Cold cloud formation due to dust Implications for aviation

Bojan Cvetkovic [1], Slobodan Nickovic [1], Goran Pejanovic [1], Slavko Petkovic [1] , Ana Vukovic [2,1] and Jugoslav Nikolic[1]

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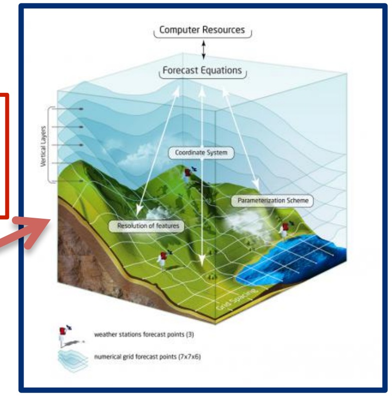
[2] Faculty of Agriculture, University of Belgrade, Belgrade, Serbia

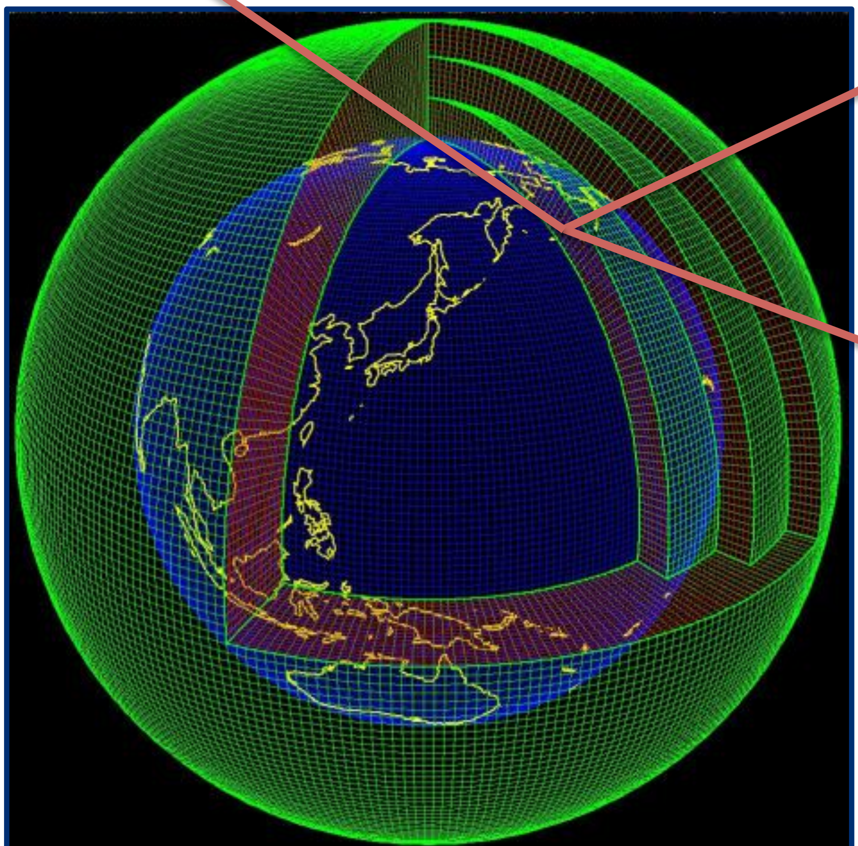
User Workshop on Dust Products for Aviation, **1 April 2020, Virtual/remote meeting**

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

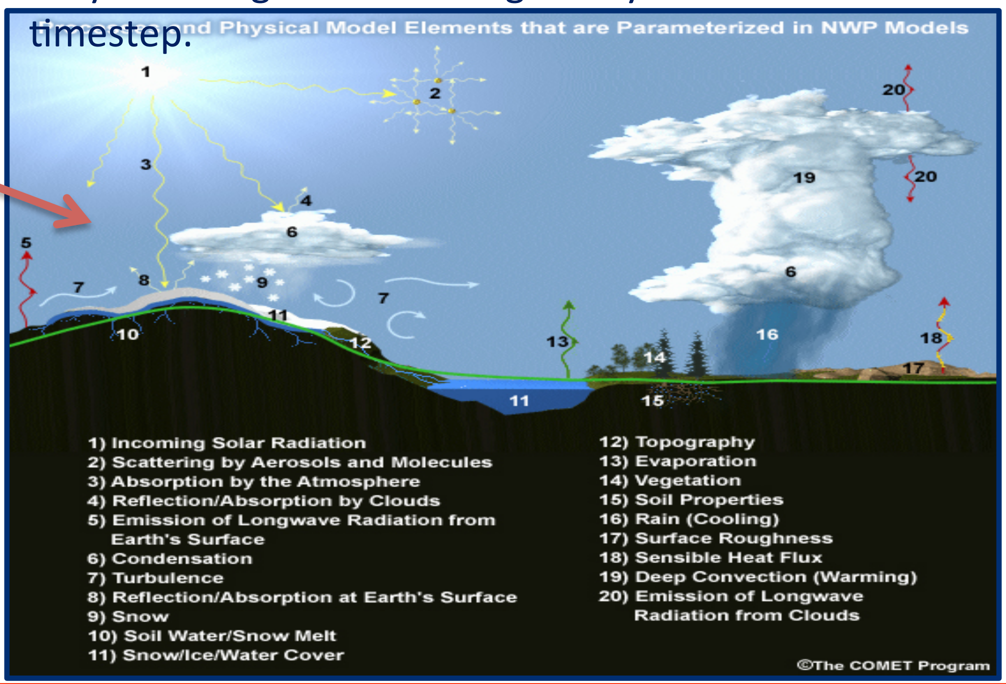
Numerically solve equations that describes physical processes in the atmosphere/ land (fluid dynamics and thermodynamics) + atmospheric dust cycle processes



