

Cold cloud formation due to dust

Implications for aviation

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Slavko Petkovic ¹, Ana Vukovic ^{2,1} and Jugoslav Nikolic¹

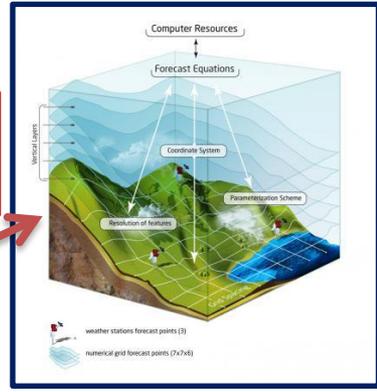
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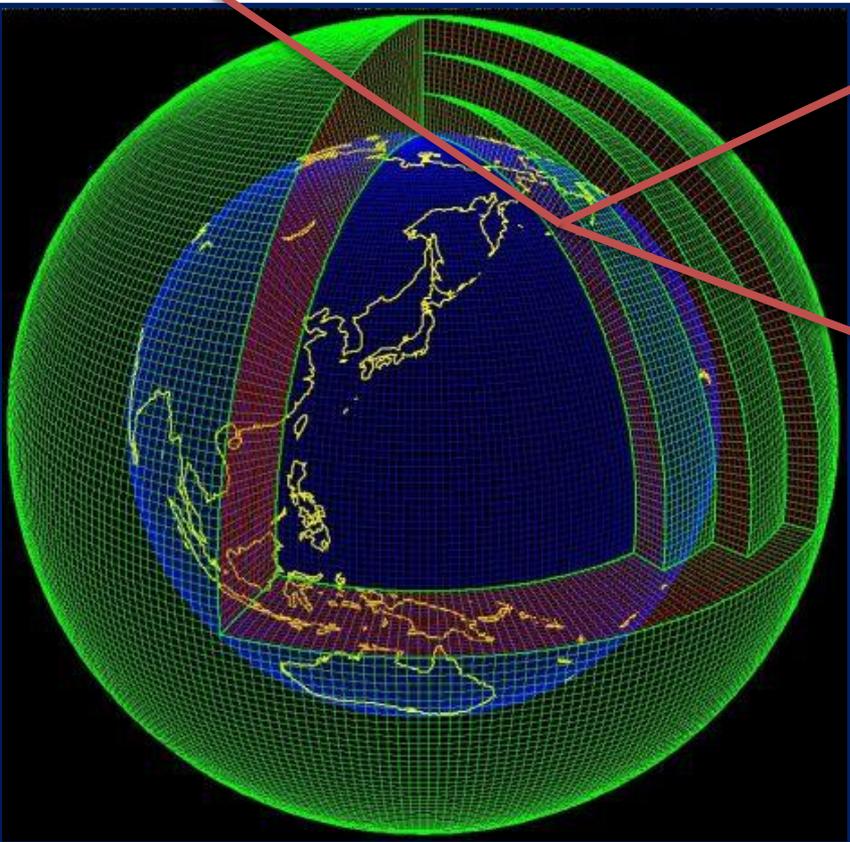
Coupled Numerical Weather Prediction (NMME) with DUST model (DREAM) concept

Numerically solve equations that describes physical processes in the atmosphere/land (fluid dynamics and thermodynamics) + atmospheric dust cycle processes

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



Separate numerical models for simulation of atmosphere/land/ocean/dust system components and processes within integrated in **one system**, where they exchange data during every model simulation timestep.



Actual atmosphere, ocean and land conditions + math. representation of physical laws → calculate future state of the atmosphere and 3D dust concentration → extremely time/processor consuming

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 $\sim 100\text{km}$)

(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 $\sim 100\text{km}$)

SHORT RANGE TRANSPORT:

Nonhydrostatic regional models

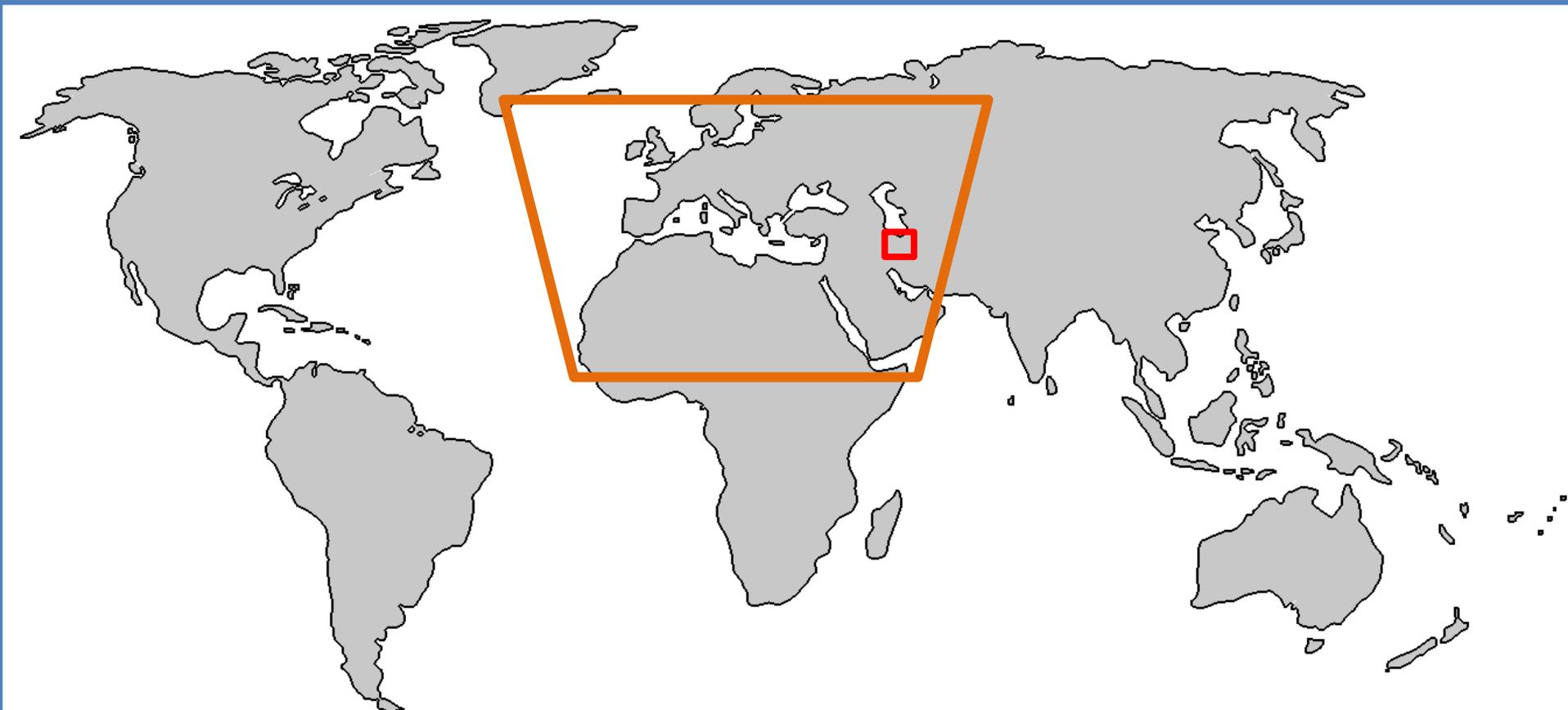
High resolution (several km)

Forecast of the dust storms

GLOBAL MODELS

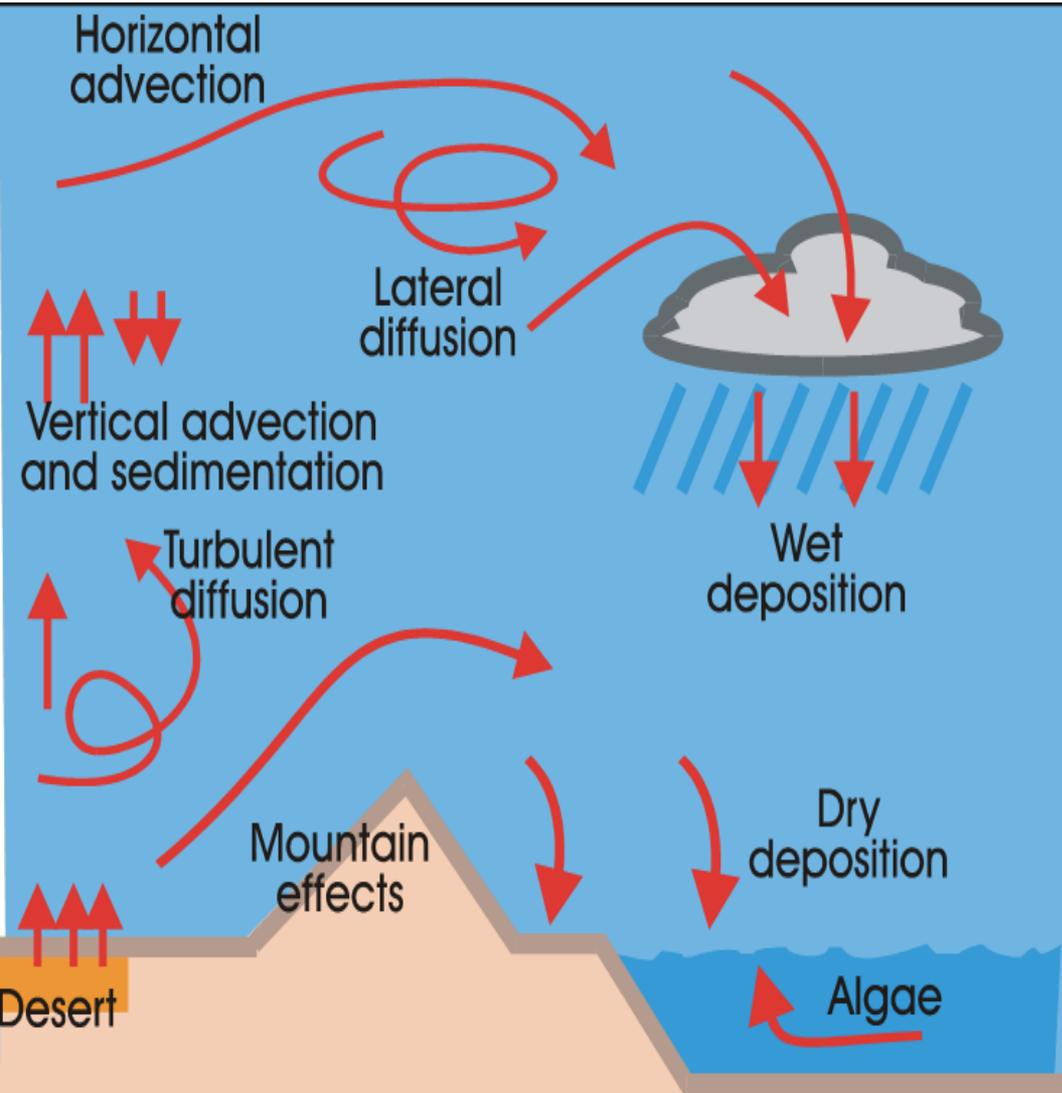
REGIONAL MODELS

NONHYDROSTATIC MODELS



Dust Regional Atmospheric Model (DREAM)

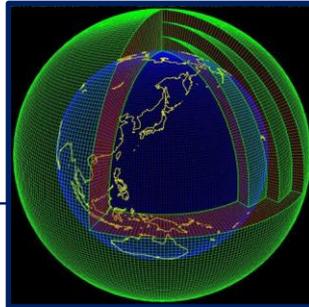
$$\frac{\partial C_k}{\partial t} = -u \frac{\partial C_k}{\partial x} - v \frac{\partial C_k}{\partial y} - (w - v_{gk}) \frac{\partial C_k}{\partial z} - \nabla \cdot (K_H \nabla C_k) - \frac{\partial}{\partial z} \left(K_Z \frac{\partial C_k}{\partial z} \right) + \left(\frac{\partial C_k}{\partial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



- 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**

To understand and model dust aerosol transport, processes ranged from micro to global scales must be considered, which explains complexity of the problem.

Dust Regional Atmospheric Model (DREAM) workflow



Dust model is coupled with atmospheric model (Eta, NMME, NMMB...)

➤ 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 **(including dust HOTSPOTS)**

Particles are assumed to be spherical.
 Particles are divided in categories by size.
 Number of categories different among models.
 Concentration of particles is calculated for each category in each model grid point.

