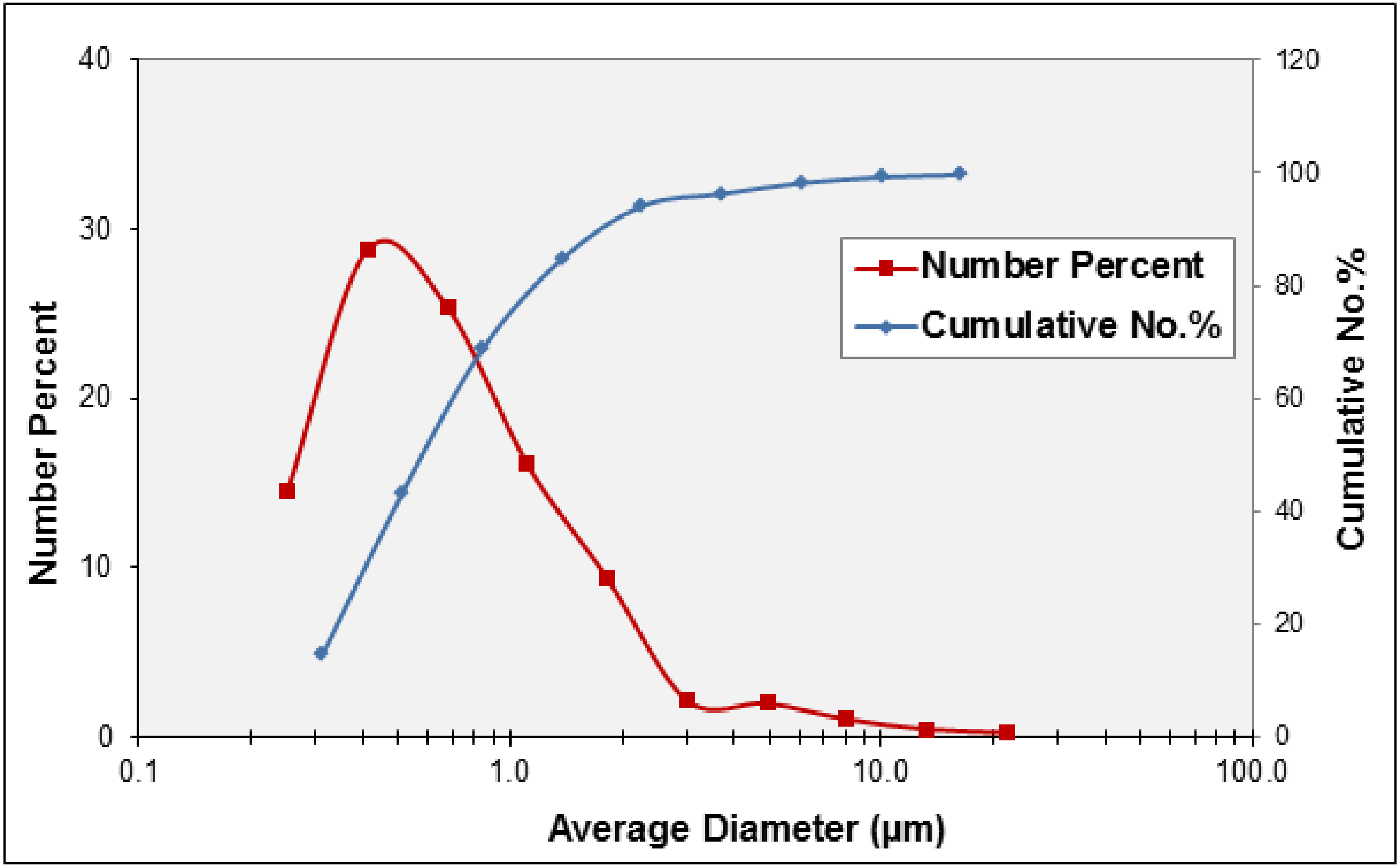
Amount of dust above and below PBL top

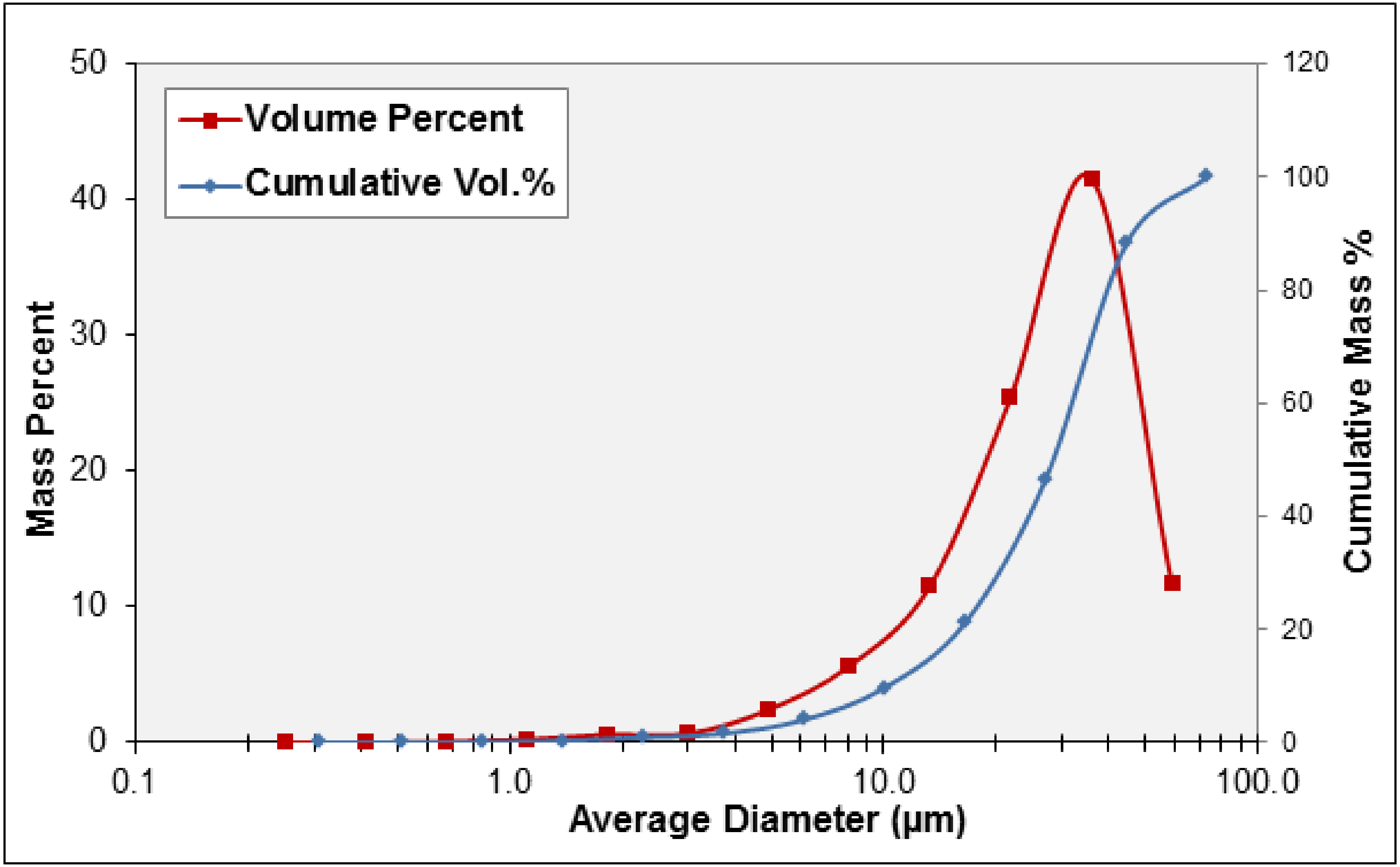


[Prakash et al., ACP 2015]

Dust Deposition at KAUST_Campus location 2016




40
30
20
10
0
Number Percent
120
100
80
60
40
20
0
Cumulative No.%
0.1
1.0
10.0
100.0
Average Diameter (µm)
Number Percent
Cumulative No.%



Volume Percent
Cumulative Vol.%
Mass Percent
Cumulative Mass %
Average Diameter (µm)
0
10
20
30
40
50
0
20
40
60
80
100
120
0.1
1.0
10.0
100.0

First Coupled Regional Ocean-Atmosphere Model of the Red Sea