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



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**

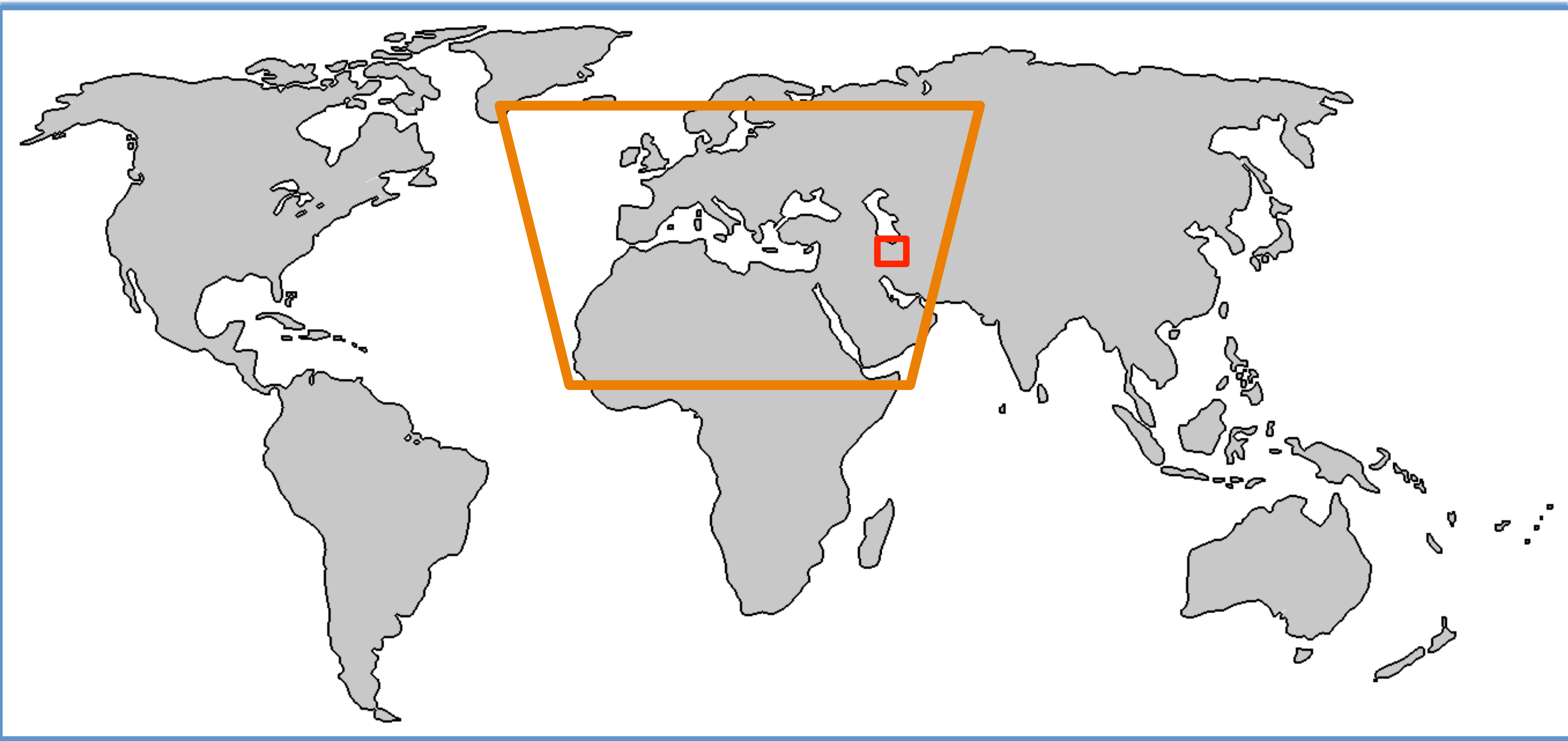
ATMOSPHERIC DUST MODELLING

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 ~100km)
(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 ~100km)

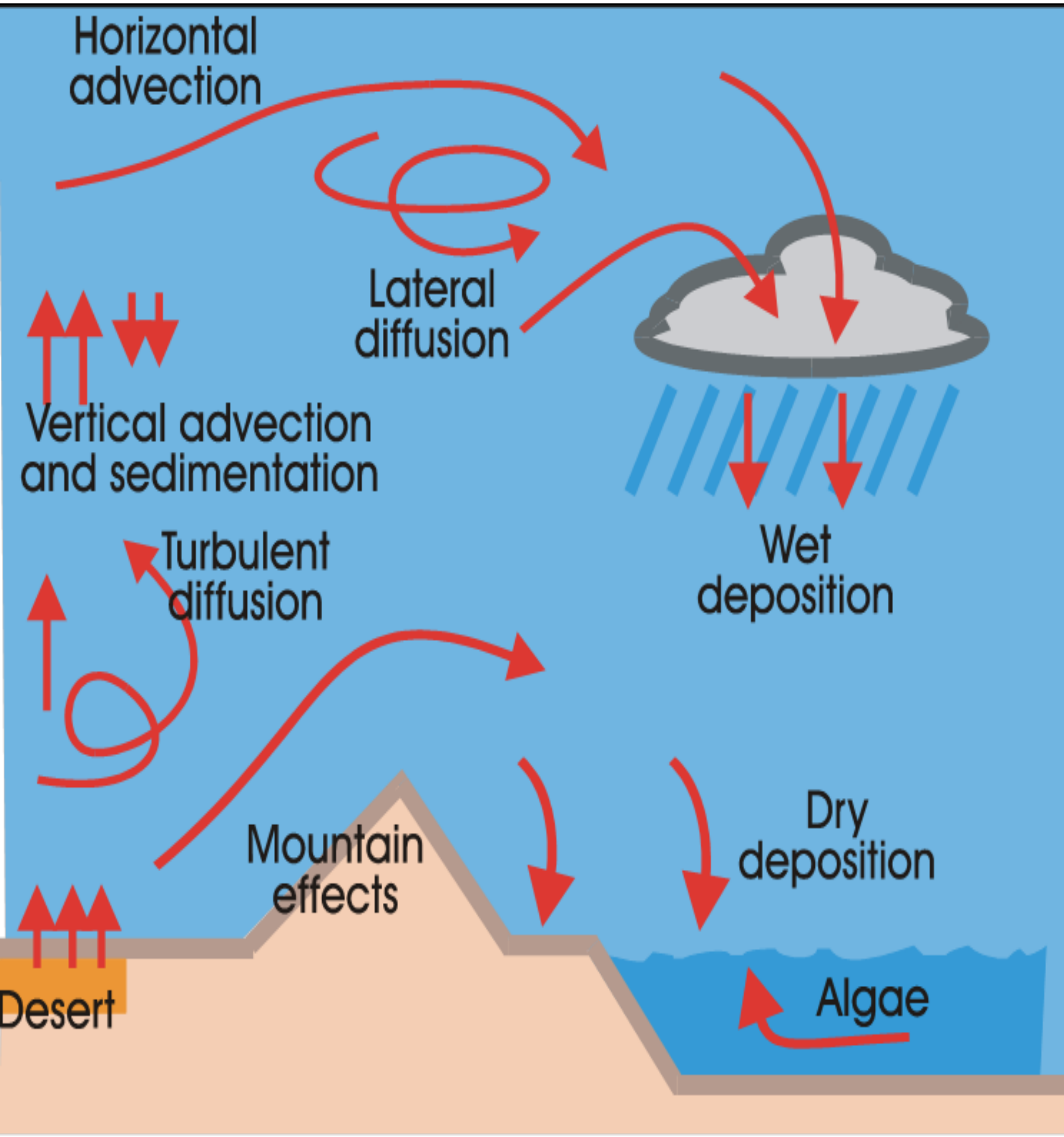
SHORT RANGE TRANSPORT:
Nonhydrostatic regional models
High resolution (several km)
Forecast of the dust storms

GLOBAL MODELS **REGIONAL MODELS** **NONHYDROSTATIC MODELS**



Dust Regional Atmospheric Model (DREAM)

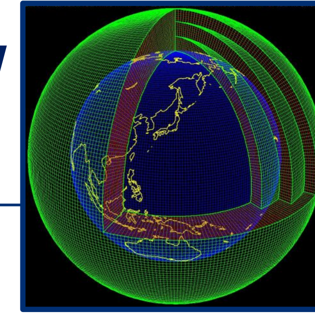
$$\frac{\partial C_k}{\partial t} = -u\frac{\partial C_k}{\partial x} - v\frac{\partial C_k}{\partial y} - \left(w - v_{gk}\right)\frac{\partial C_k}{\partial z} - \nabla\left(K_H \nabla C_k\right) - \frac{\partial}{\partial z}\left(K_Z \frac{\partial C_k}{\partial z}\right) + \left(\frac{\partial C_k}{\partial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



- **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.