Example for DREAM
 8 particle size categories: 0.15, 0.25, 0.45, 0.78, 1.3, 2.2, 3.8, 7.1μm

k=1 k=2 k=3 k=4 k=5 k=6 k=7 k=8

Kernel of dust modeling – to solve equation:

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



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)

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

Dust storm forecast: Nonhydrostatic high resolution simulation of intense dust event

(Vukovic et al. 2014)

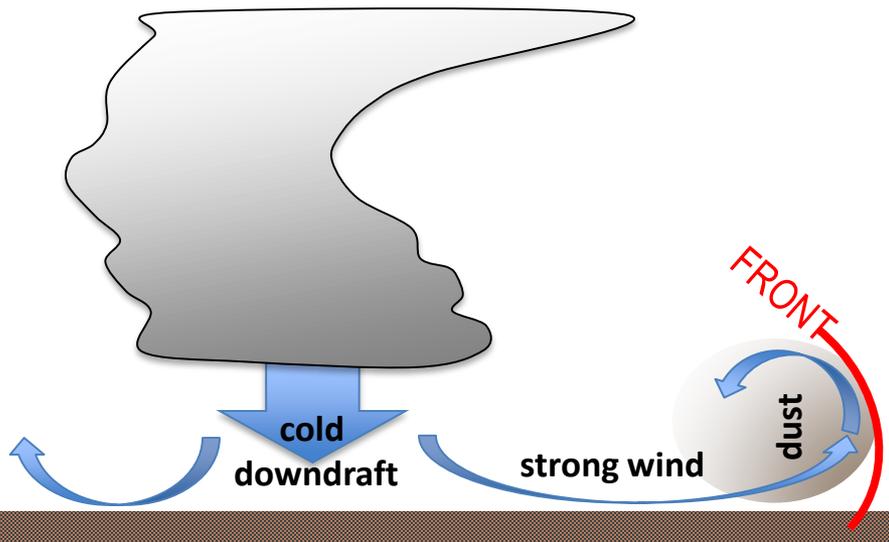
Haboob: cold downdraft from supercell clouds forms strong surface winds, intensive dust uplift, forms wall of dust

Atmos. Chem. Phys., 14, 3211–3230, 2014
www.atmos-chem-phys.net/14/3211/2014/
doi:10.5194/acp-14-3211-2014
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Atmospheric Chemistry and Physics Open Access

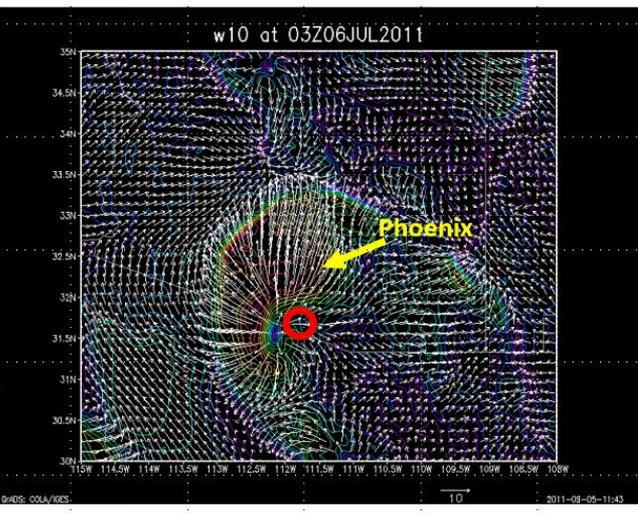
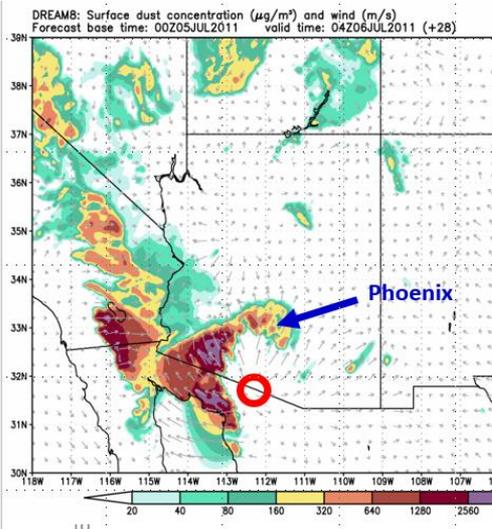
Numerical simulation of “an American haboob”

A. Vukovic^{1,2}, M. Vujanovic^{1,2}, G. Pejanovic², J. Andric³, M. R. Kumjian⁴, V. Djurdjevic^{2,5}, M. Dacic², A. K. Prasad⁶, H. M. El-Askary^{6,7}, B. C. Paris⁸, S. Petkovic², S. Nickovic^{9,10}, and W. A. Sprigg^{11,12}



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

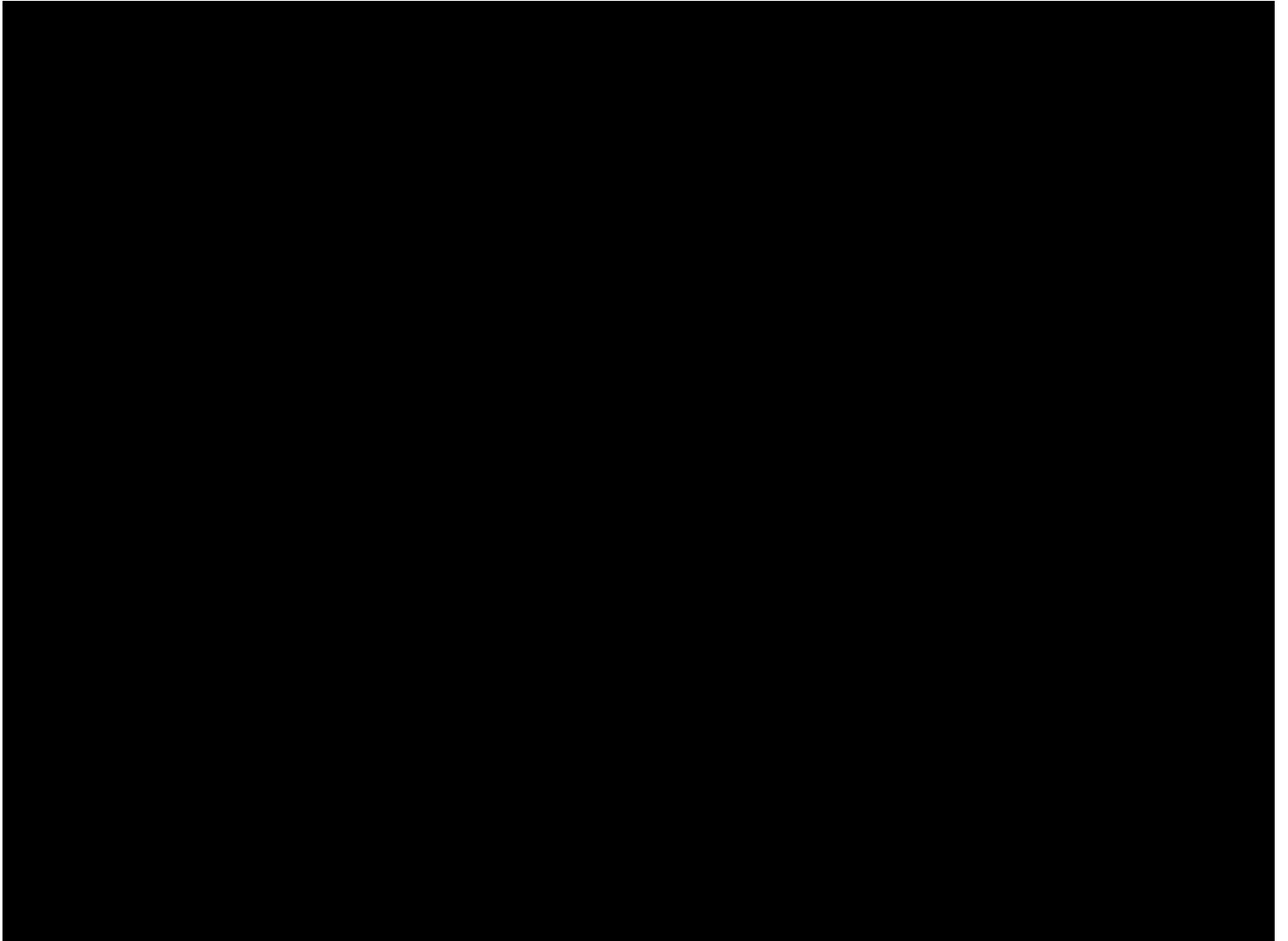
- Tucson – Phoenix; Front wide ~150km; travelled distance ~250km; Dust wall height ~1500-2000m
- 02UTC 6. JULY reached SE Phoenix; 02-04 UTC cross over Phoenix



KUWAIT April 2018 HABOOB - DUST STORM



KUWAIT April 2018 HABOOB - DUST STORM



STUDY CASE: TEHRAN DUST STORM 2ND JUNE 2014



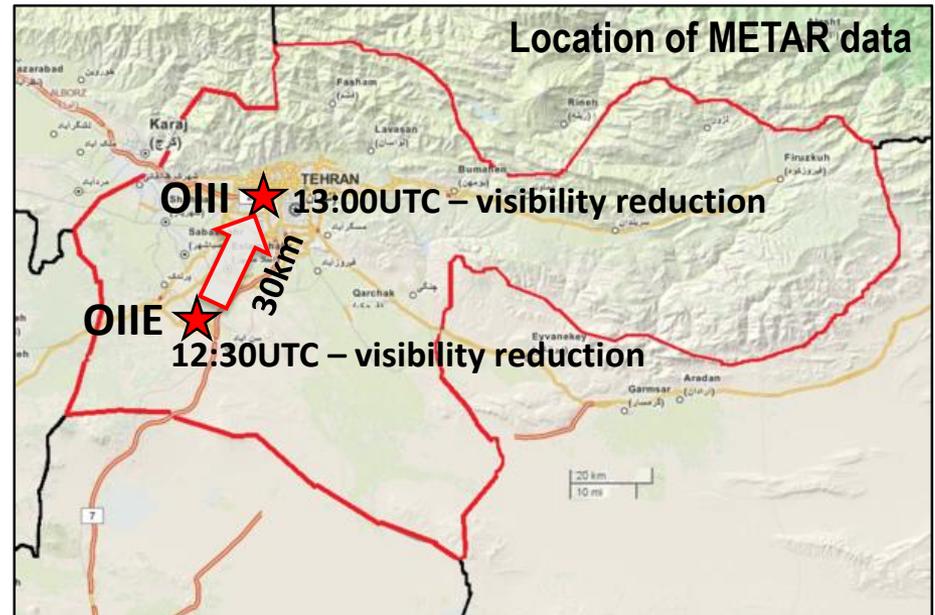
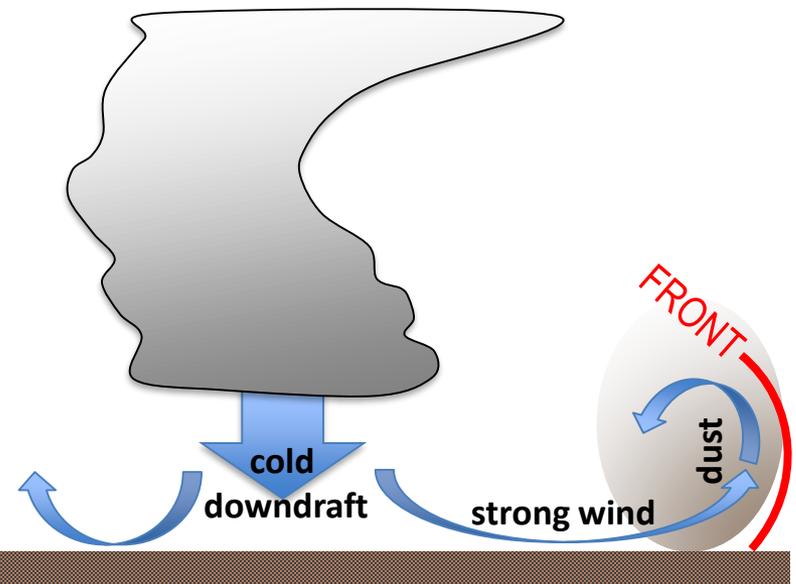
Simulation of small scale (local; several 100km), intense (several 1000 $\mu\text{g}/\text{m}^3$ PM10) & short lived (few hours) dust storms

Information from reports

- reached city at 04:50 p.m. local time;
- passing of the sand storm over the fixed site lasted about 15min;
- storm duration less than 2h;
- reduction of visibility to ~10m; wind velocity reached 110 km/h;
- temperature dropped from 33C to 18C in several min;
- at least 5 deaths, 82 injured; multiple vehicle collision;
- 50 000 residential units lost power.