In Short Wave Spectrum:
Mie, Spheroidal particles, T-matrix and geometric optics + SEVIRI optical depth
(Osipov, 2015, Brindley, 2015)

In Long Wave Spectrum:
Mie, None-Spherical Particles

Size Distribution from the AERONET climatology

→ Spectral optical properties $\varepsilon(\lambda)$, $\omega(\lambda)$, $g(\lambda)$ → Atmosphere (WRF, RRTMG) ↔ (30 min) Ocean (ROMS)

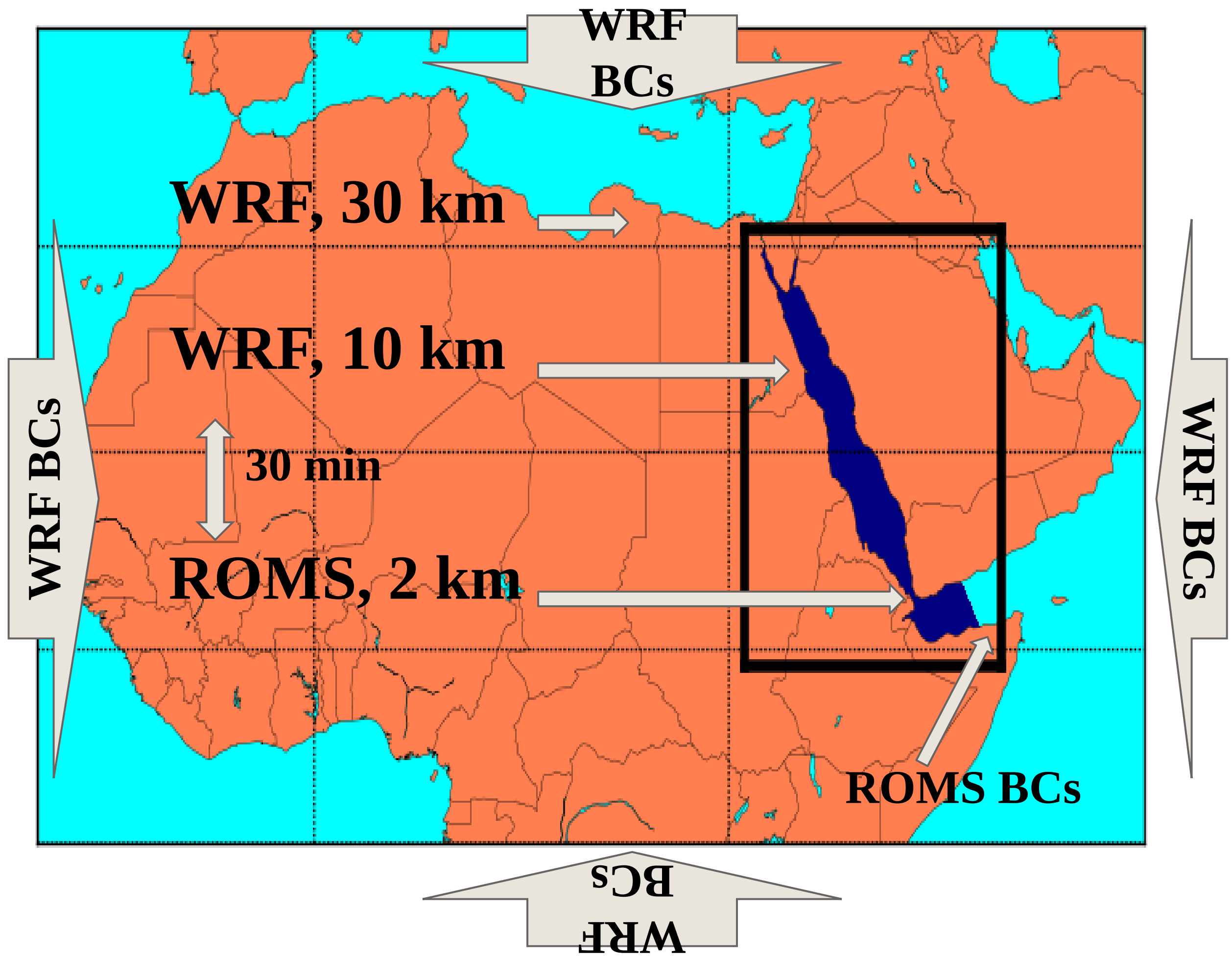
Framework:
A Coupled Ocean Atmosphere Wave Sediment Transport Modeling System (COAWST)