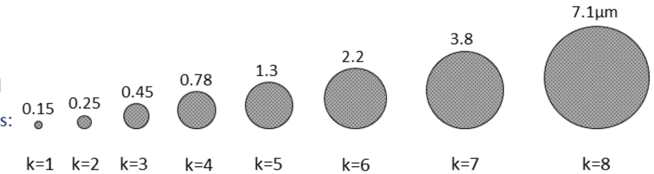
Particles are divided in categories by size.

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:



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)

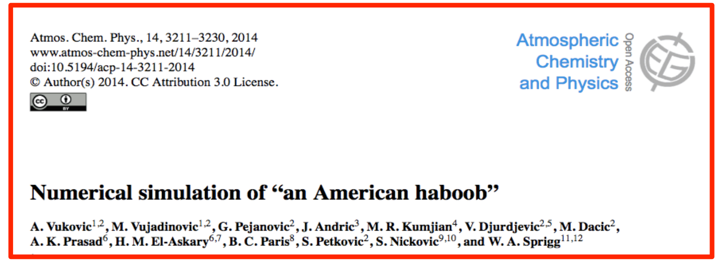
using updated values of soil moisture and friction velocity calculate dust emission for each of 8 bins

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

(Nickovic et al., 2001)

C is calculated for each particle size category C_k(k=1,…,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)

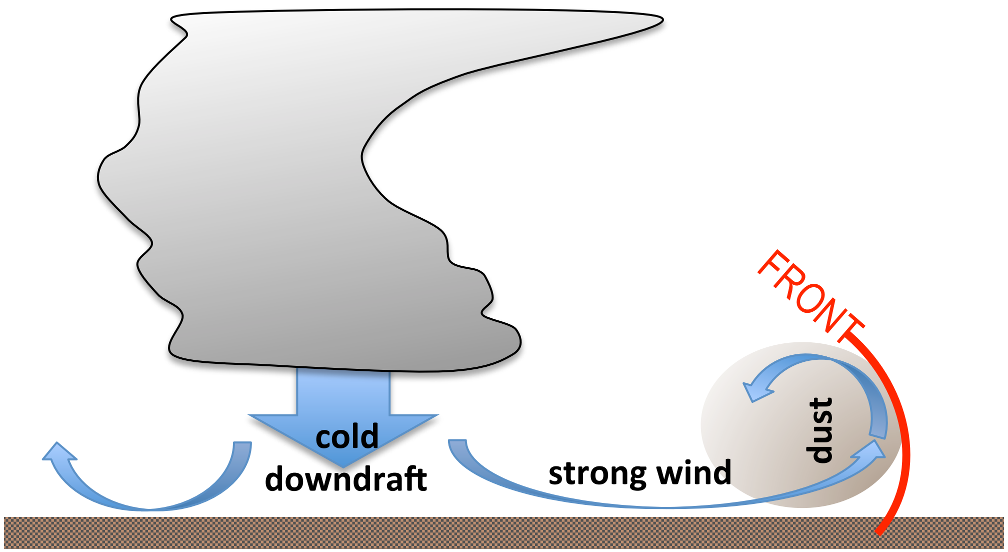

Atmos. Chem. Phys., 14, 3211–3230, 2014
www.atmos-chem-phys.net/14/3211/2014/
doi:10.5194/acp-14-3211-2014

Atmospheric Chemistry and Physics
Open Access

Numerical simulation of "an American haboob"

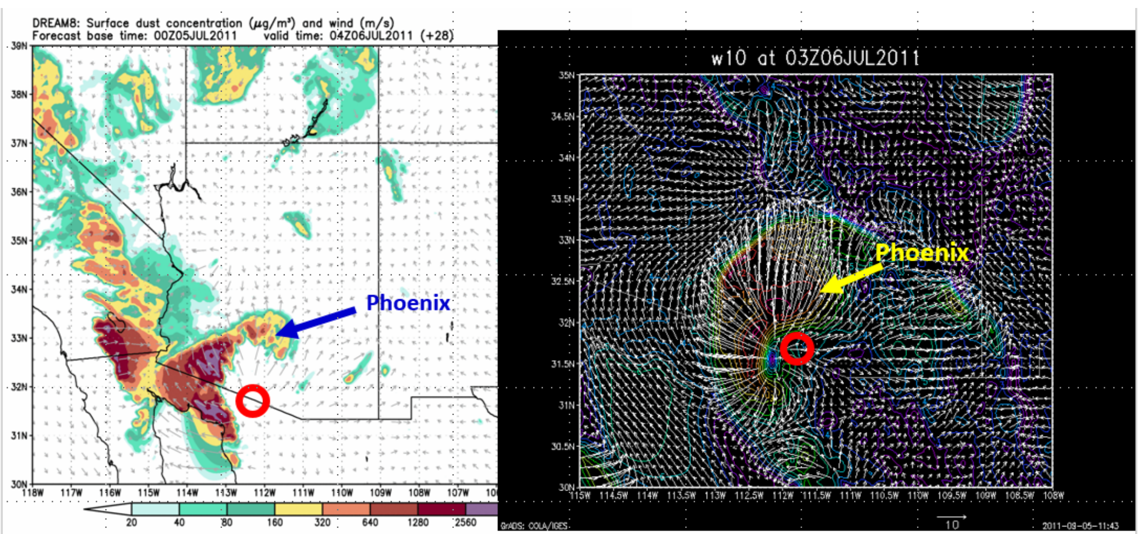
A. Vukovic[1,2], M. Vujadinovic[1,2], G. Pejanovic[2], J. Andric[3], M. R. Kumjian[4], V. Djurdjevic[2,5], M. Dacic[2], A. K. Prasad[6], H. M. El-Askary[6,7], B. C. Paris[8], S. Petkovic[2], S. Nickovic[9,10], and W. A. Sprigg[11,12]