Theory

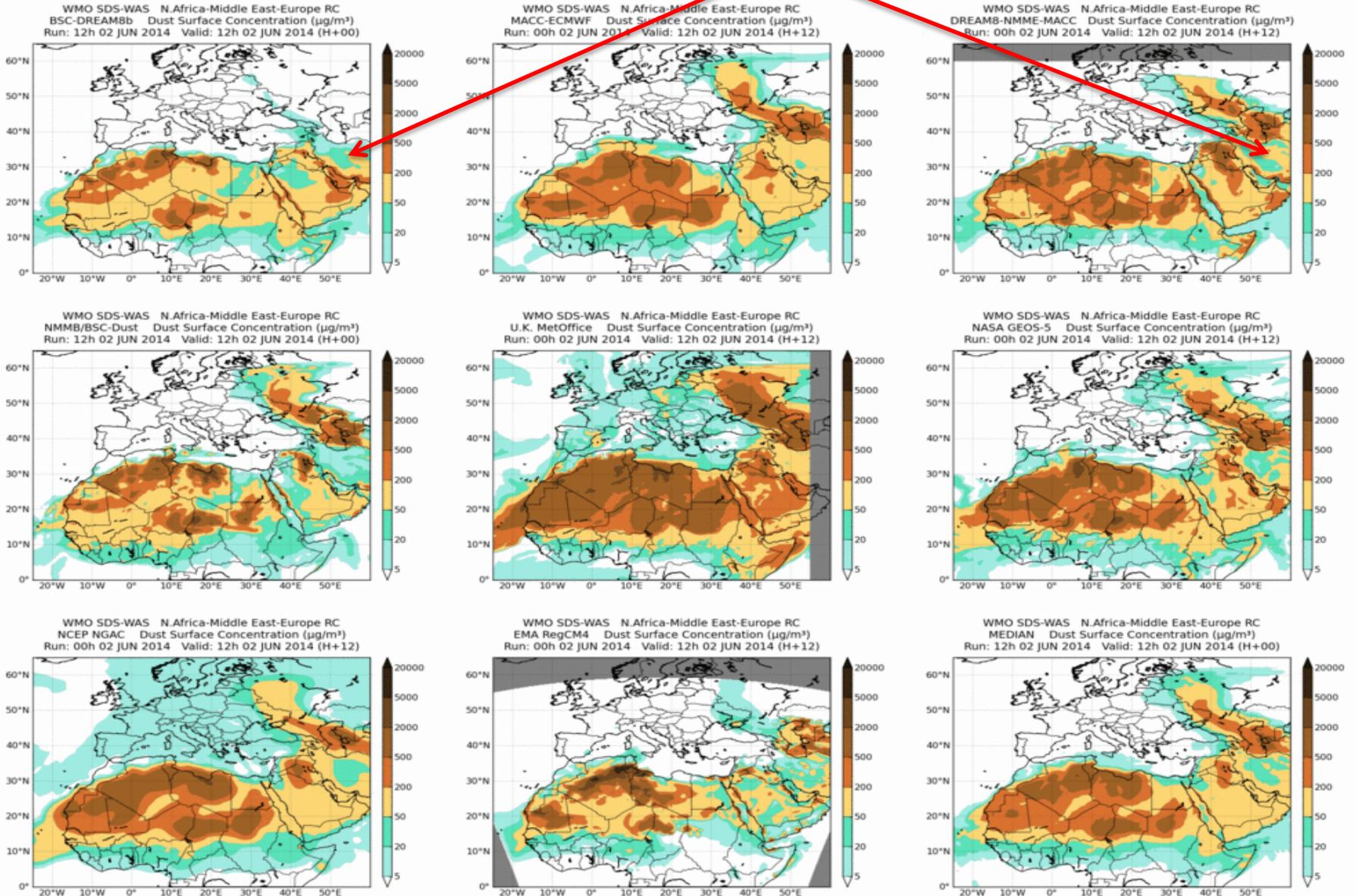
- Intensive cold downbursts from convective cells produced high velocity surface wind, creating cold front which was lifting, mixing and pushing dust towards the city;
- Expected: high wind speed, drop in temperature, rise in humidity, rise in pressure, reduction of visibility.



Operational models (15-20 km resolution) **CAN NOT** resolve small-scale intensive dust storms (HABOOB)
Forecasted surface dust concentration 100-200 micrograms per cubic meter (**several thousands in dust storms**)

Surface dust concentration

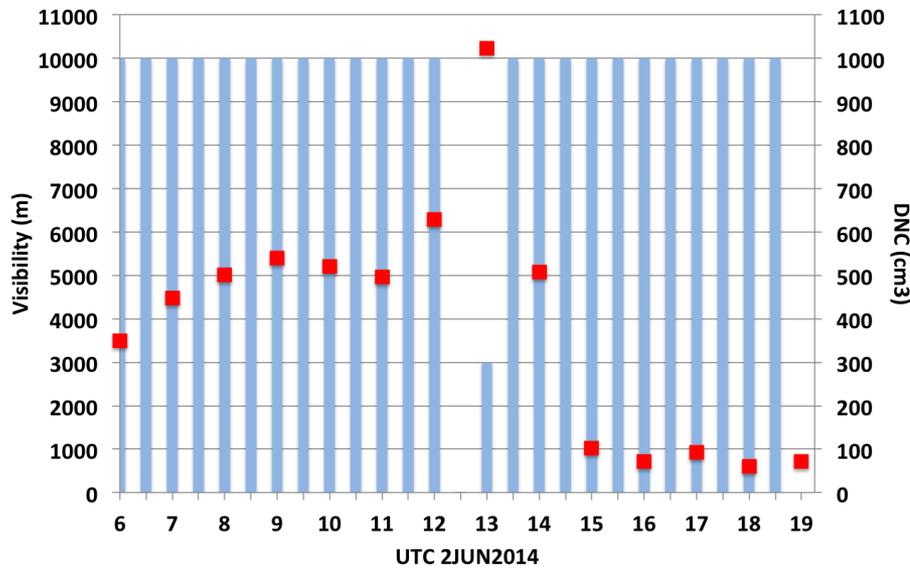
TEHRAN



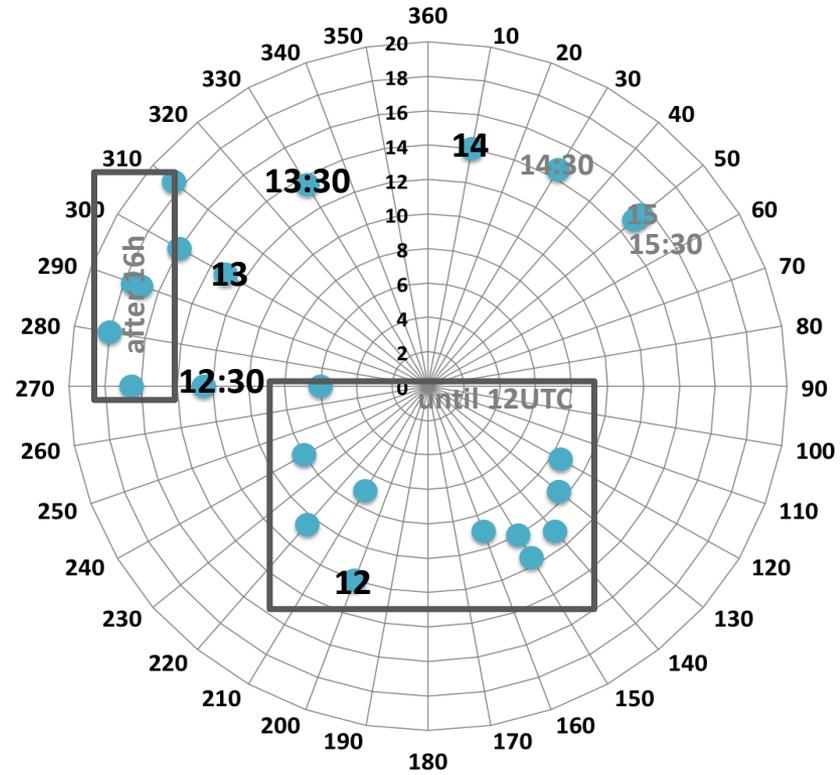
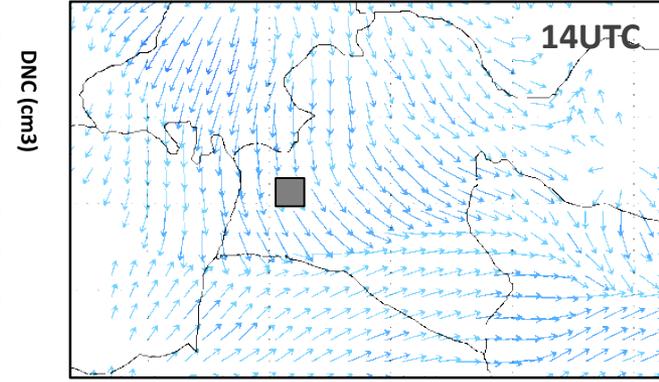
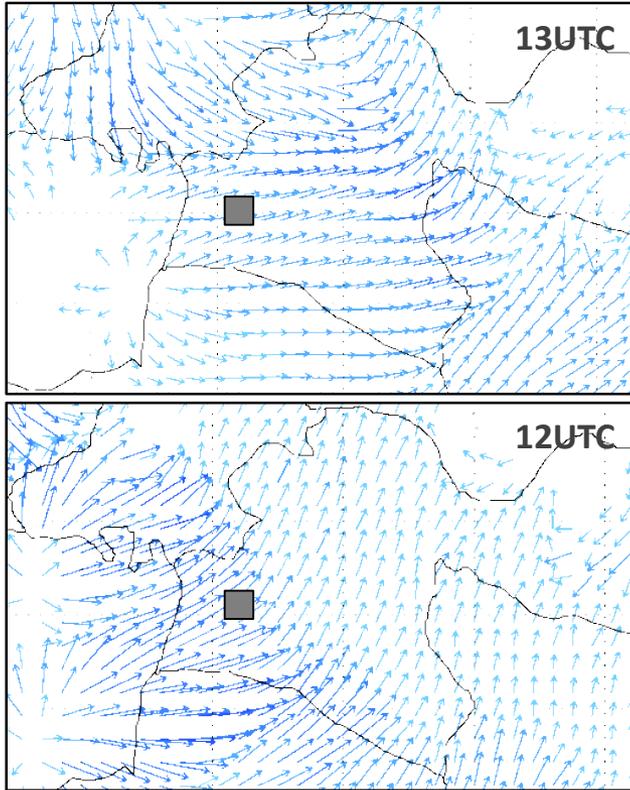
Imam Khomeini airport OIIE

Visibility reduced to 20m at 12:30UTC.
Model output data available on 1h.