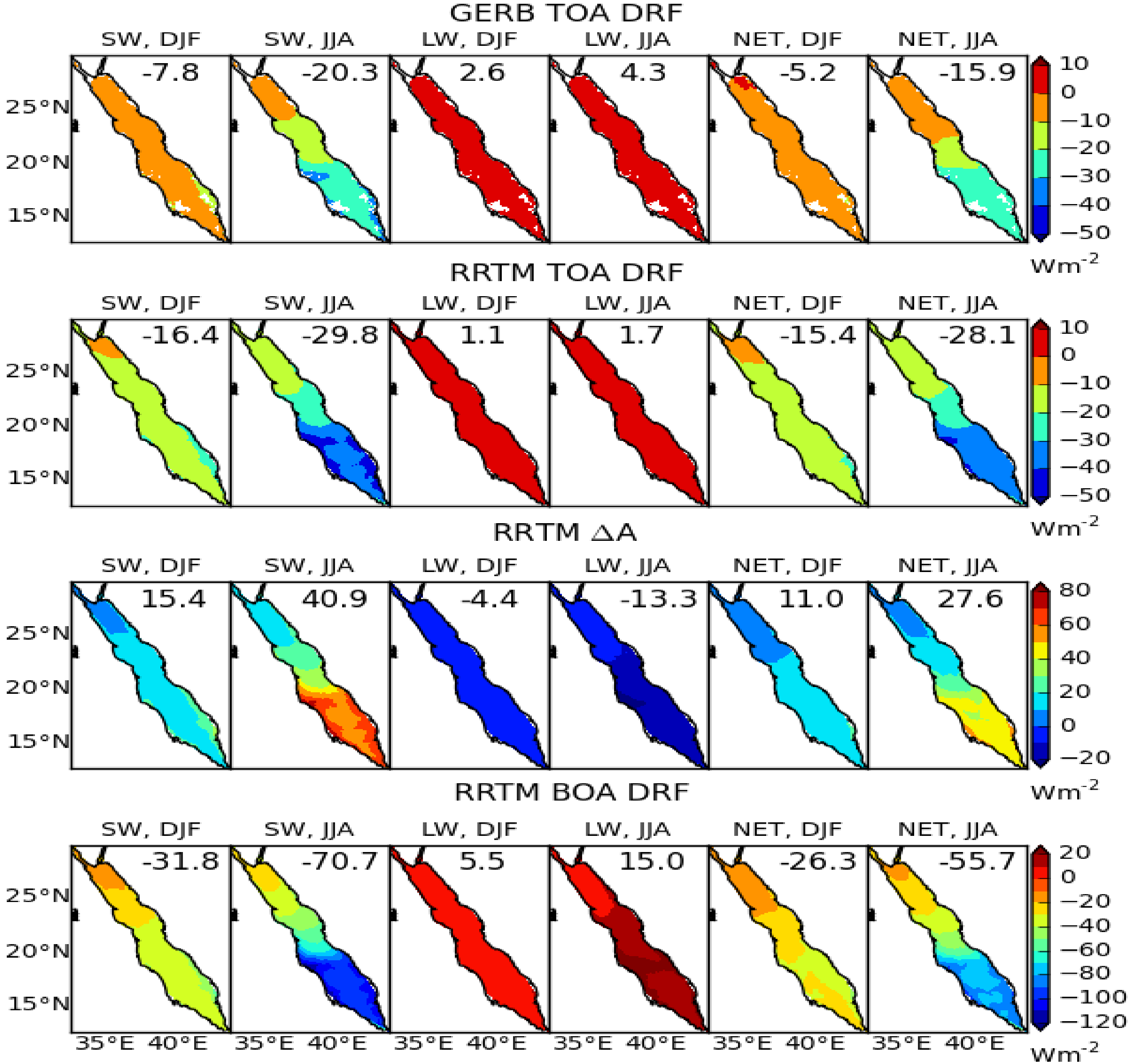
Atmosphere:
Weather Research and Forecasting Model (WRF)

Ocean:
Regional Ocean Modeling system (ROMS)

Boundary Conditions:
ERA-INTERIM

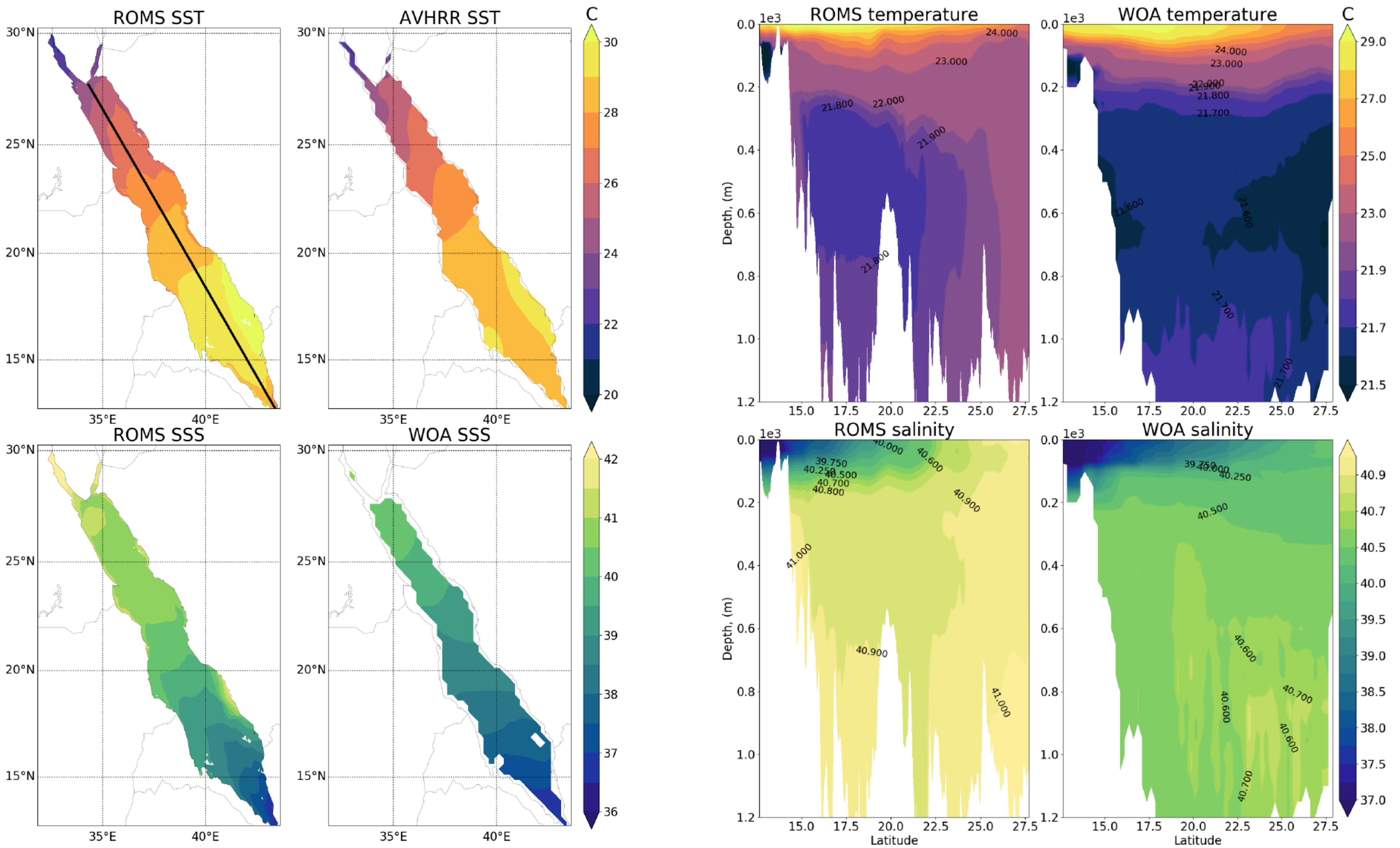
Experiments:
Perturbed (with DUST) – P
Control (without DUST) – C
Runs for the 1996-2016 period