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



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

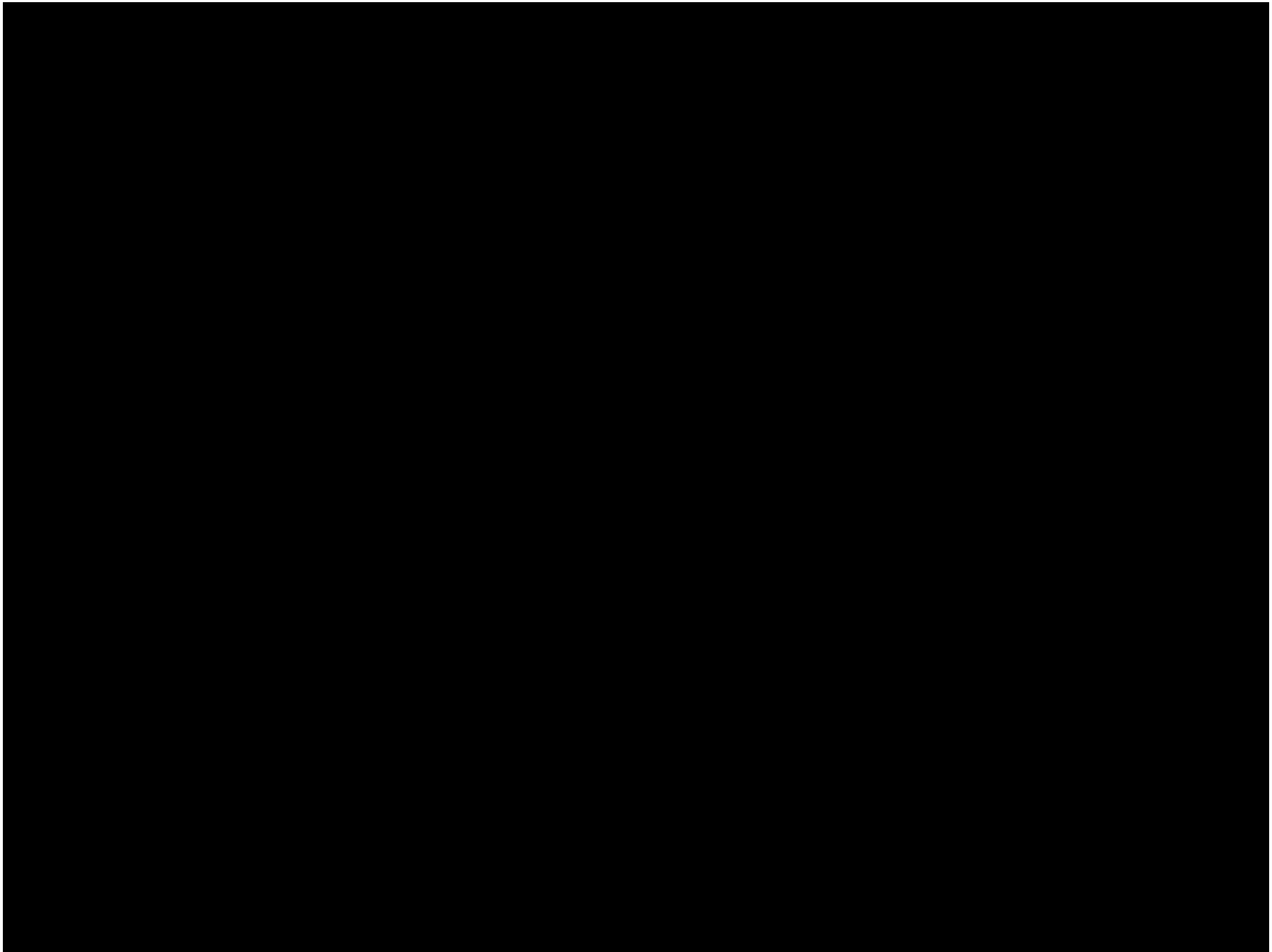
- Tucson – Phoenix; Front wide ~150km; travelled distance ~250km; Dust wall height ~1500-2000m
- 02UTC 6. JULY reached SE Phoenix; 02-04 UTC cross over Phoenix



NASA Applied Science support led to this high-resolution forecast and simulation capability

KUWAIT April 2018 HABOOB - DUST STORM

KUWAIT April 2018 HABOOB - DUST STORM

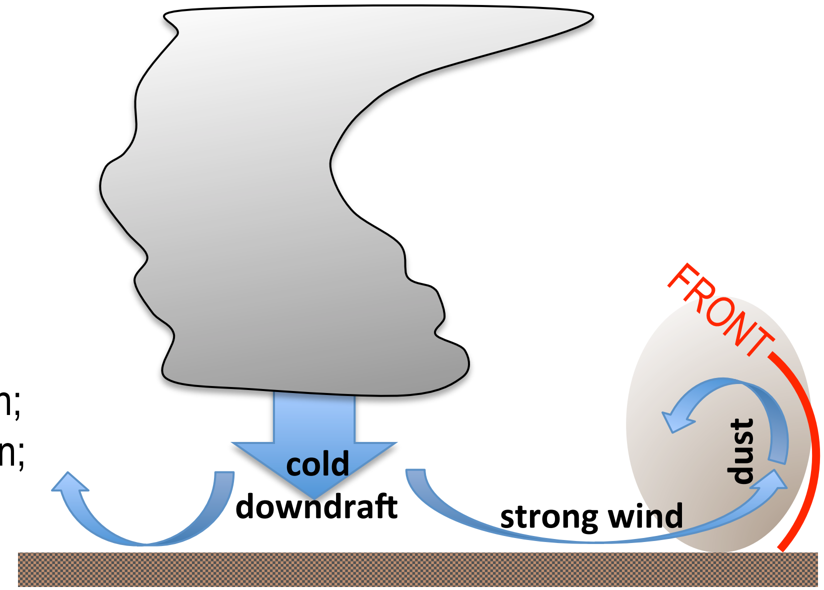


STUDY CASE: TEHRAN DUST STORM 2ND JUNE 2014

Simulation of small scale (local; several 100km), intense (several 1000ug/m3 PM10) & short lived (few hours) dust storms

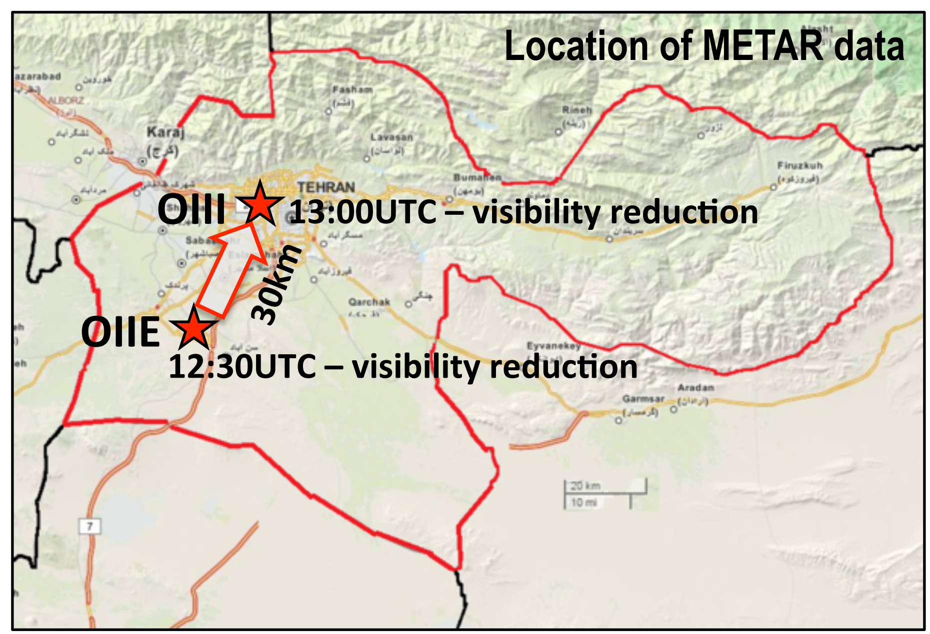
Information from reports

- 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.