Observed visibility & model DNC



Observed wind direction & model wind

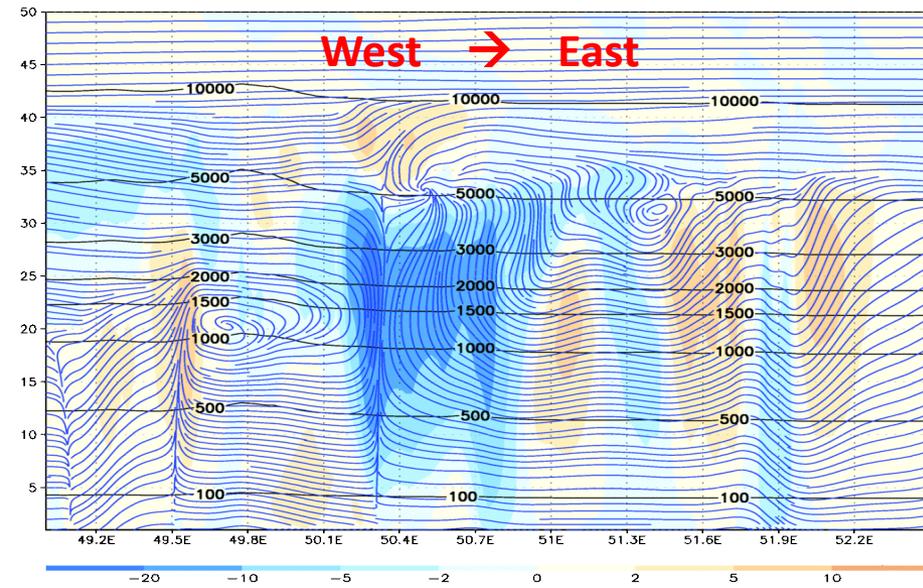


3 6 9 12 15 20

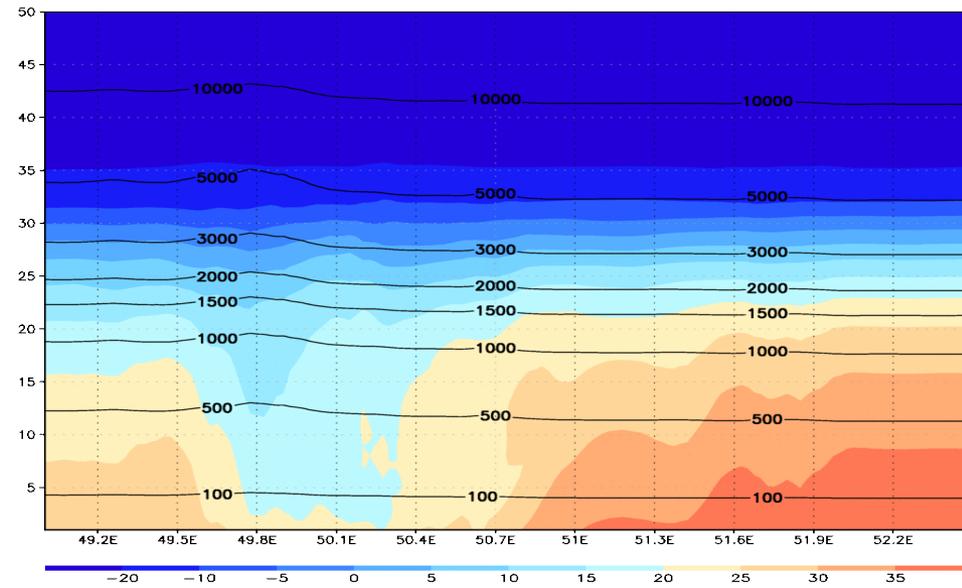
Vertical cross section along 35N

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

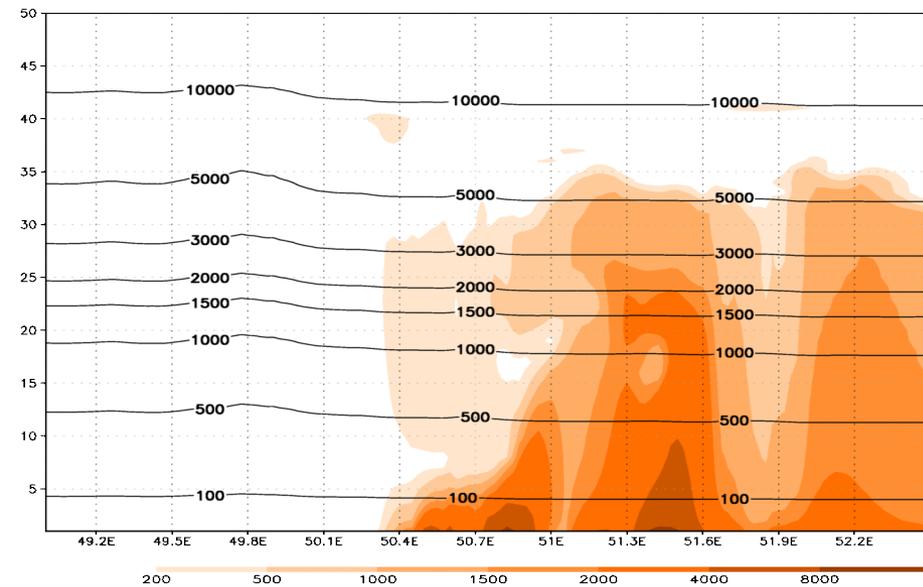
Streamlines (u,w) and vertical wind velocity



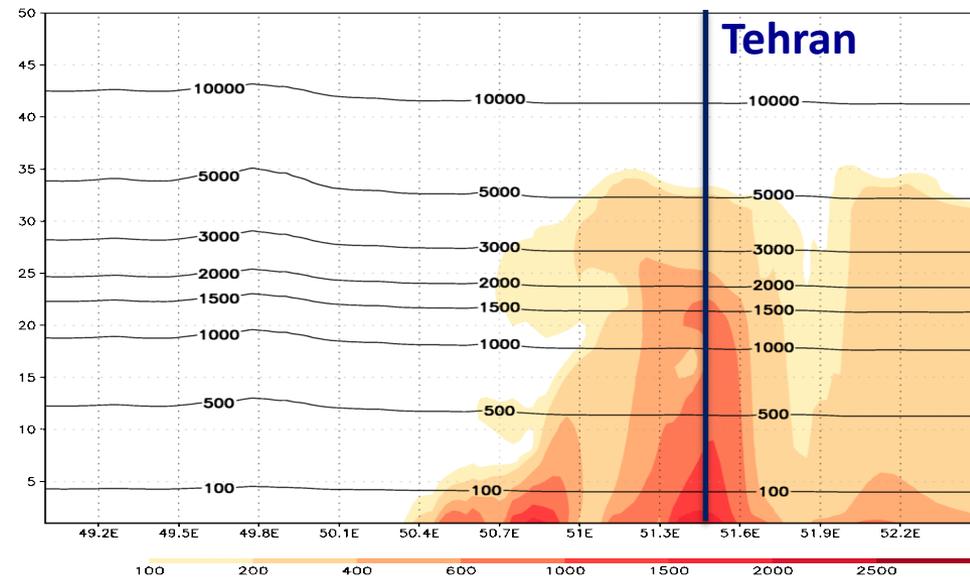
Temperature



Dust PM10 concentration

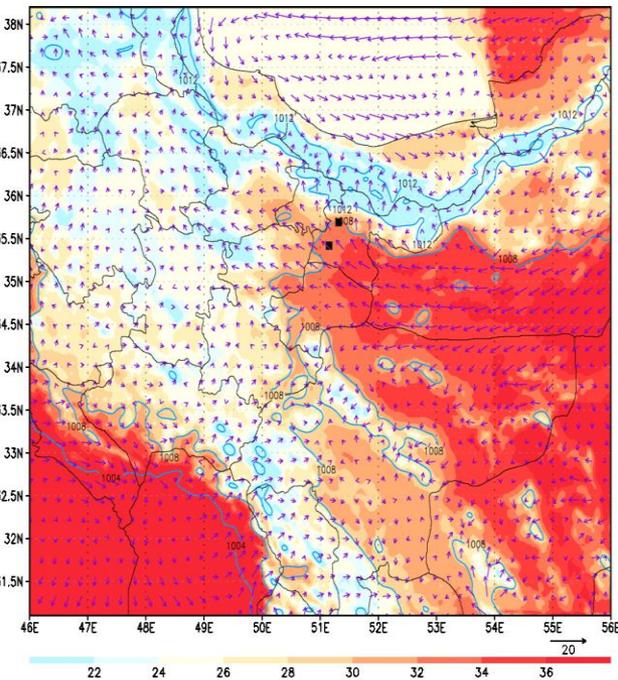


DNC – dust number concentration

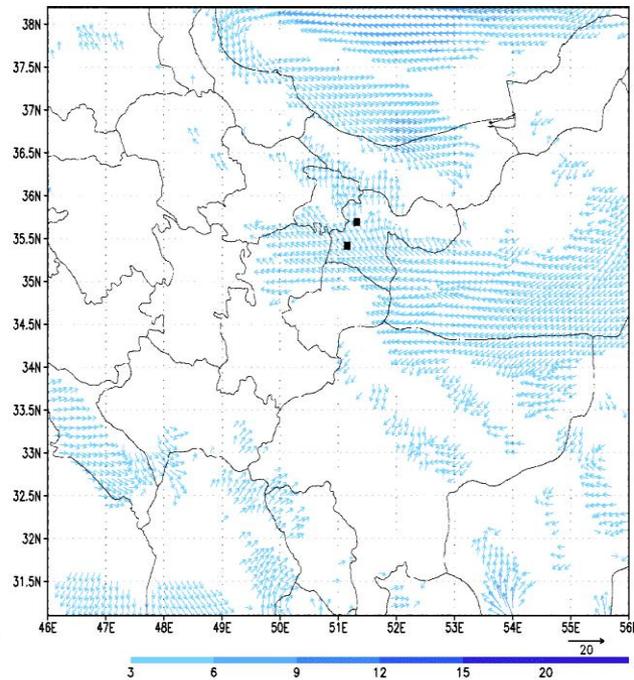


NMME-DREAM (SEEVCCC) simulation results for the period June 2nd 2014 06-20 UTC

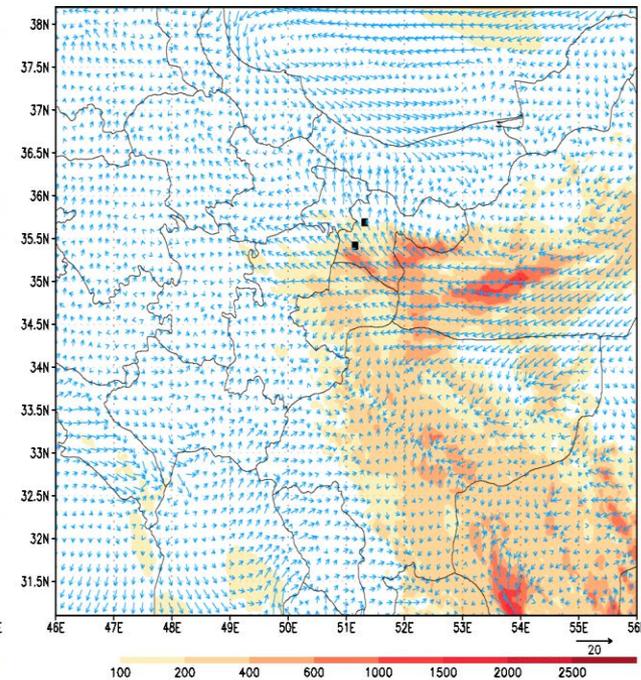
DREAM8 forecast: T2m [°C] PSL [mb] and 10m wind [m/s]
Forecast base time: 01JUN2014 12UTC Valid: 02JUN2014 06UTC (+18h forecast)



DREAM8 forecast: 10m wind [m/s]
Forecast base time: 01JUN2014 12UTC Valid: 02JUN2014 06UTC (+18h forecast)



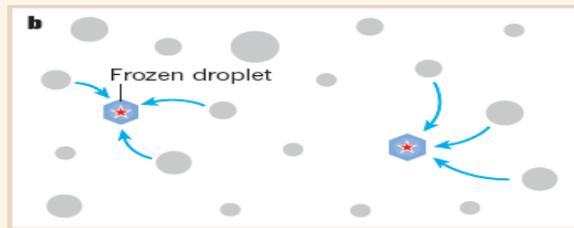
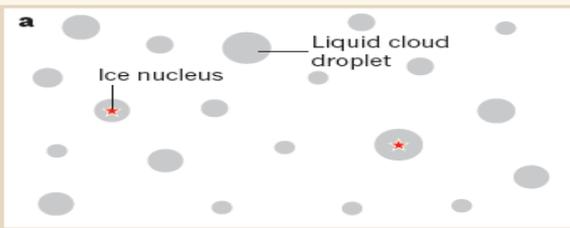
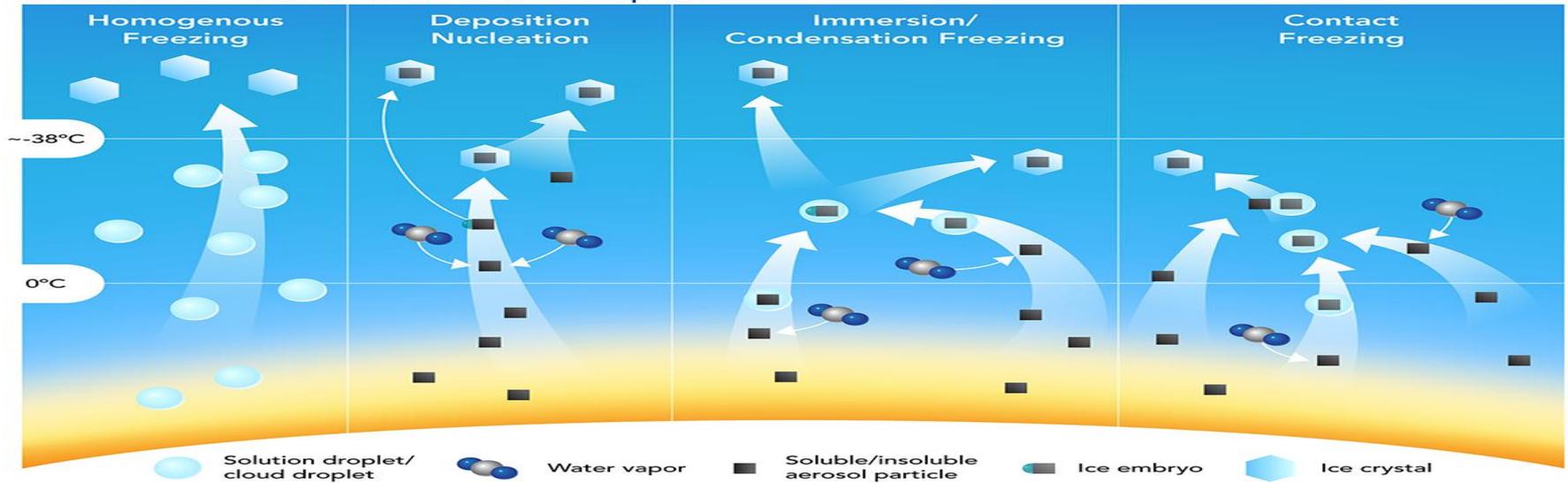
DREAM8 forecast: DNC – Surface dust number conc [1/cm³] and 10m wind [m/s]
Forecast base time: 01JUN2014 12UTC Valid: 02JUN2014 06UTC (+18h forecast)