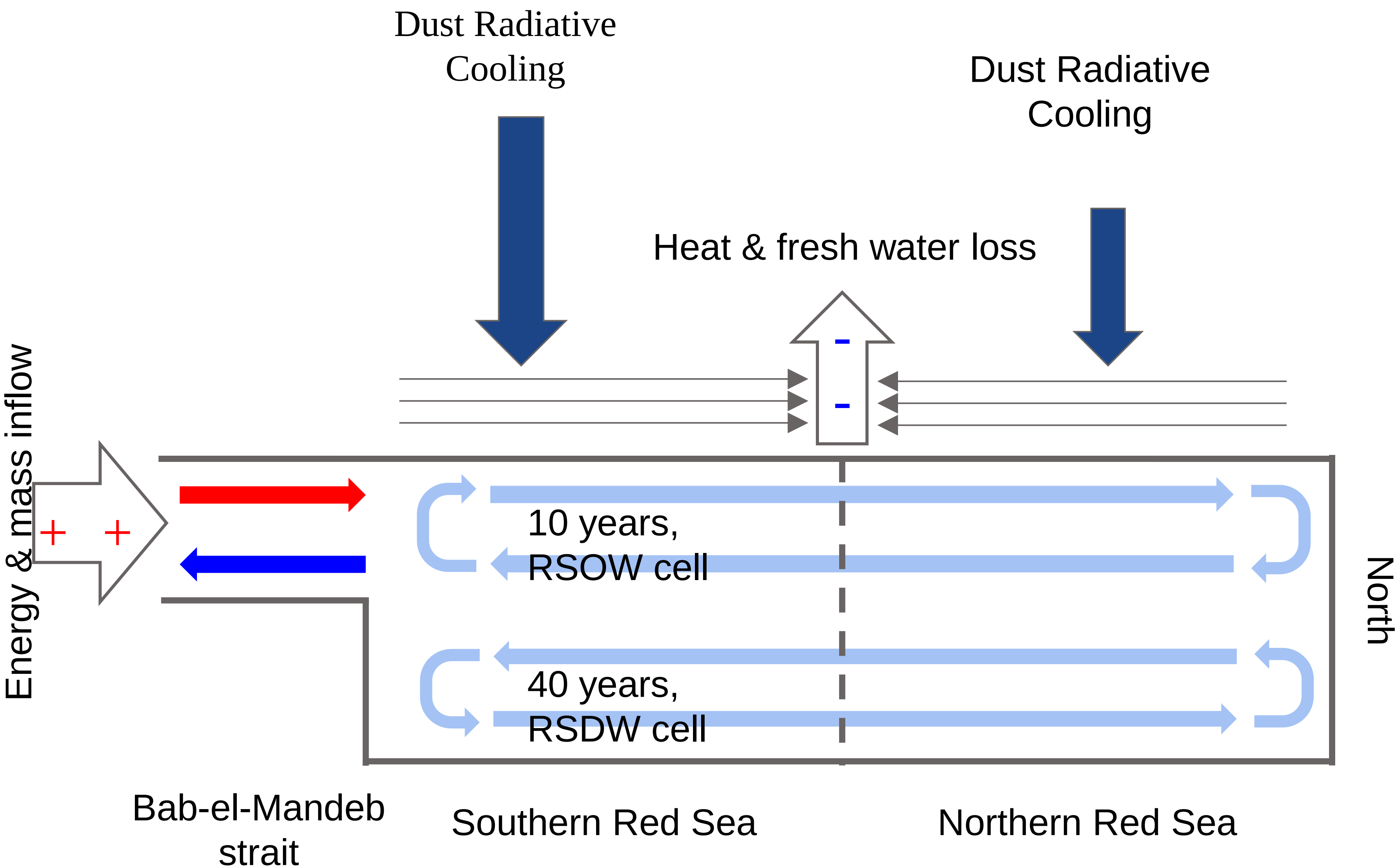


GERB TOA DRF
SW, DJF
SW, JJA
LW, DJF
LW, JJA
NET, DJF
NET, JJA
-7.8
-20.3
2.6
4.3
-5.2
-15.9
RRTM TOA DRF
-16.4
-29.8
1.1
1.7
-15.4
-28.1
RRTM ΔA
15.4
40.9
-4.4
-13.3
11.0
27.6
RRTM BOA DRF
-31.8
-70.7
5.5
15.0
-26.3
-55.7
25°N
20°N
15°N
35°E 40°E
Wm-2
10 0 −10 −20 −30 −40 −50
80 60 40 20 0 −20
20 0 −20 −40 −60 −80 −100 −120