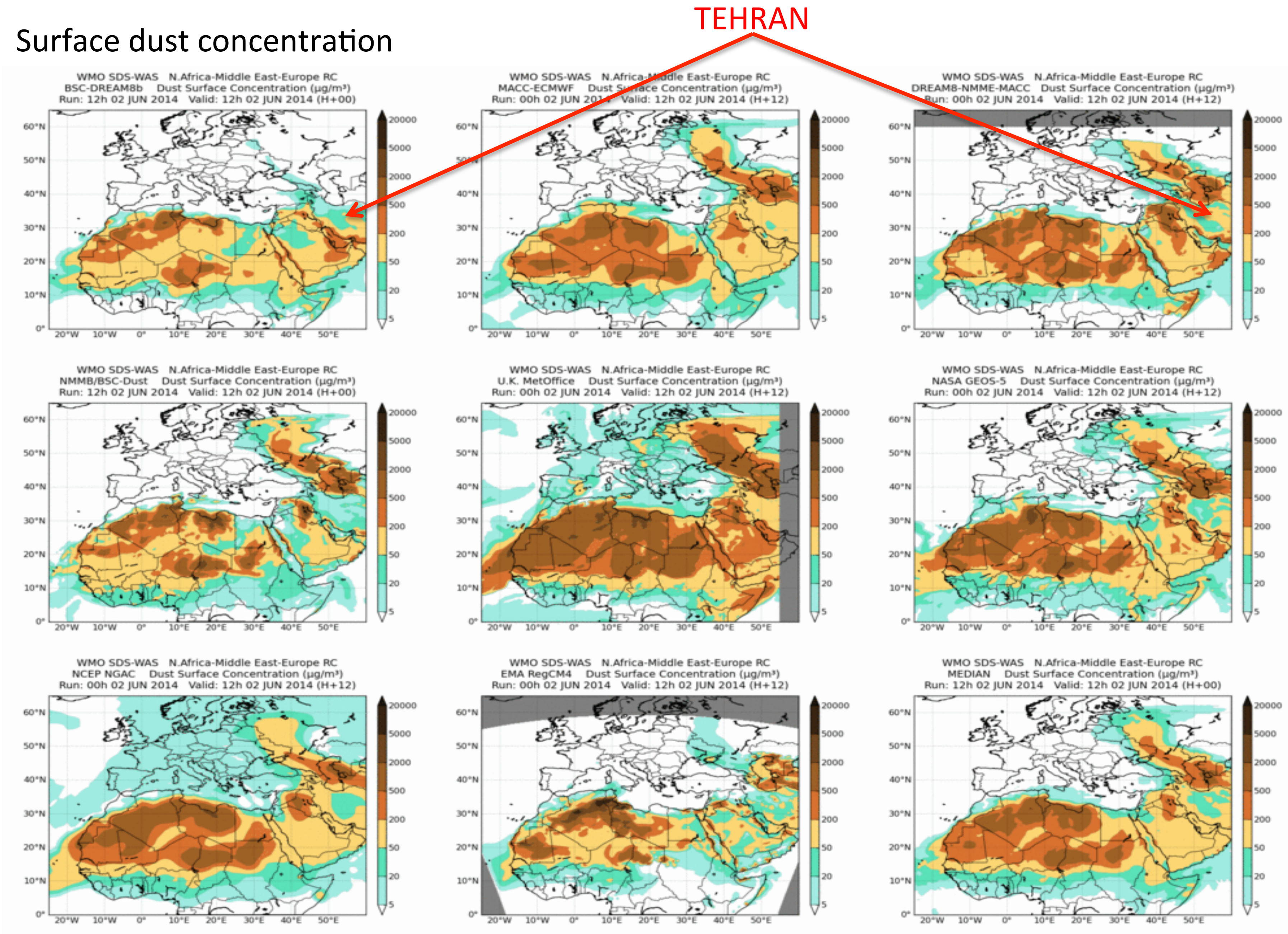
Theory

- 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)

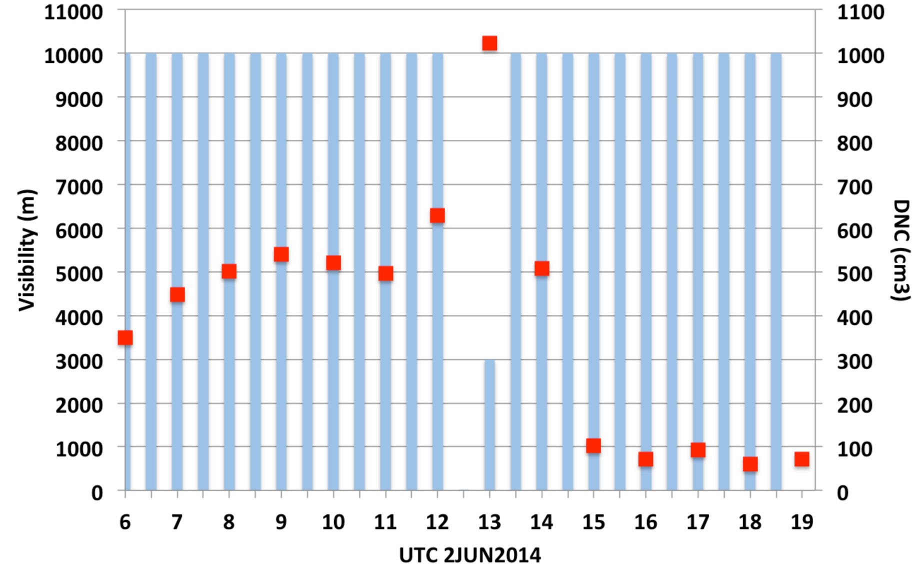
Surface dust concentration

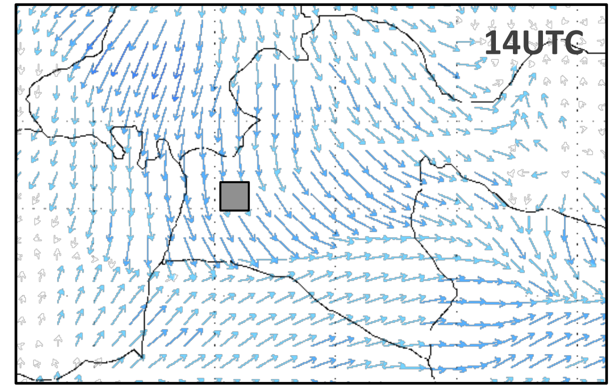


Imam Khomeini airport OIIE

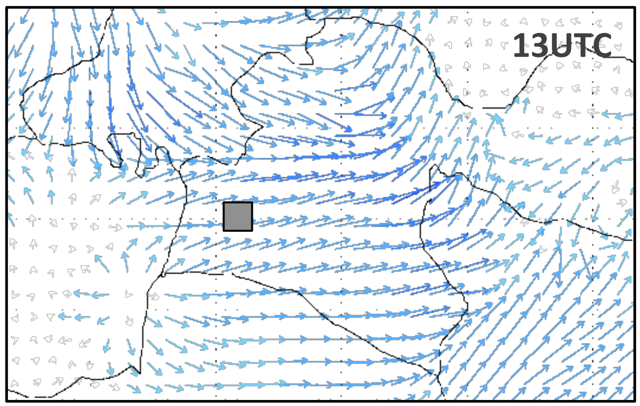
Visibility reduced to 20m at 12:30UTC.
Model output data available on 1h.