Heterogeneous cold clouds formation

- Dominant process in the atmosphere
- Cold and mixed phase clouds are dominant in the atmosphere (75% of all clouds)
- 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

Ice Nucleation Mechanisms in the Atmosphere



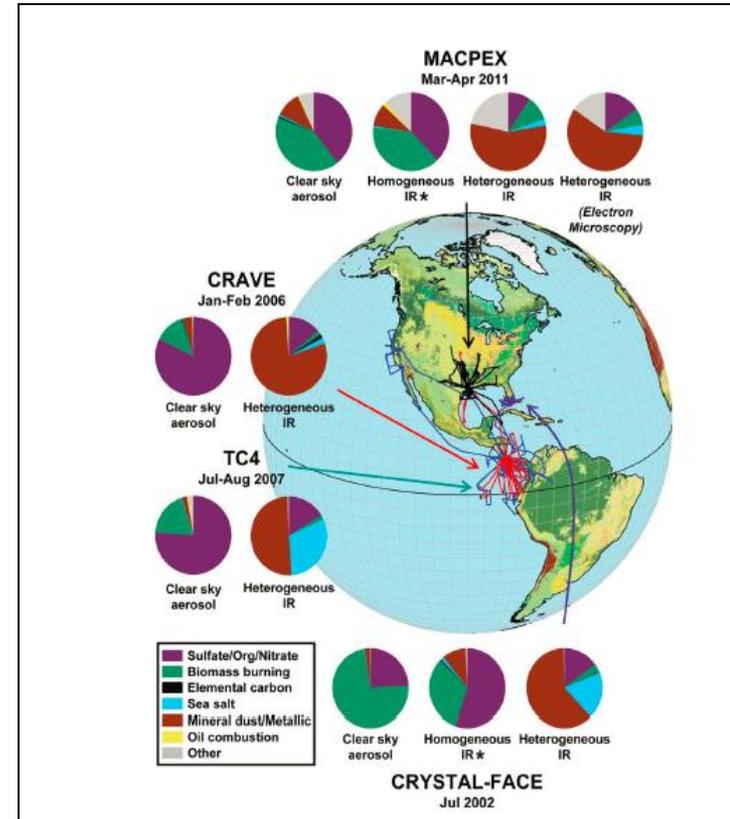
Ice formation and precipitation

Koop and Mahowald, Nature, 2013

Recent findings from observations (Ice Nuclei in ice crystals)

Cziczo et al., Science (2013)

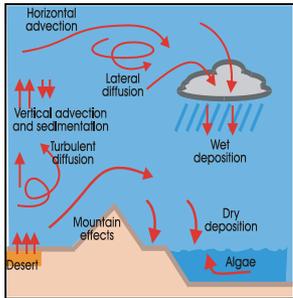
- 2/3 of residues in ice crystals from high clouds are dust+dust metallic oxides particles
- Small dust concentration needed to trigger the process
- Heterogeneous freezing is dominant process
- Minimal surface coating (no dust aging observed)
- Dust as ice nuclei found far from any of major desert sources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



Dust C

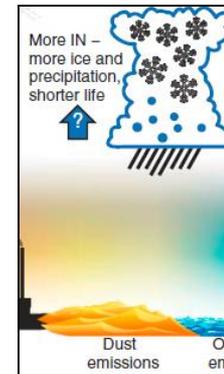
T, RH

NMM model

DREAM model

Parameterization of IN in DREAM

-55 °C	DEPOSITION Steinke et al. 2015 $n_{IN} = pS_{dust} \exp(-q(T-273.16) + (rRH_{ice} - 100))$
-35 °C	IMMERSION DeMott al. 2015 $n_{IN} = C(n_{dust})^{(\alpha(273.16-T)+\beta)} \exp(\gamma(273.16-T)+\delta)$
-20 °C	IMMERSION DeMott al. 2015 (out of the scheme validity) $n_{IN} = C(n_{dust})^{(\alpha(273.16-T)+\beta)} \exp(\gamma(273.16-T)+\delta)$
-5 °C	



n_{IN}

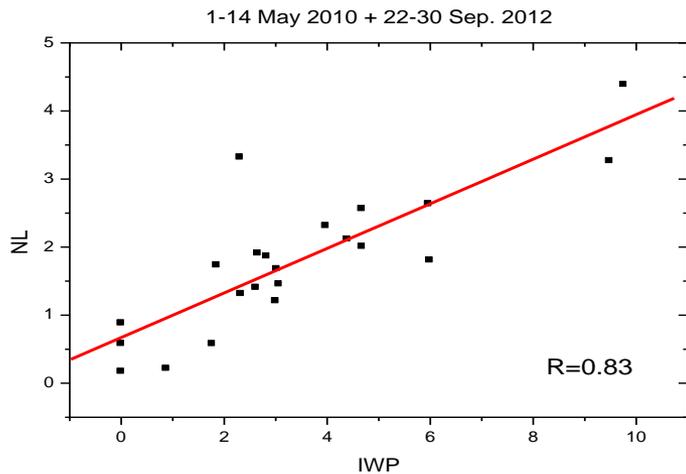
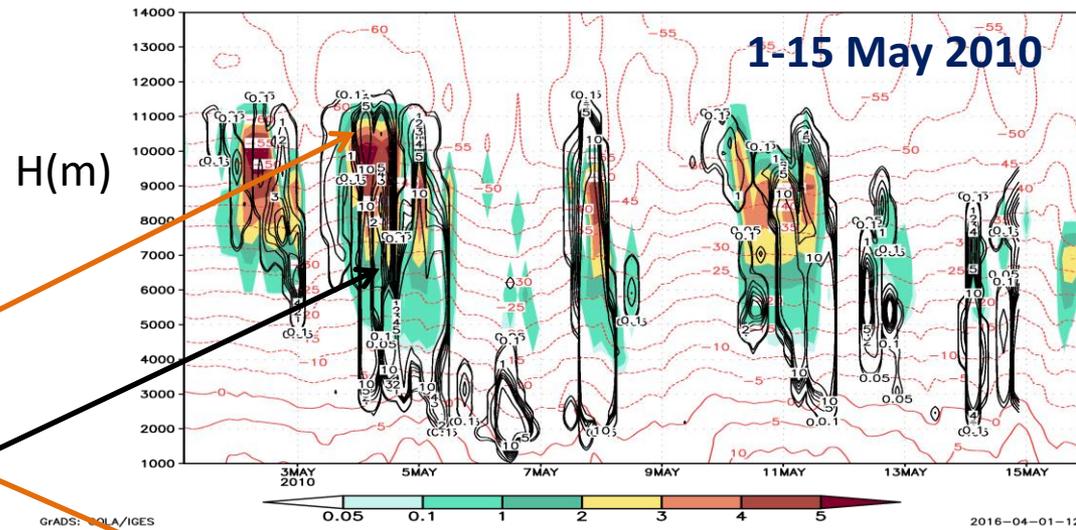
NMMB Thompson dust-friendly cold cloud microphysics

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

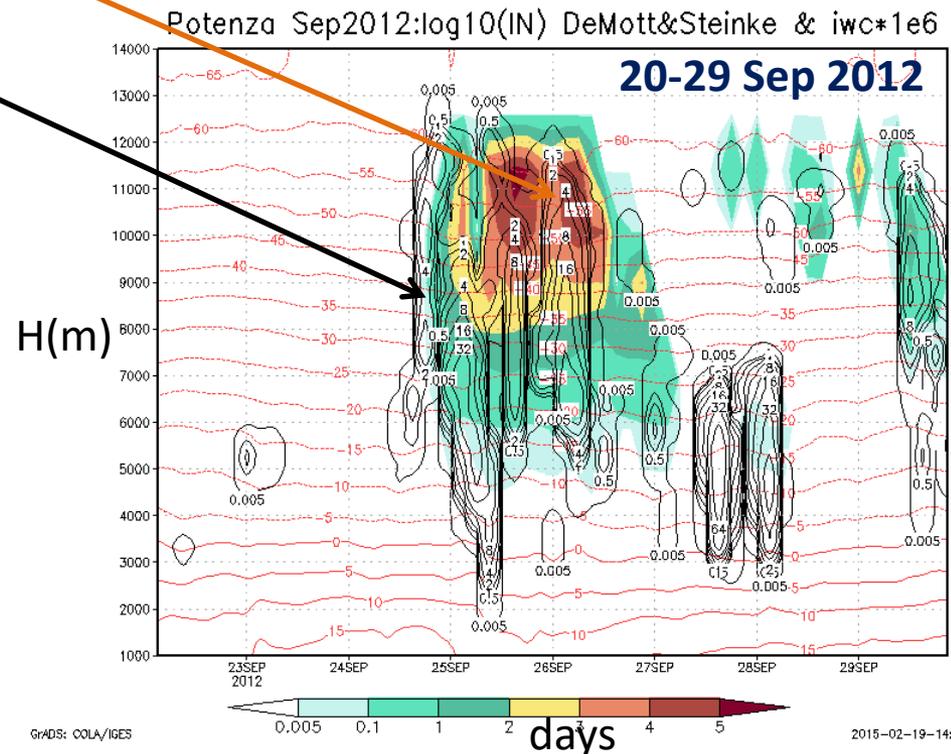
Model well reproduced timing, duration and position of #IN

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)



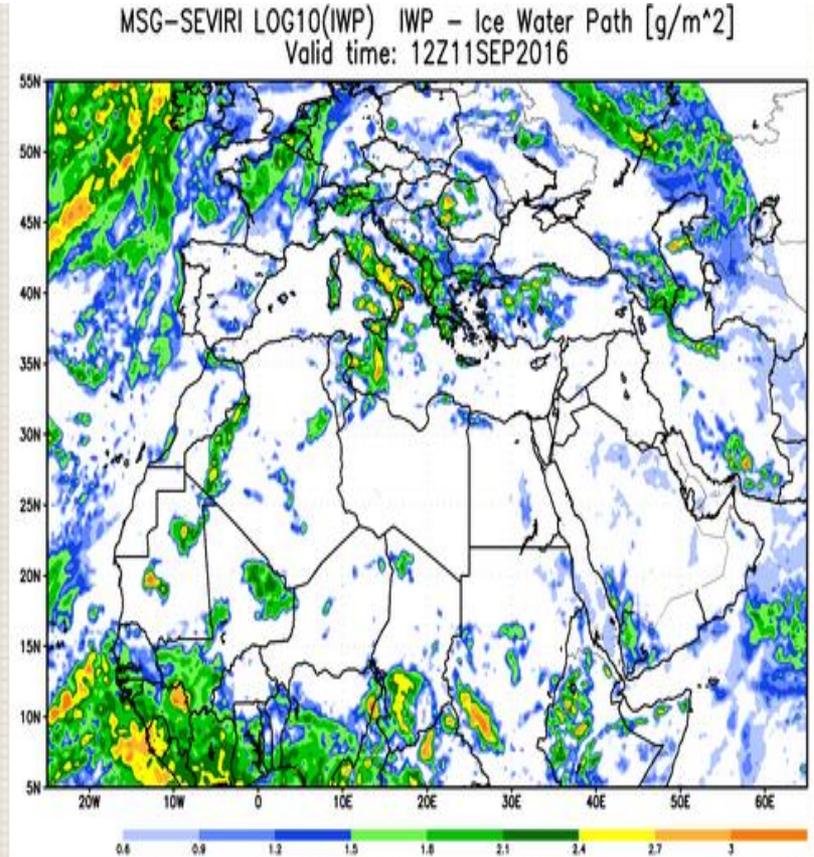
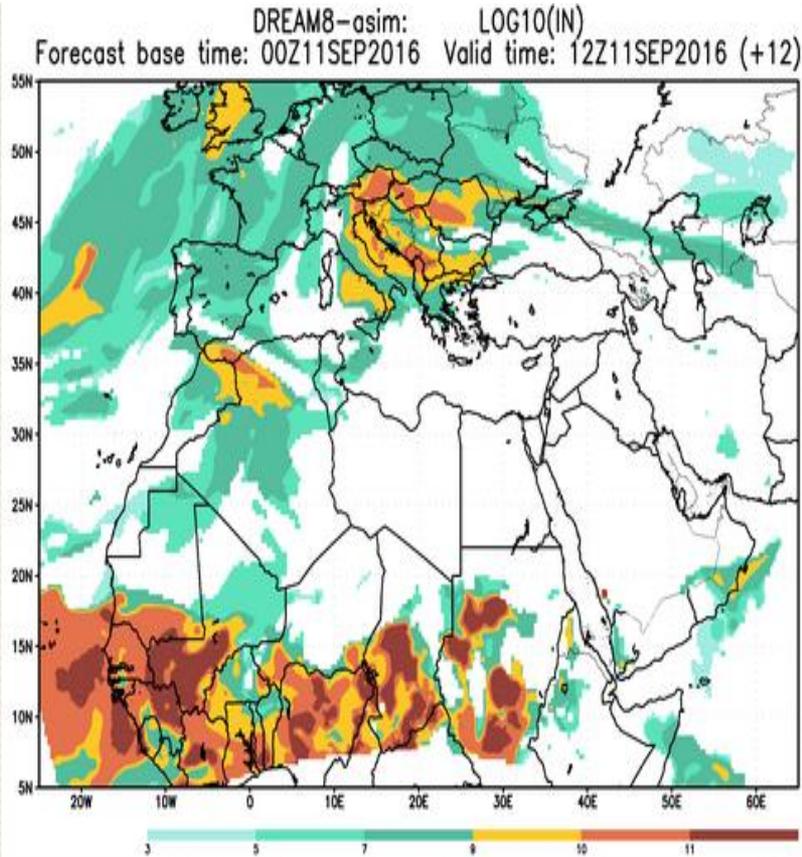
Daily averaged vertical loads
 Potenza, May 2010 & Sep 2012