Red Sea simulations using ROMS/WRF coupled model



Dust Ompact on the Red Sea



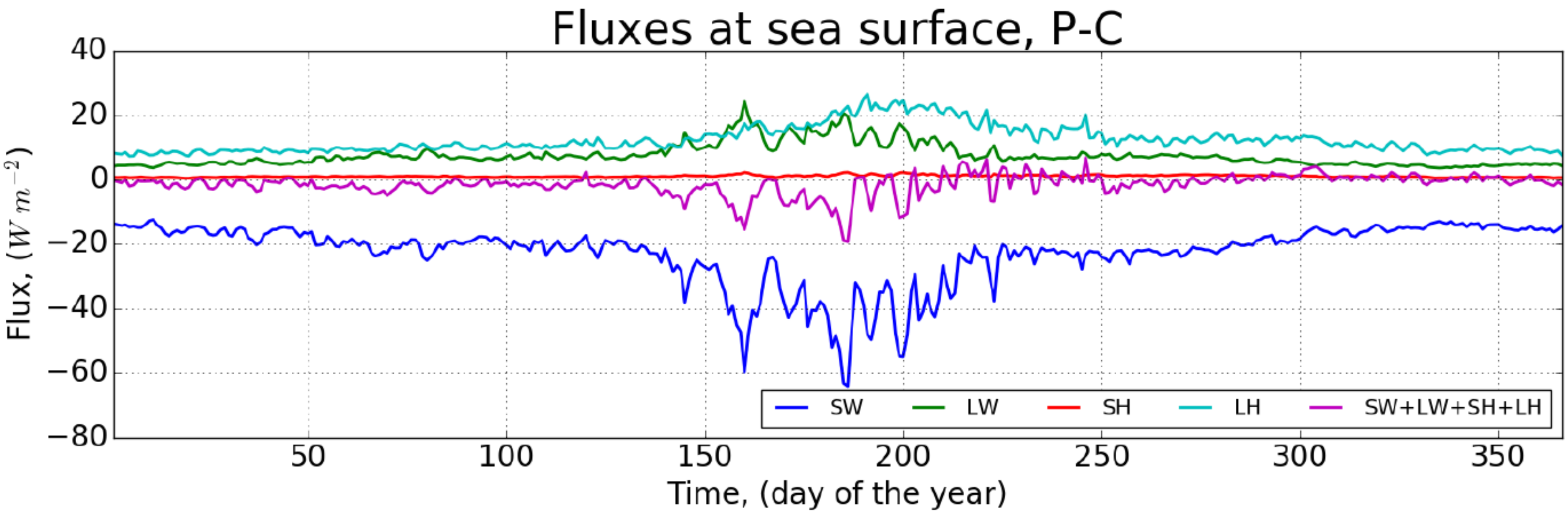
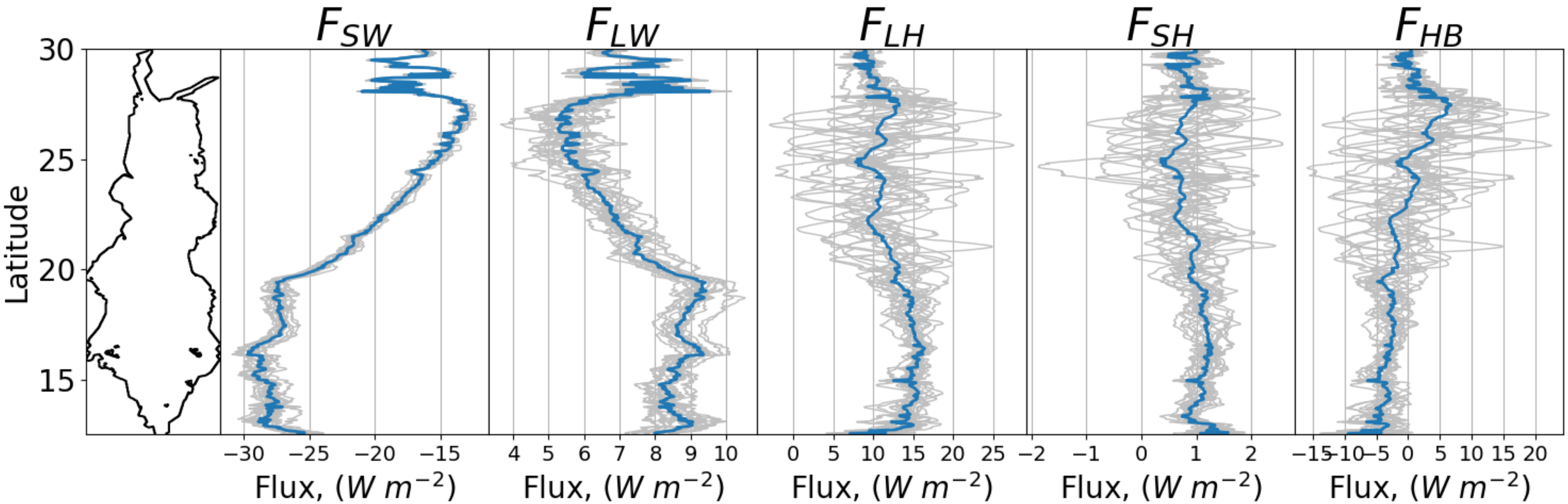


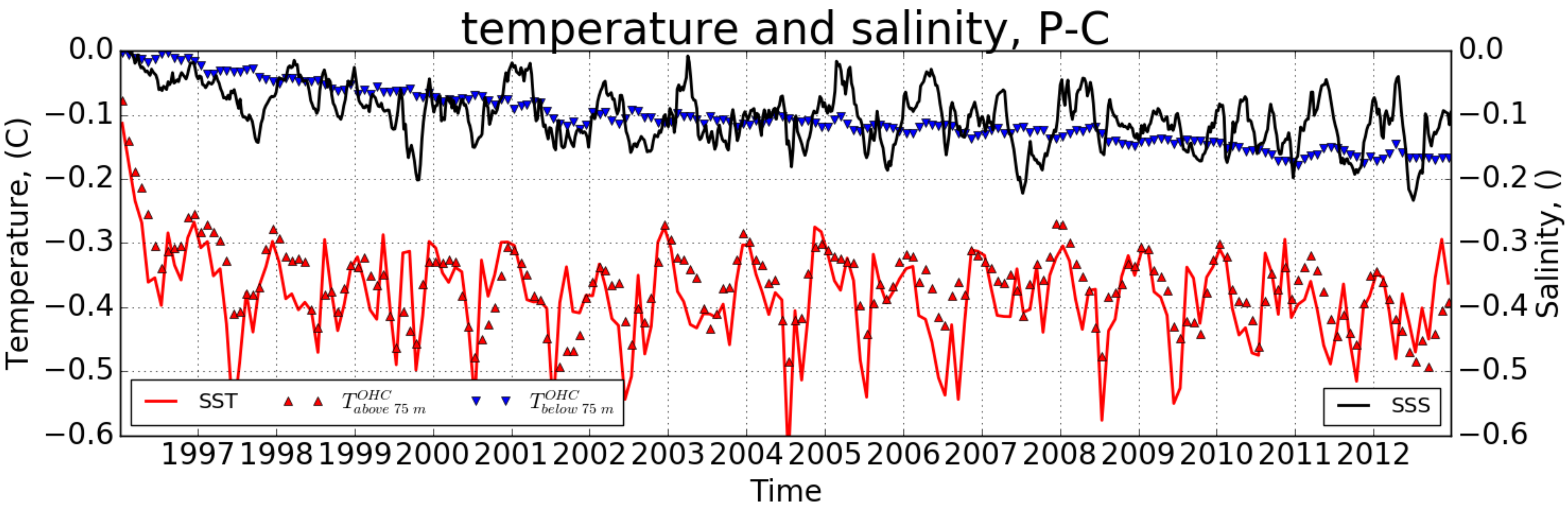
Figure 3. Climatological daily net (downward minus upward) fluxes anomaly (perturbed minus control run) as a response to the dust radiative forcing at the sea surface spatially averaged over the Red Sea.