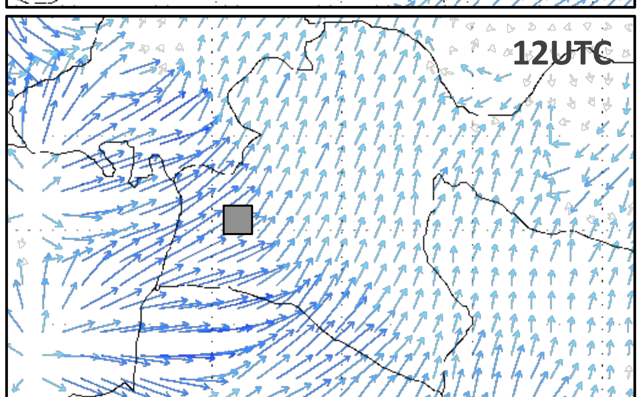
Observed visibility & model DNC

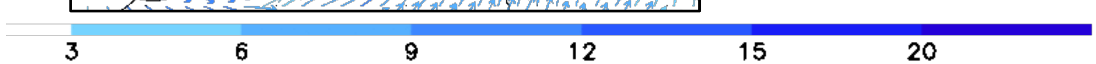


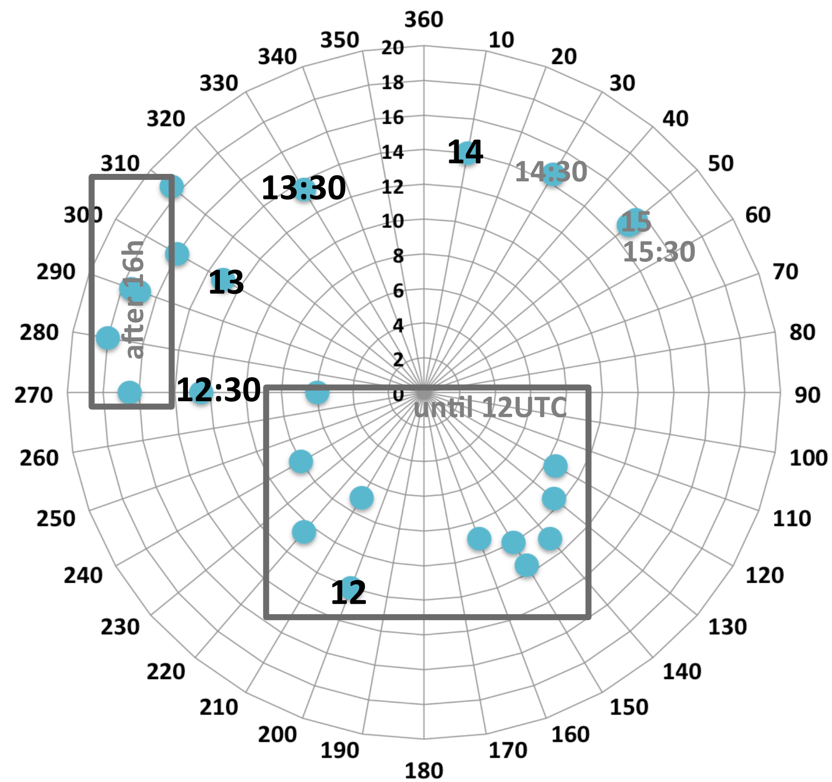


Observed wind direction & model wind





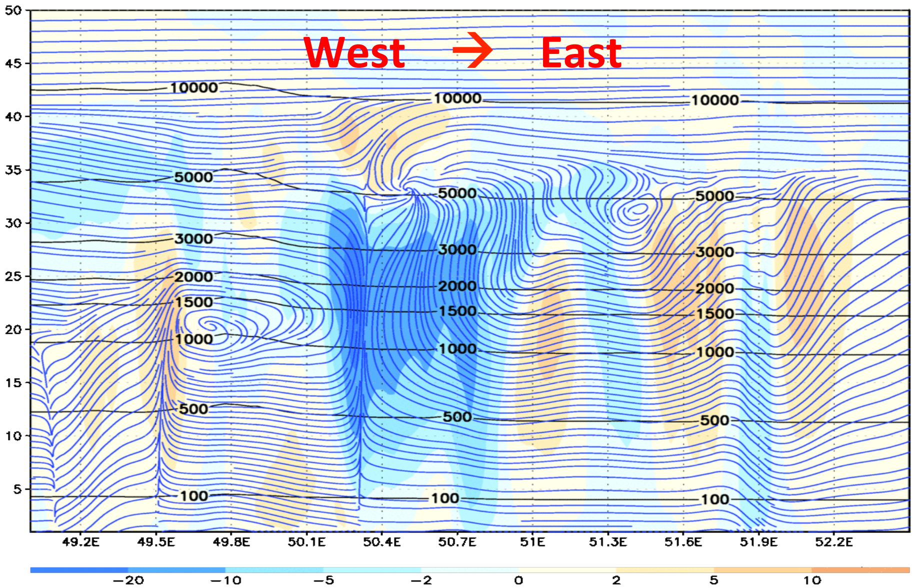




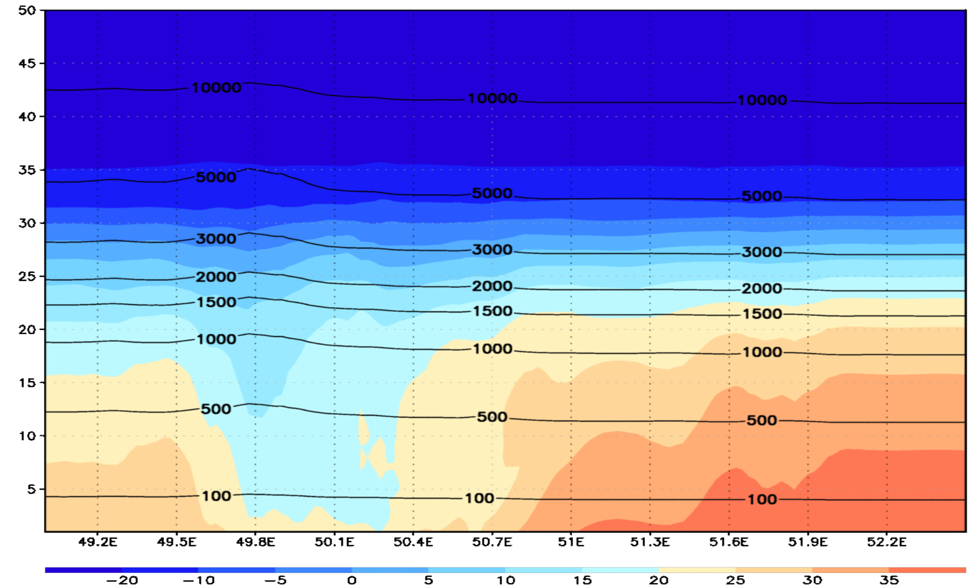
Vertical cross section along 35N

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

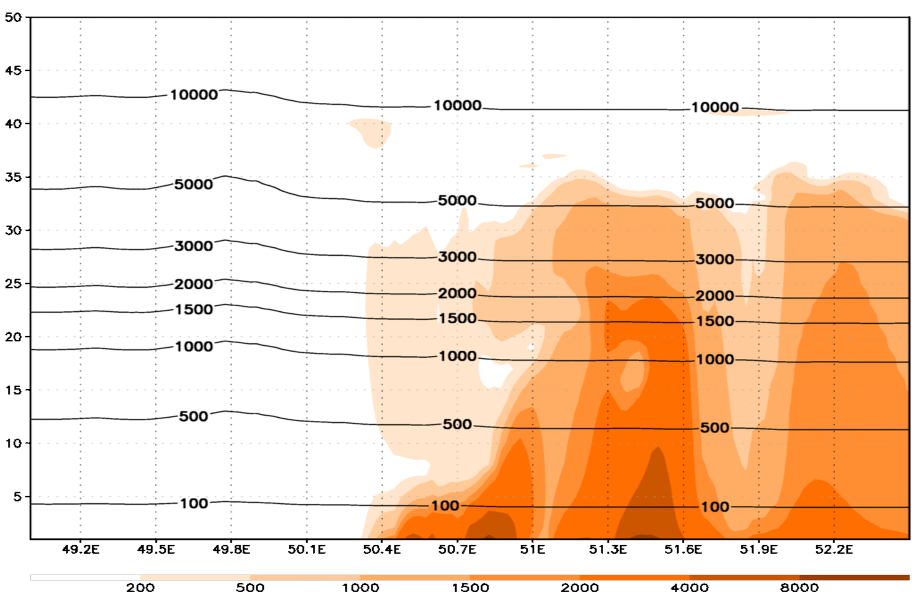
Streamlines (u,w) and vertical wind velocity