Daily IN maps

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

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

AIR FRANCE AF477

A HYPOTHESIS ON DUST ROLE IN THE ACCIDENT

1st June 2009

Airbus A330-203 operated by Air France
flight AF447

From Rio de Janeiro (Brasil) – Paris (France)

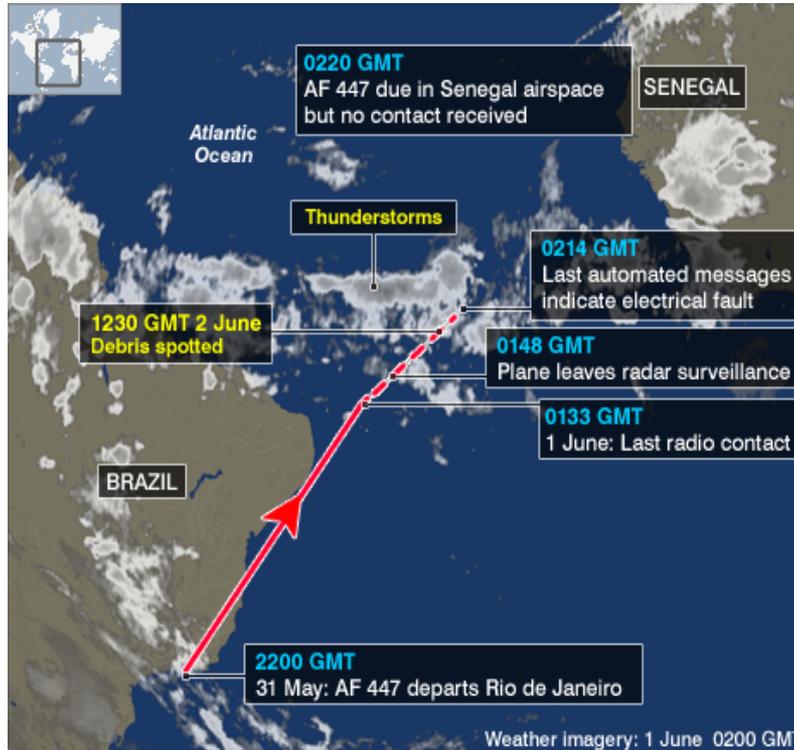
AIR FRANCE AF477 ACCIDENT REPORT

Air France Flight 447



F-GZCP, the aircraft lost in the accident, shown here at Charles de Gaulle Airport two years before the crash

Accident	
Date	1 June 2009
Summary	Entered high-altitude stall; impacted ocean
Site	Atlantic Ocean near waypoint TASIL11:9 3°03'57"N 30°33'42"W
Aircraft	
Aircraft type	Airbus A330-203
Operator	Air France
IATA flight No.	AF447
ICAO flight No.	AFR447
Call sign	AIRFRANS 447
Registration	F-GZCP
Flight origin	Rio de Janeiro–Galeão Airport
Destination	Paris–Charles de Gaulle Airport
Occupants	228
Passengers	216
Crew	12
Fatalities	228
Survivors	0



Pitot tube



Interim Report n°2

on the accident on 1st June 2009 to the Airbus A330-203 registered F-GZCP operated by Air France flight AF 447 Rio de Janeiro – Paris

As of 3 November 2009, Airbus had identified thirty-two events that had occurred between 12 November 2003 and 1st June 2009⁽¹⁸⁾. According to Airbus these events are attributable to the possible destruction of at least two Pitot probes by ice. Eleven of these events occurred in 2008 and ten during the first five months of 2009.

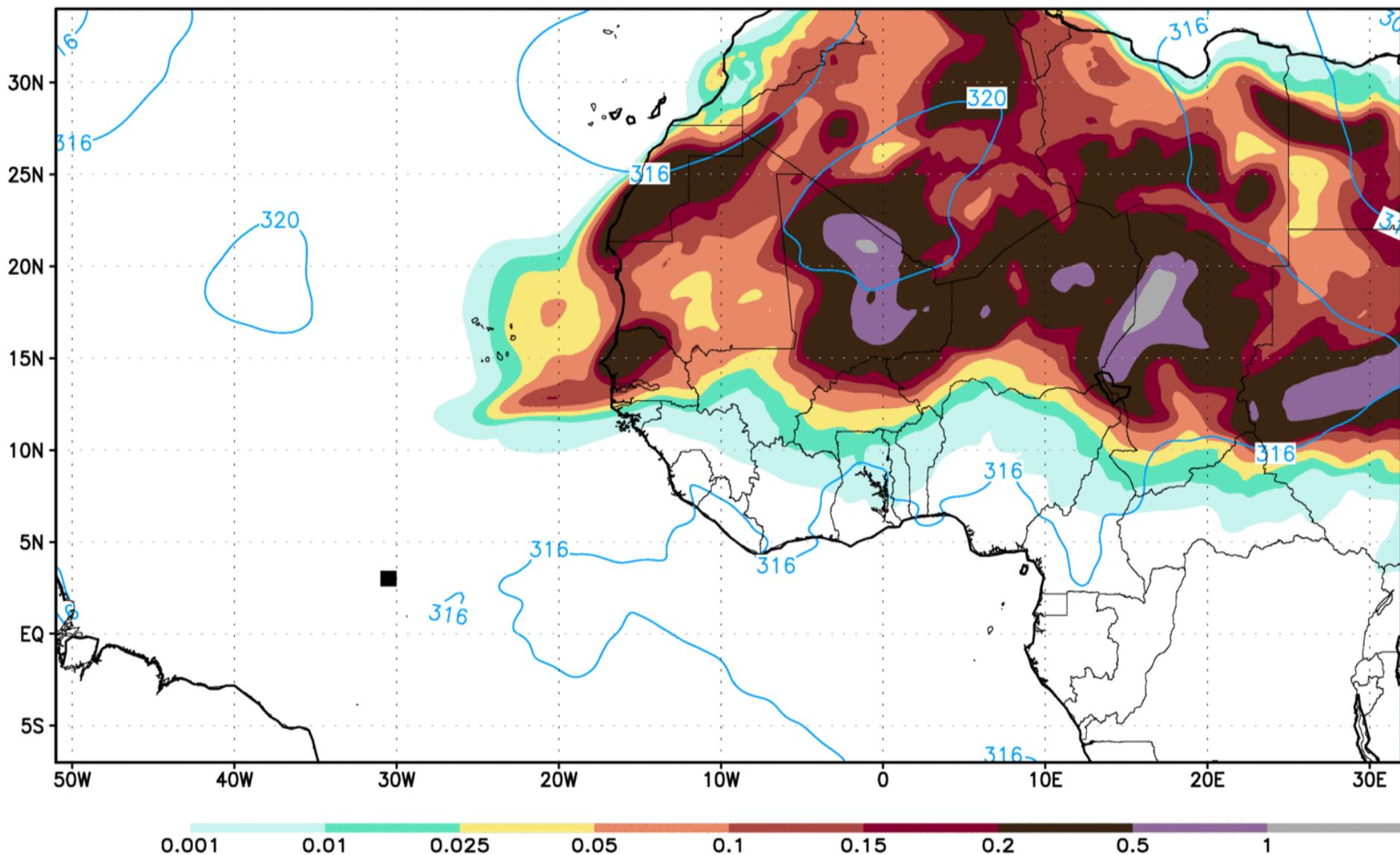
Goodrich 0851GR probes either with Goodrich type 0851HL or by Thales type C16195AA probes before 31 December 2003. According to the analysis carried out at the time, the most likely cause of the problem was the presence of ice crystals and/or water in the Goodrich 0851GR type Pitot probes within the upper limits of the original specifications.

BEA

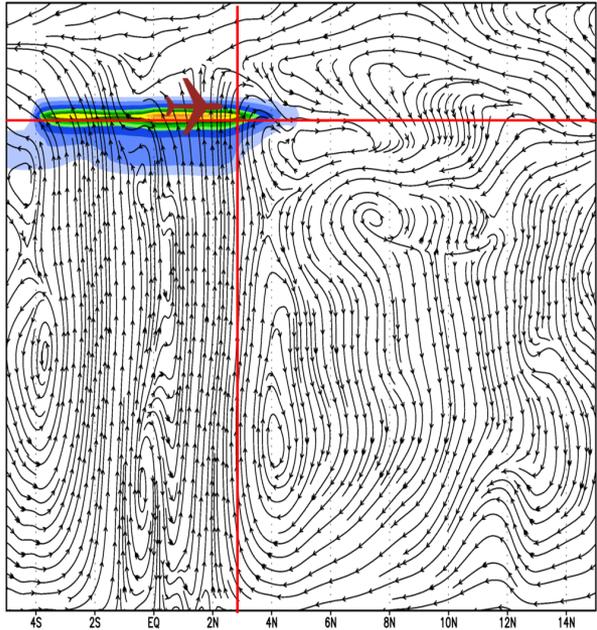
Bureau d'Enquêtes et d'Analyses pour la sécurité de l'aviation civile

INTENSIVE LONG-RANGE TRANSPORT OF AFRICAN DUST TOWARDS EQUATORIAL MID-ATLANTIC REGION

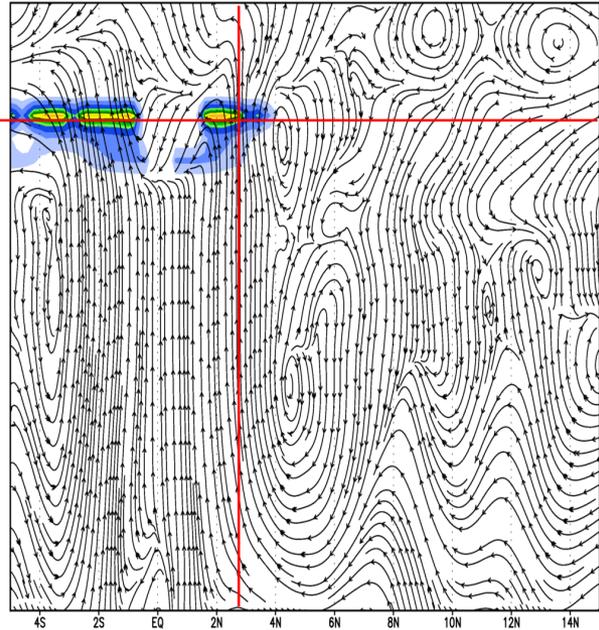
DREAM8-assim: Dust load (g/m^2) and 700 hPa geopotential (gpm)
Forecast base time: start Valid time: 26MAY2009 00UTC



DREAMB-assim: LOG10(IN) [IN - number of ice nuclei] and wind [streamlines]
 Time: 1 June 2009 00 UTC



DREAMB-assim: LOG10(IN) [IN - number of ice nuclei] and wind [streamlines]
 Time: 1 June 2009 03 UTC