Forcing Along the Rd Sea Axes



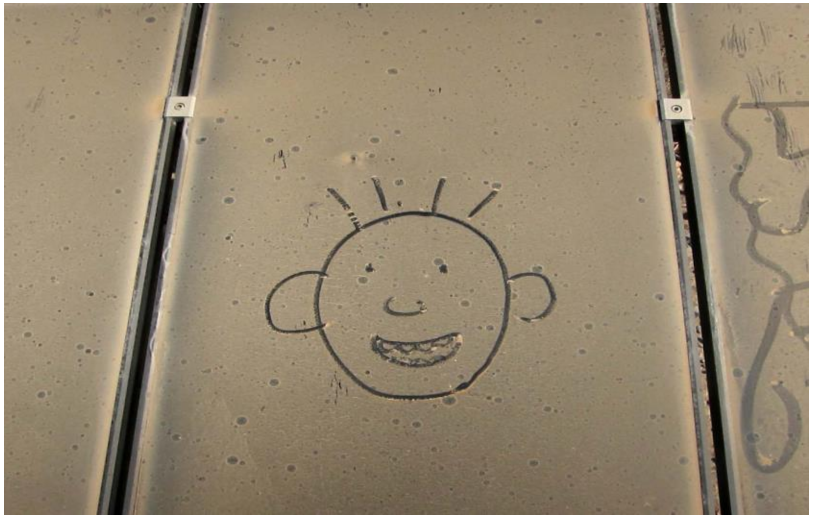
Net fluxes anomalies (left to right, SW, LW, LH, SW and heat budget) due to dust aerosol at the sea surface. Hairline lines indicate individual years and their mean is shown by the thick blue line. Diagnostics variables are spatially averaged across the Red Sea axis. Red Sea land mask contours are provided (left column) as a spatial reference.

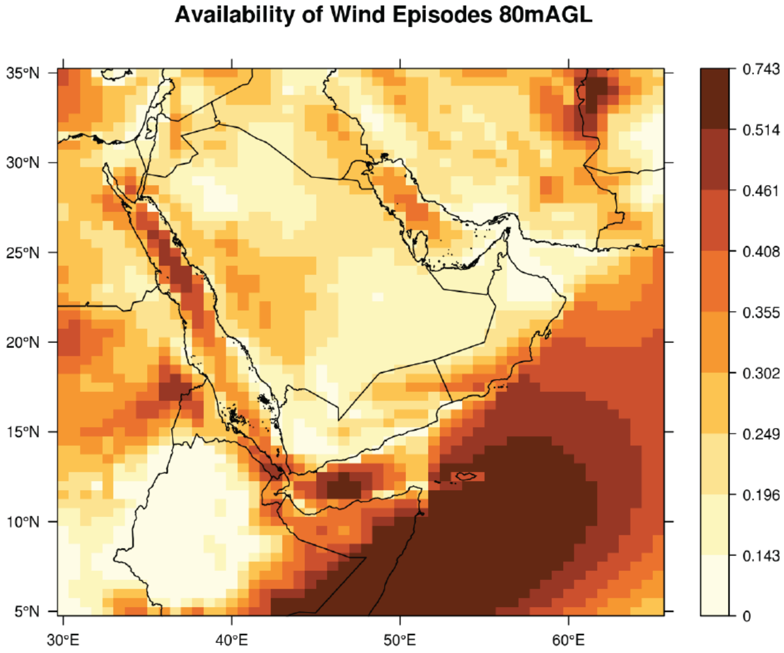
RESPONSE



Spatially averaged monthly temperature and salinity anomalies. SST, and T above and below 75 m are plotted against left vertical axis and SSS (salinity) is plotted against right vertical axis.

Renewable Energy Assessments in the Kingdom of Saudi Arabia: Solar and Wind Power Resources





Eulerian-Lagrangian approach to calculate fine-scale dust particles transport and deposition

+

CFD code (OpenFOAM):
Navier-Stokes equations are solved accounting for momentum exchange between particles and surrounding fluid.

Particle code (ODE):

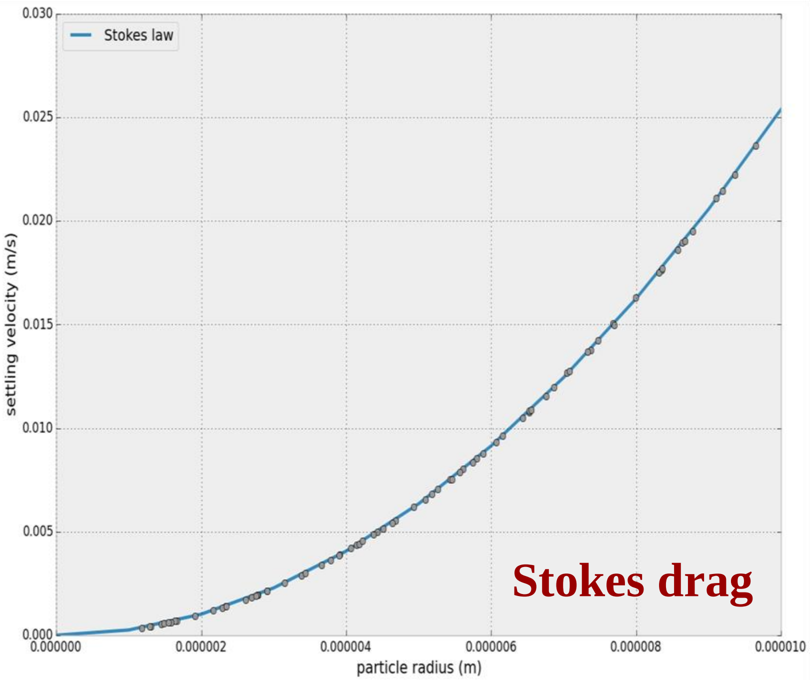
Particle trajectories, collisions between particles and collisions of particles with the boundaries.