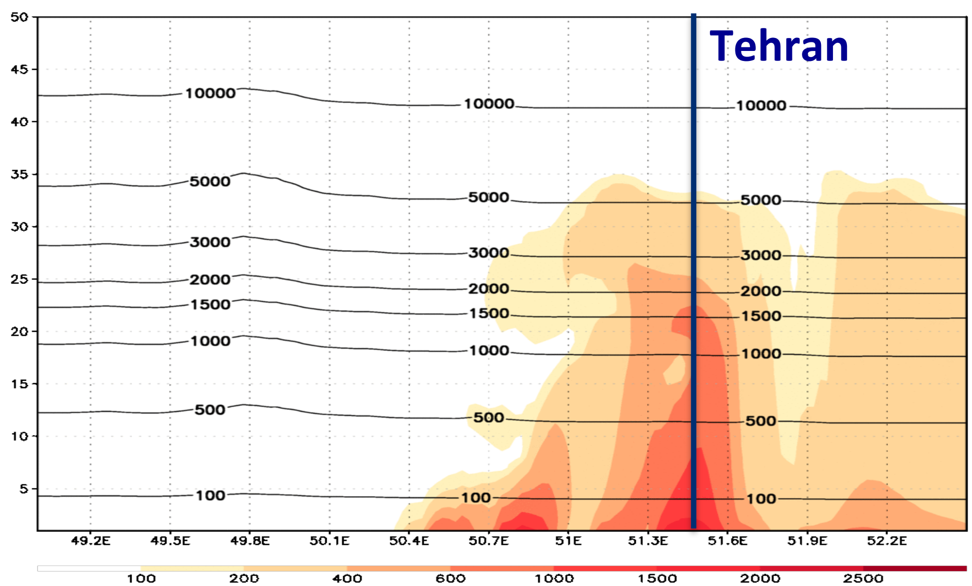
Temperature



Dust PM10 concentration

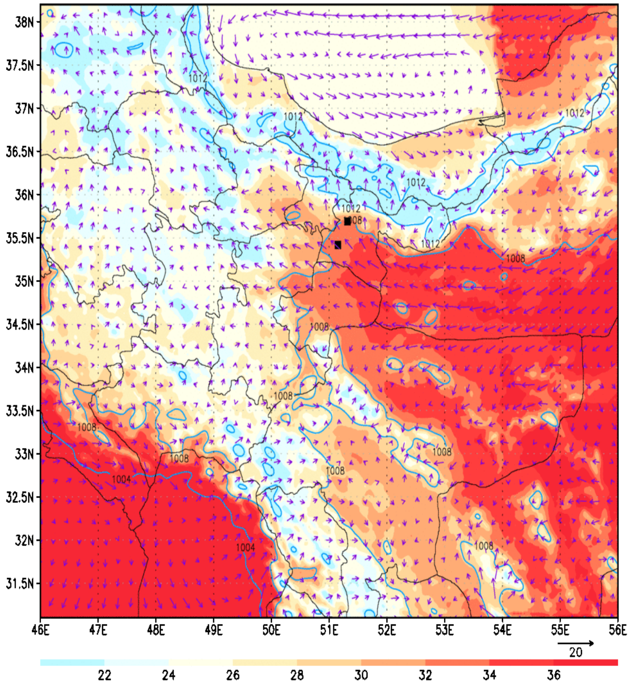


DNC – dust number concentration

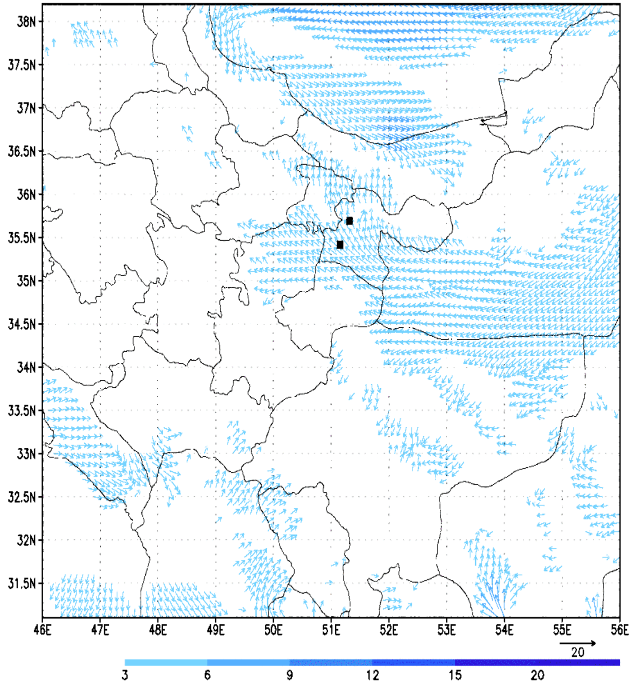


NMME-DREAM (SEEVCCC) simulation results for the period June 2nd 2014 06-20 UTC

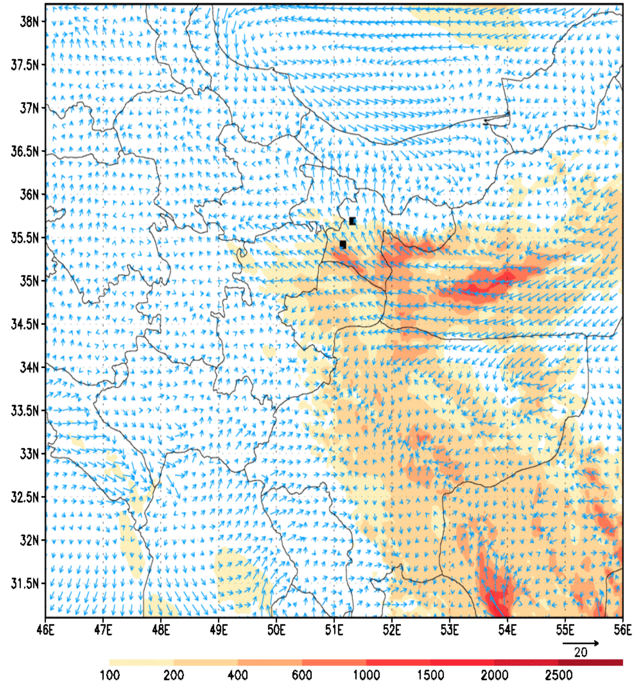
DREAM8 forecast: T2m [°C] PSL [mb] and 10m wind [m/s]
Forecast base time: 01JUN2014 12UTC   Valid: 02JUN2014 06UTC (+18h forecast)