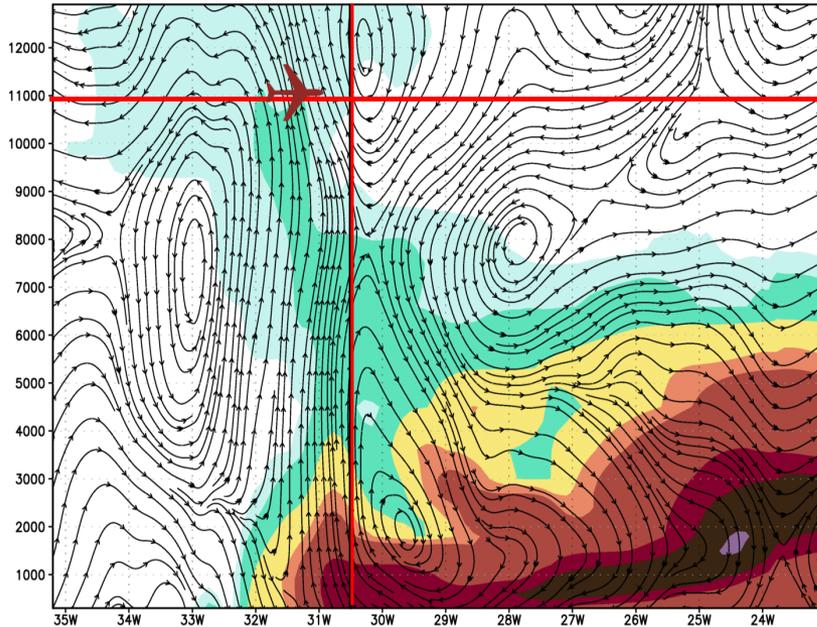
Cross at LON 30W; LAT 5S-15N, FL330

Zoom on 1st June at 2h15 UTC



Satellite picture of the storm cloud top temperature

NMME-DREAM: Cross section Natal (Brasil) - Cape Verde DUST
 Valid time: 01JUN2009 01UTC



Ice nucleation induced by the dust particles

Intense updraft of dust particles by strong convection → interaction with supercooled water → intense ice nucleation in the accident zone

AIR ALGERIE AH5017

A HYPOTHESIS ON DUST ROLE IN THE ACCIDENT

24th July 2014

McDonnell Douglas MD-83 operated by Air Algerie
flight AH5017

From Ouagadougou (Burkina Faso) to Algiers (Algeria)



EC-LTV, the aircraft involved, photographed in January 2013

Accident

Date 24 July 2014
 Summary Crashed after high altitude stall in icing conditions
 Site Near Gossi, Mali
 15°08'08"N 01°04'49"W

Aircraft

Aircraft type McDonnell Douglas MD-83
 Operator Swiftair for Air Algérie
 IATA flight No. AH5017
 ICAO flight No. DAH5017
 Call sign AIR ALGERIE 5017
 Registration EC-LTV
 Flight origin Ouagadougou Airport, Burkina Faso
 Destination Houari Boumediene Airport, Algiers, Algeria
 Occupants 116
 Passengers 110
 Crew 6
 Fatalities 116
 Survivors 0

AIR ALGERIE AH5017 ACCIDENT REPORT



Pitot tube



MINISTÈRE DE L'ÉQUIPEMENT,
 DES TRANSPORTS ET DU DÉSENVLOPPEMENT
 COMMISSION D'ENQUÊTE SUR LES
 ACCIDENTS ET INCIDENTS
 D'AVIATION CIVILE

REPUBLIQUE DU MALI
 UN PEUPLE - UN BUT - UNE FOI

FINAL REPORT

Accident
 on 24 July 2014
 near Gossi (Mali)
 to the McDonnell Douglas DC-9-83 (MD-83)
 registered EC-LTV
 operated by Swiftair S.A.

Approved on 22 April 2016

N'Faly CISSE

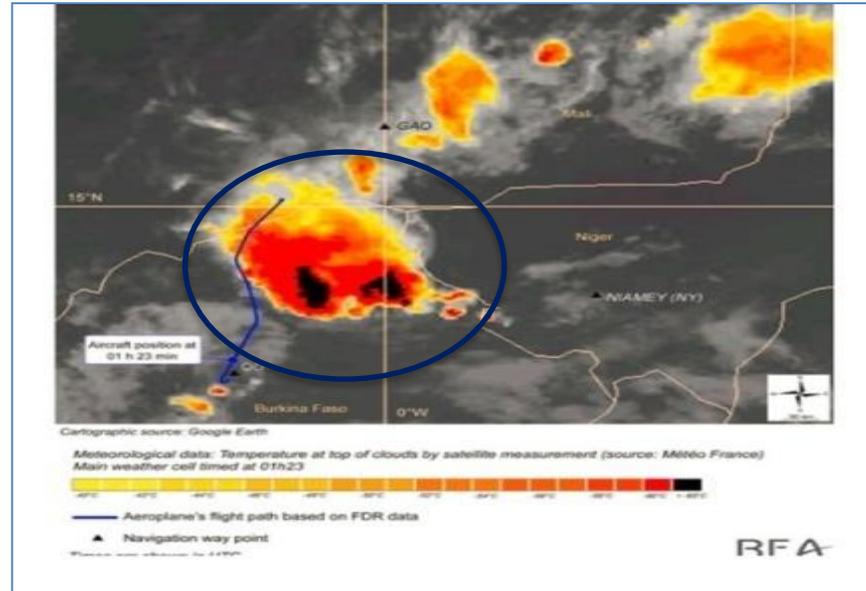


The accident resulted from a combination of the following events:

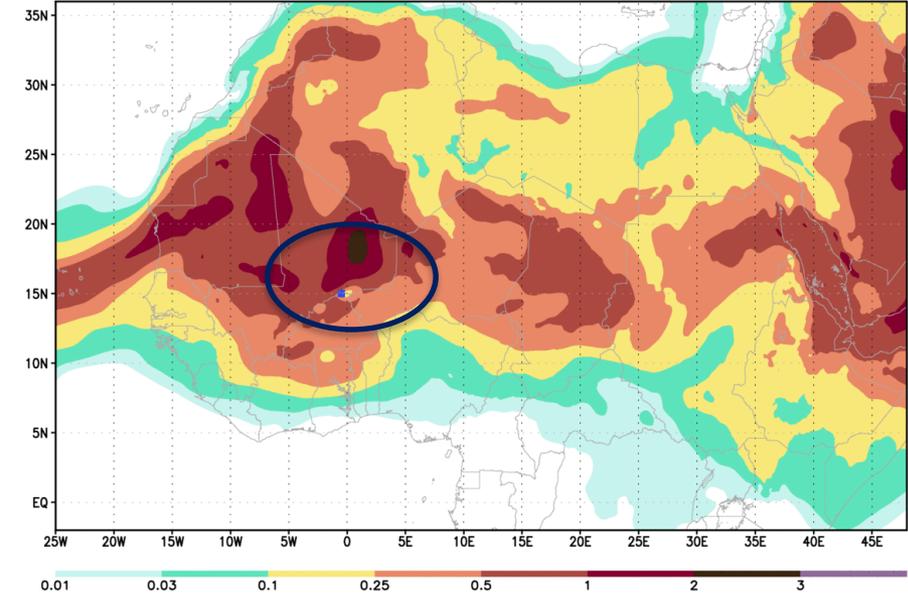
- non-activation by the crew of the engine's anti-icing system ;
- **obstruction of the PT2 pressure sensors, likely by ice crystals**, leading to erroneous EPR values that caused the autothrottle to limit the thrust delivered by the engines below the level of thrust required to maintain FL310 ;
- the crew's late reaction to the decrease in speed and to the erroneous EPR values, possibly linked to the workload associated with avoiding the convective system and to the difficulties in communicating with air traffic control ;
- the crew's lack of reaction to the appearance of buffet, the stickshaker and the stall warning ;
- the absence of appropriate flight control inputs by the crew to recover from the stall situation.

The presence of a storm cell close to the aeroplane's flight path, as well as the absence of activation of the engine anti-ice systems (see 1.16.4) at the time the phenomenon occurred, makes more likely an obstruction of the P₁₂ pressure sensors on the right engine, then on the left engine, **resulting from icing**. The reappearance of EPR values consistent at the end of the flight indicates that the icing of the pressure sensors disappeared, probably under the effect of the increase in temperature during the drop.

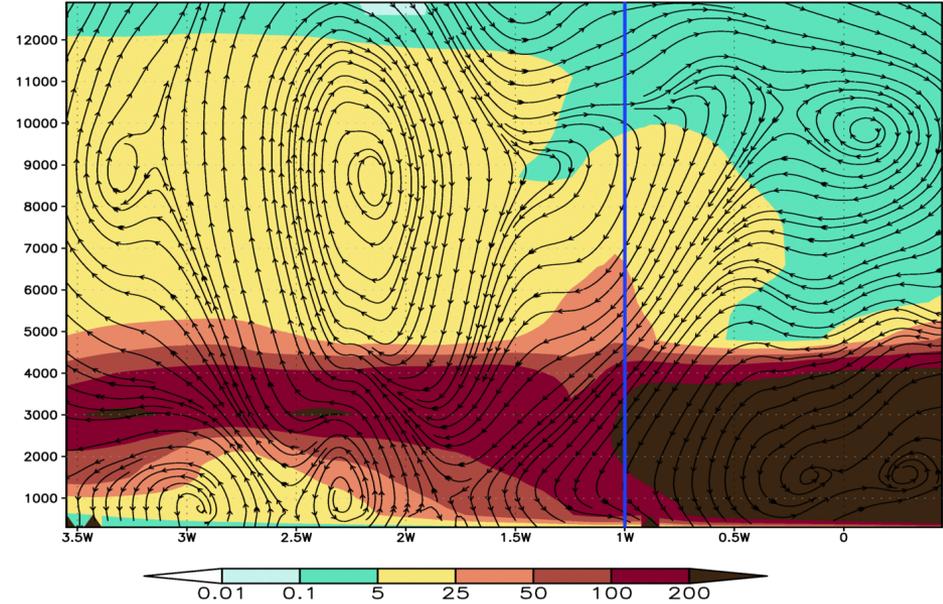
Satellite picture of the storm - cloud top temperature



NMME-DREAM forecast: Dust load (g/m³)
Valid time: 24JUL2014 01UTC



NMME-DREAM: Cross section BEFORE CRASH DUST
Valid time: 24JUL2014 01UTC

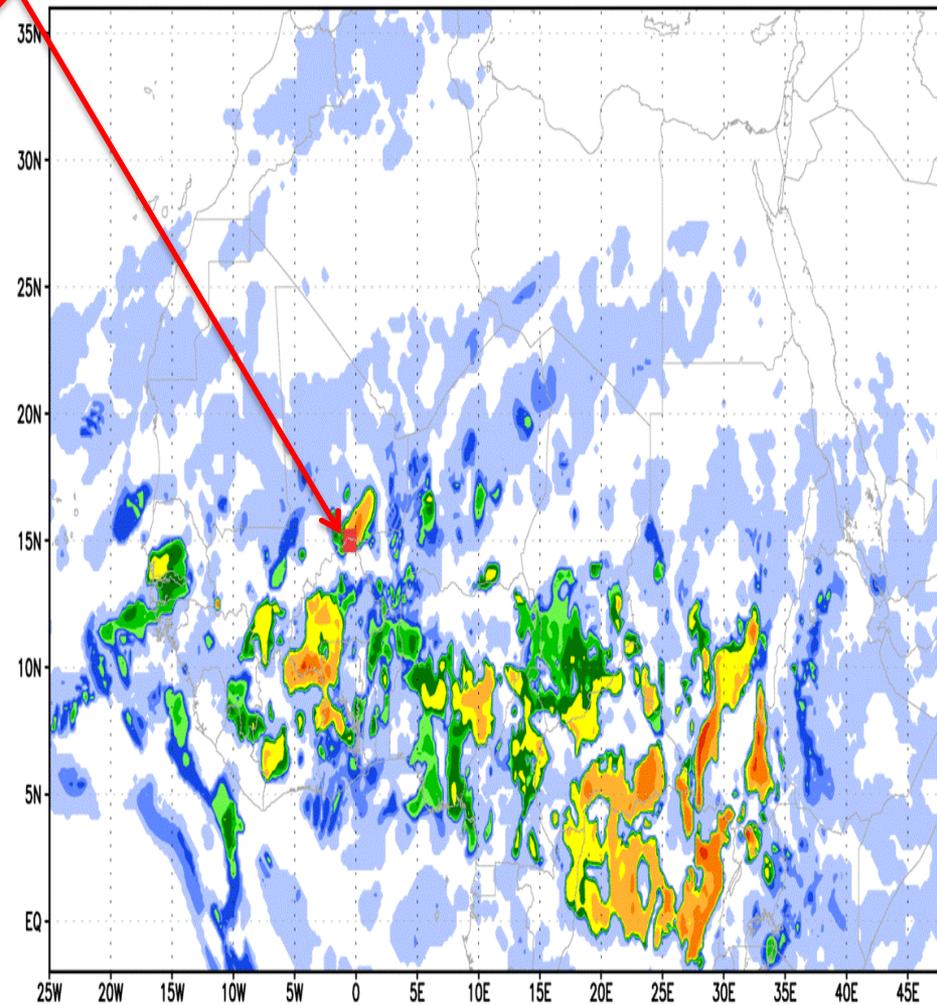
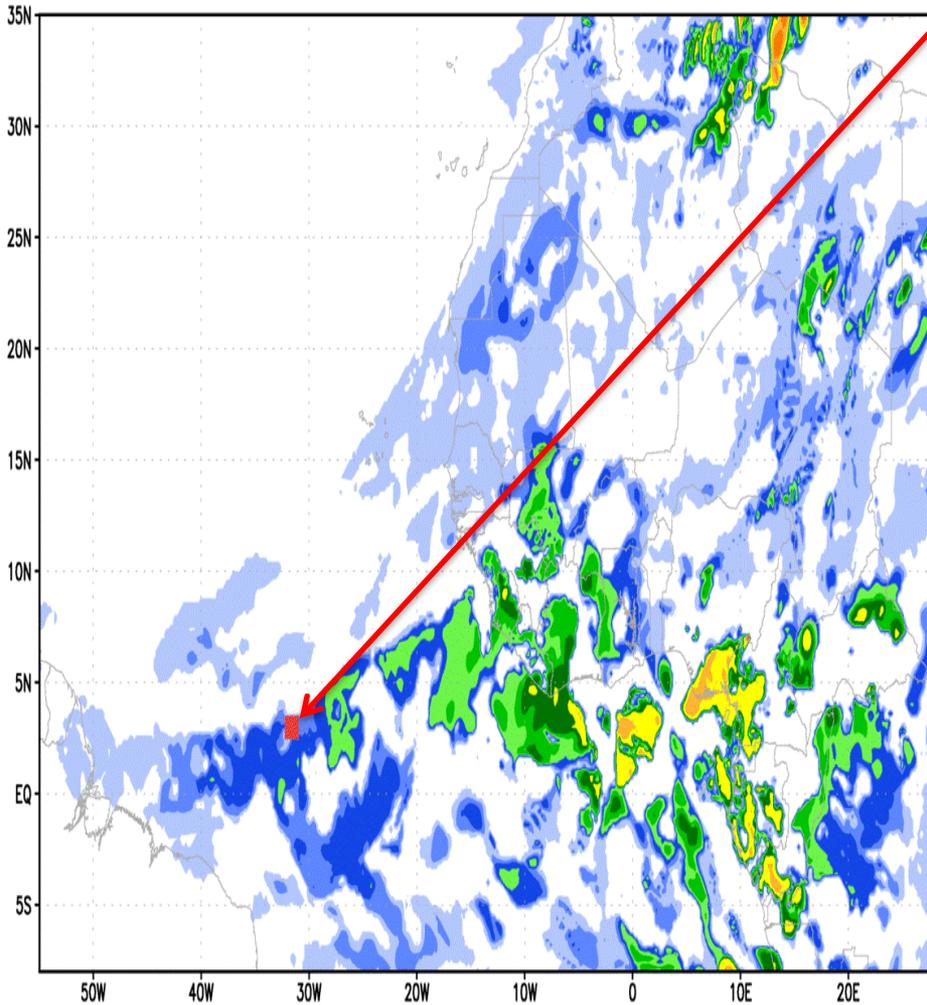