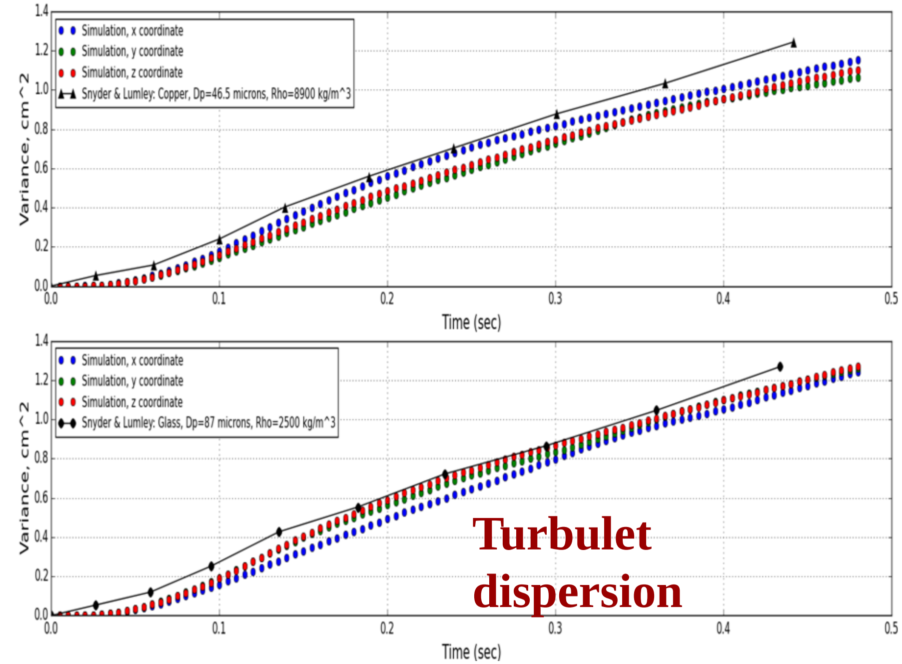
$$\frac{\partial \alpha_f \rho_f}{\partial t} + \nabla \cdot \left(\alpha_f \rho_f \mathbf{u}_\mathrm{f} \right) = 0$$

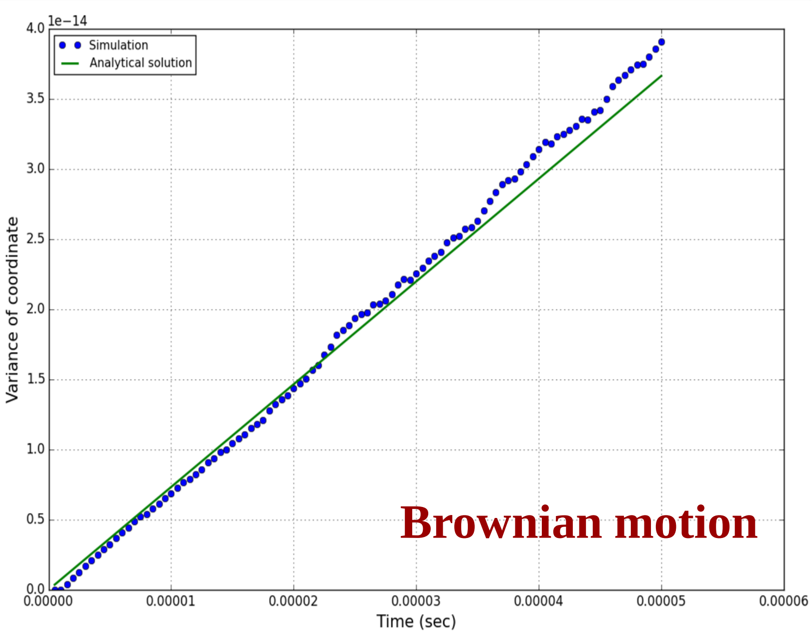
$$\frac{\partial \left(\alpha_f \rho_f \mathbf{u}_\mathrm{f} \right)}{\partial t} + \nabla \cdot \left(\alpha_f \rho_f \mathbf{u}_\mathrm{f} \mathbf{u}_\mathrm{f} \right) = -\alpha_f \nabla p + \nabla \cdot \left(\alpha_f \boldsymbol{\tau}_f \right) + \alpha_f \rho_f \mathbf{g} - f_{drag}$$

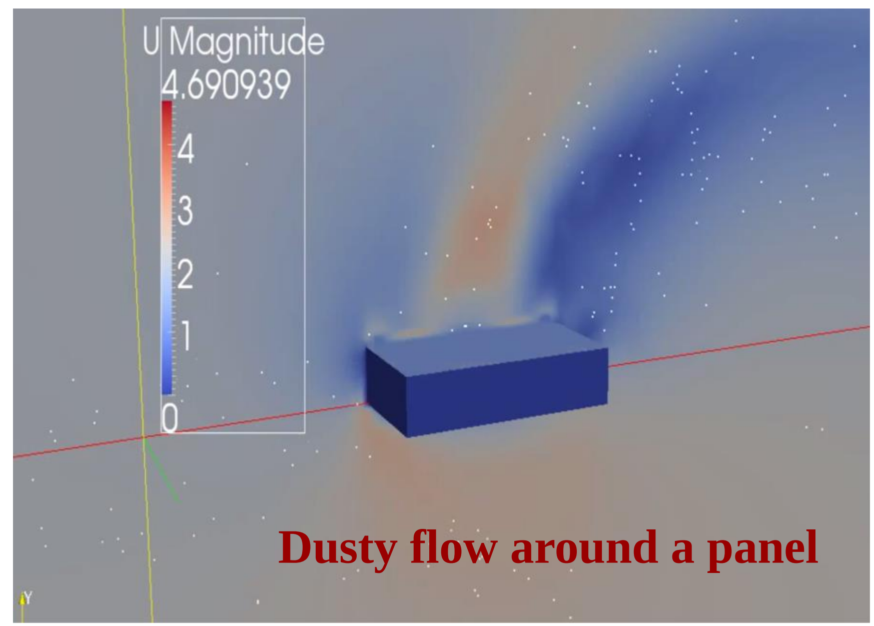
$$\alpha_\mathrm{f} = 1 - \sum_{k=1}^{n_\mathrm{p}} V_{\mathrm{p}k} / \Delta V, \qquad f_\mathrm{drag} = \frac{1}{\Delta V} \sum_{i=1}^{n_p} \boldsymbol{F}_{\mathrm{drag},i}$$

Validation and applications



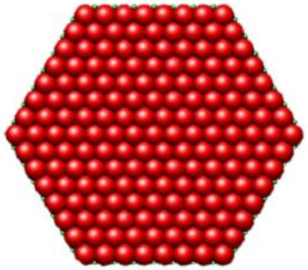






Interaction of Dust Particles with a Surface
Study Particles Potentials Using Molecular Dynamics

Clay fractions: illite, kaolinite and smectite
3 unit cell (3 fractions) => 3 supercells