Vertically integrated log₁₀ IN

AIR FRANCE AF477

Crash site

AIR ALGERIE AH5017

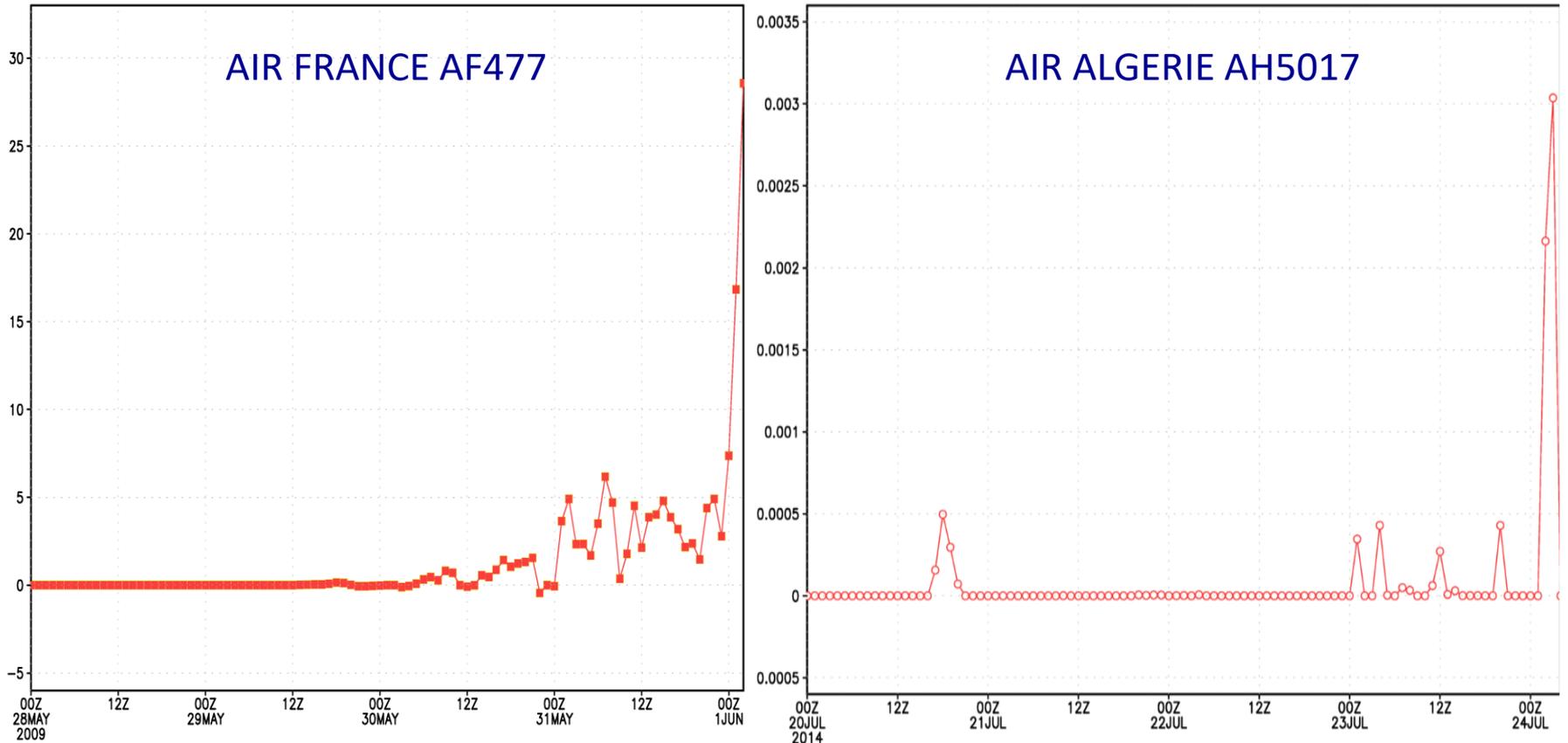


ICING INDEX

We introduced Icing index as a function of vertical velocity and IN

IN depends on dust concentration, temperature and relative humidity

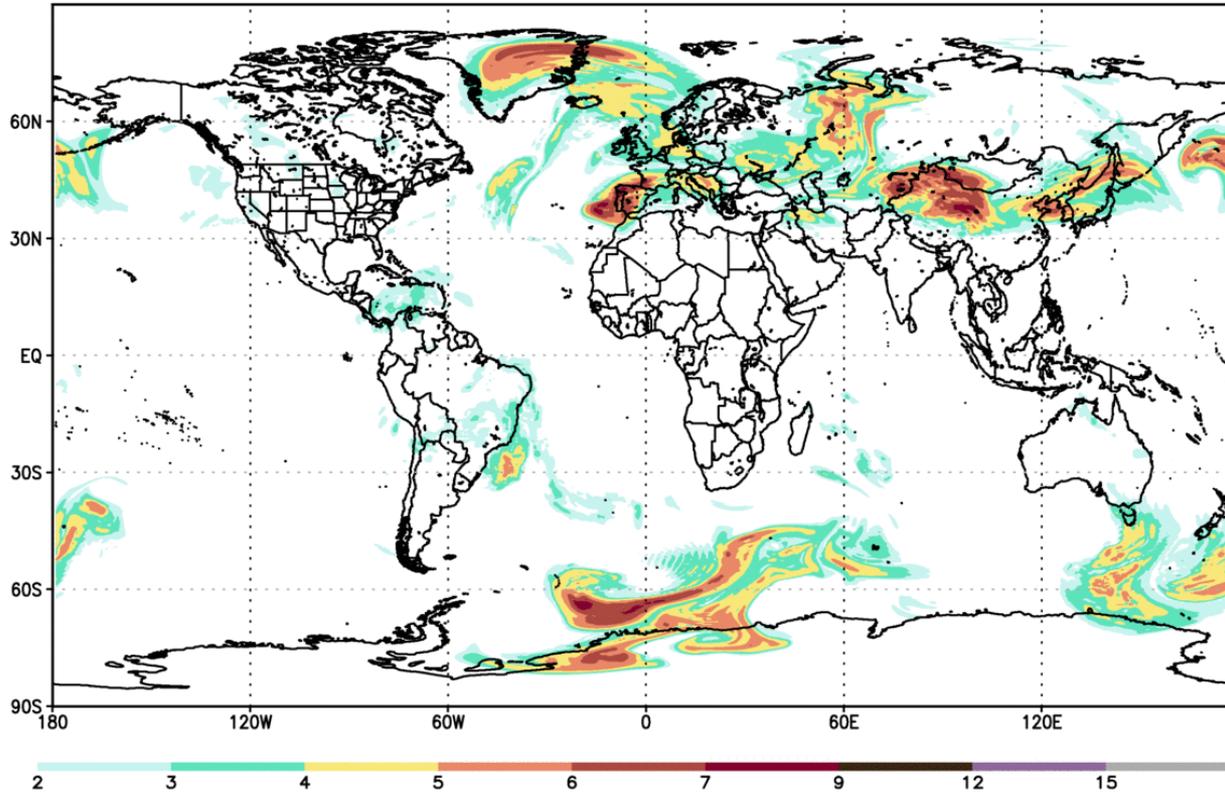
More details you will find soon when we publish the paper



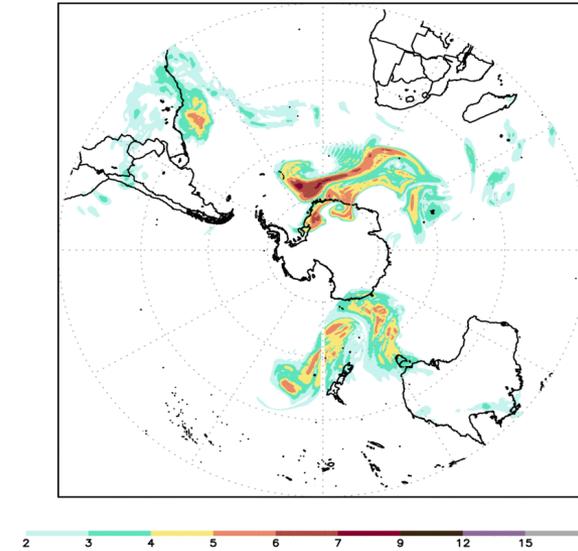
We developed methodology to forecast/predict Icing index globally

Global NMMB-DREAM model Belgrade

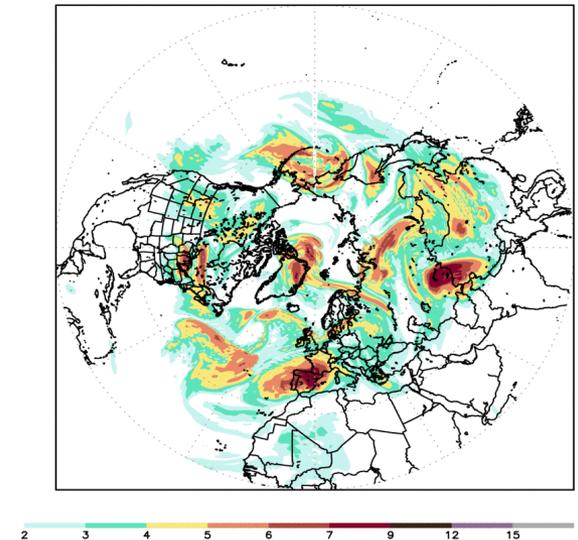
NMME-DREAM forecast: $\log_{10}(\text{IN})$ (IN #/lit) Ullrich
Valid time: 22JAN2020 09UTC



NMME-DREAM forecast: $\log_{10}(\text{IN})$ (IN #/lit) Ullrich
Valid time: 22JAN2020 09UTC



NMME-DREAM forecast: $\log_{10}(\text{IN})$ (IN #/lit) Ullrich
Valid time: 24JAN2020 09UTC



The method is unique since for the first time:

- Mineral dust contribution to icing included (not only conventional parameters such as T, W, RH)
- Upper atmosphere icing forecast (above 6-7 km)
- Global and regional forecast

Thank you kindly for your attention!