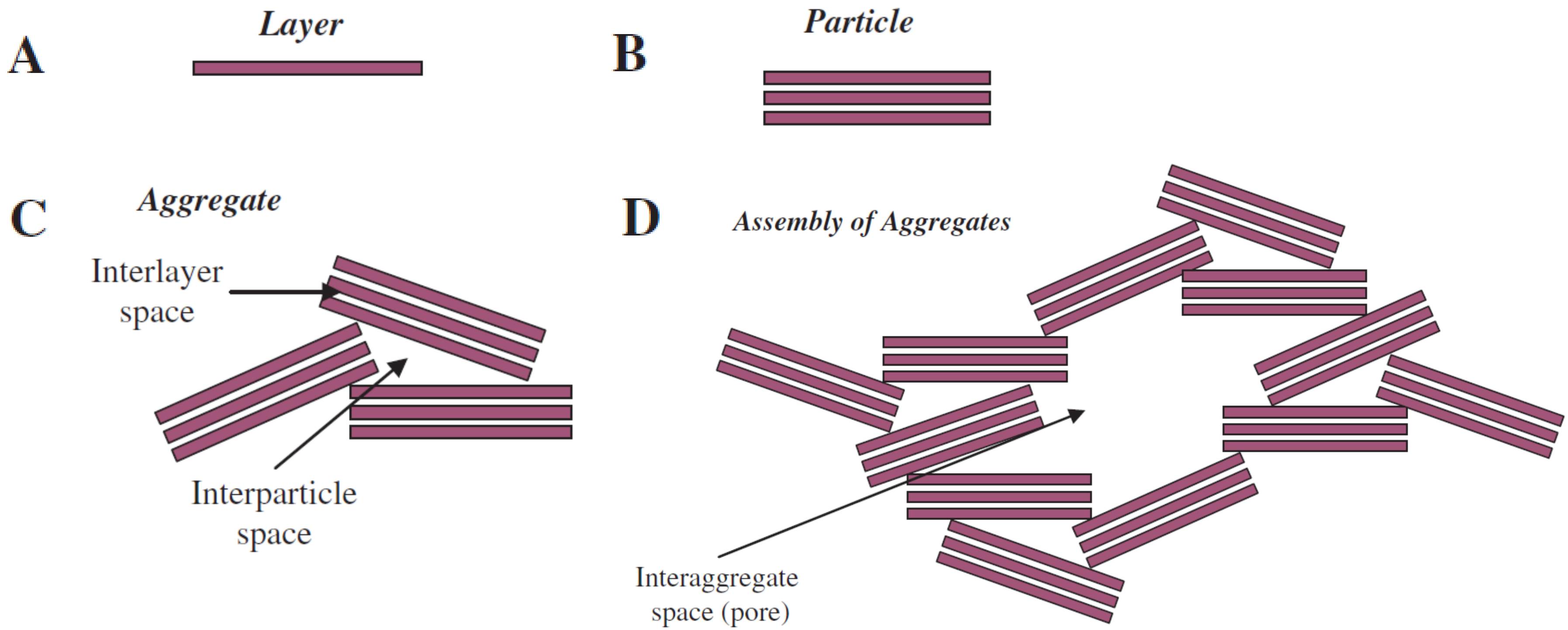


Hexagonal pieces with different diameter
=> MD simulation => clay particle

Details of MD simulations

Kaolinite – ClayFF
Illite – ClayFF (?)
Smectite - ?

Complex Clay Particles



A) clay layer; B) particle, made up of stacked layers;
C) aggregate, showing interlayer space and interparticle space;
D) assembly of aggregates, enclosing interaggregate space (pore).

Assembly of layers is ‘**Particle**’ and assembly of particles is ‘**Aggregate**’.

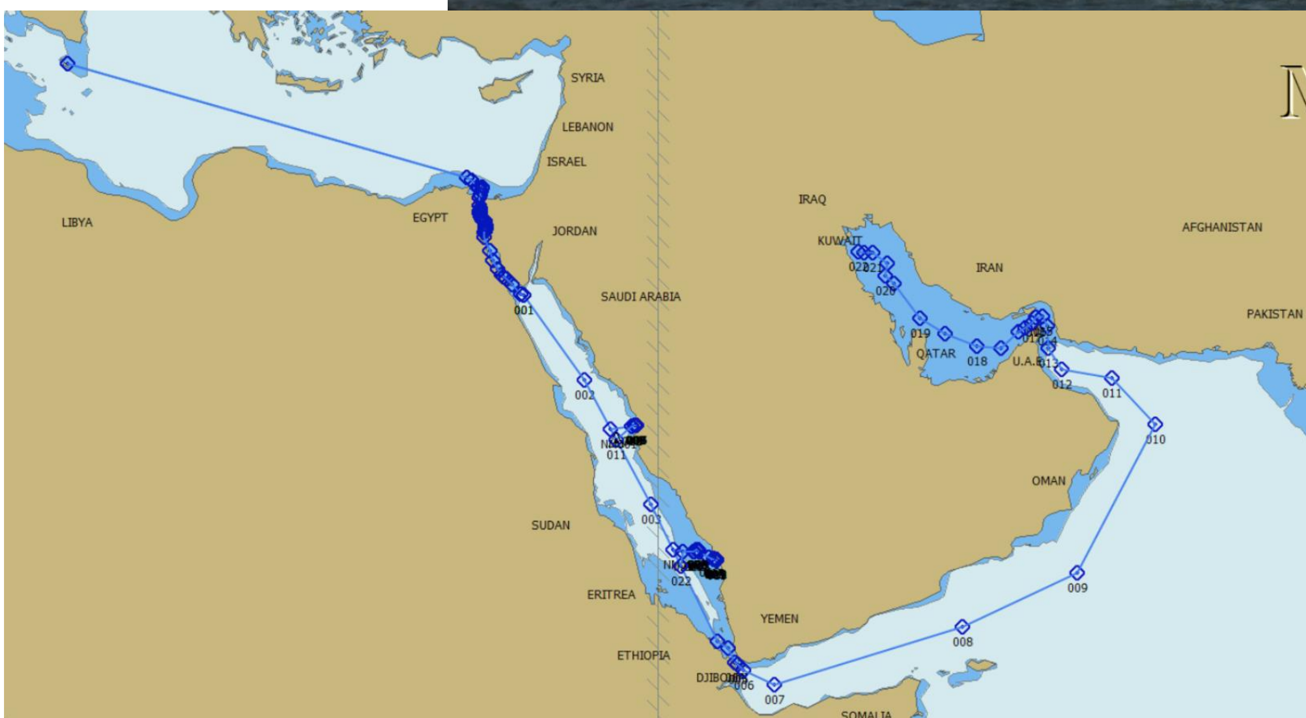
SUMMARY

- Dust forcing in the source regions on regional level is extremely high
- Dust is very effective in causing circulation anomalies
- Dust effect on the Red Sea is huge and is not accounted in any model
- Regional climate studies do not account for aerosol effect
- Dust mass balance is poorly known; observations of dust deposition and emission are required
- Dust radiative, biological, and medical effects are crucially dependent from dust chemical composition; observations of dust mineralogy and chemical composition are required

MAX Planck Institute for Chemistry

Cruise along the Arabian Peninsula in July 2017

30 scientists with instruments on board



In the scope of the Joint Max Planck – KAUST project on interaction of dust with anthropogenic pollutants