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

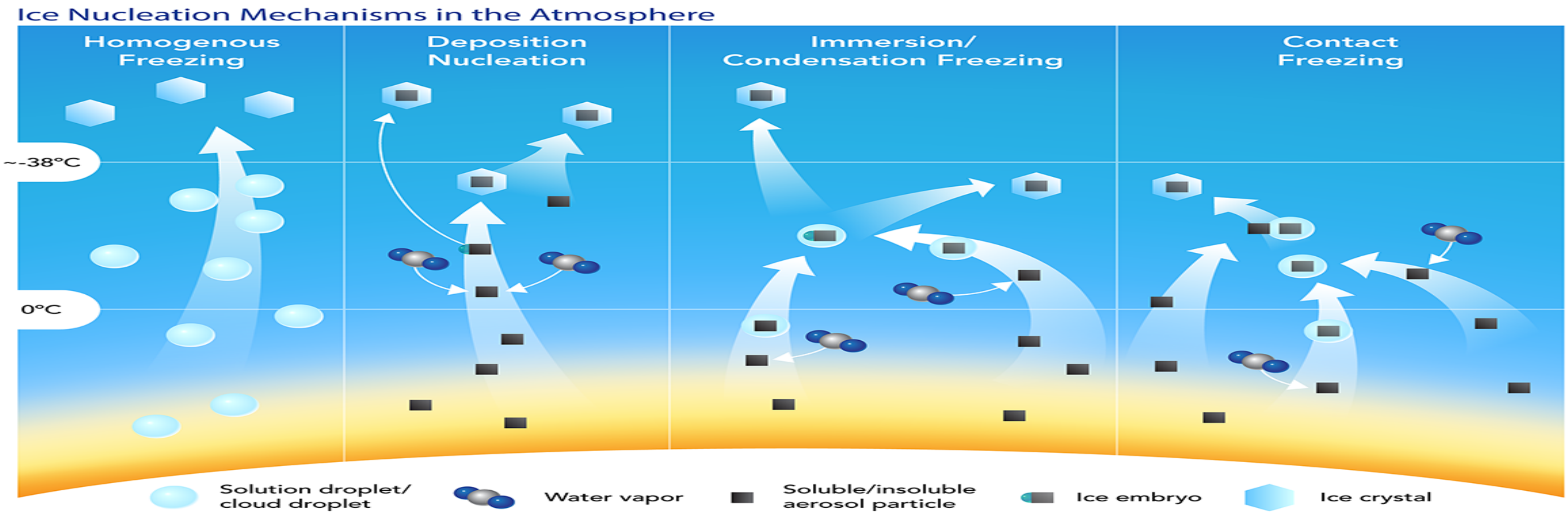


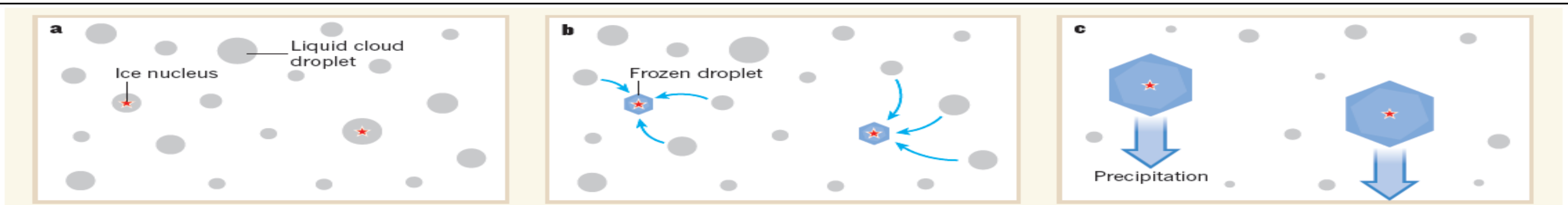
DREAM8 forecast: DNC – Surface dust number conc [1/cm³] and 10m wind [m/s]
Forecast base time: 01JUN2014 12UTC   Valid: 02JUN2014 06UTC (+18h forecast)



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





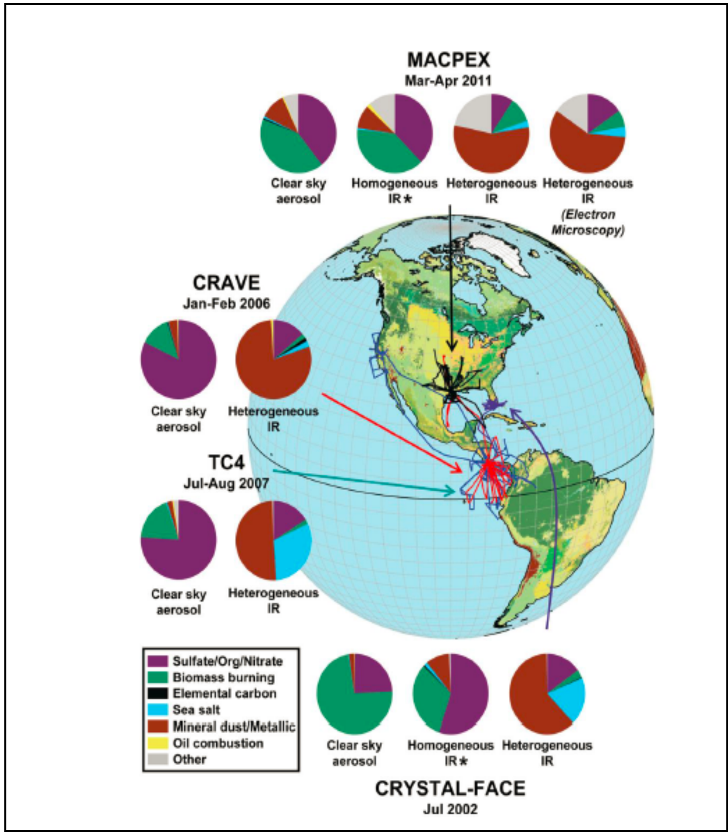
Ice formation and precipitation

Koop and Mahowald, Nature, 2013

Recent findings from observations (Ice Nuclei in ice crystals)

Cziczo at al., Science (2013)

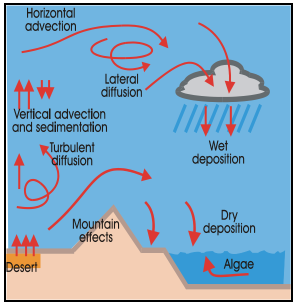
- 2/3 of residues in ice crystals from high clouds are dust+dust metallic oxides particles
- Small dust concentration needed to trigger the process
- Heterogeneous freezing is dominant process
- Minimal surface coating (no dust aging observed)
- Dust as ice nuclei found far from any of major desert sources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



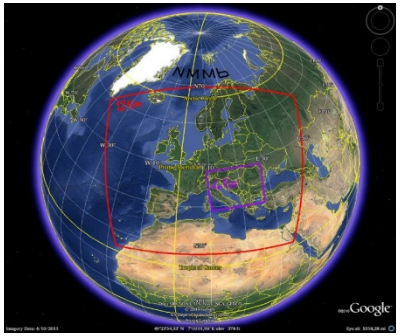
Flight tracks of ice cloud residual measurements for four aircraft campaigns spanning a range of geographic regions and seasons

Improving precipitation forecast

'Cooking' cold clouds: our recipe



DREAM model



NMM model

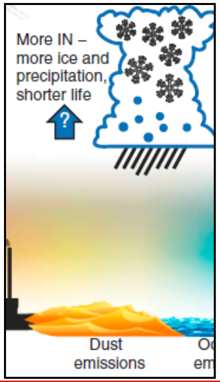
Dust C → **T, RH**

Parameterization of IN in DREAM

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

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

n_{IN} →



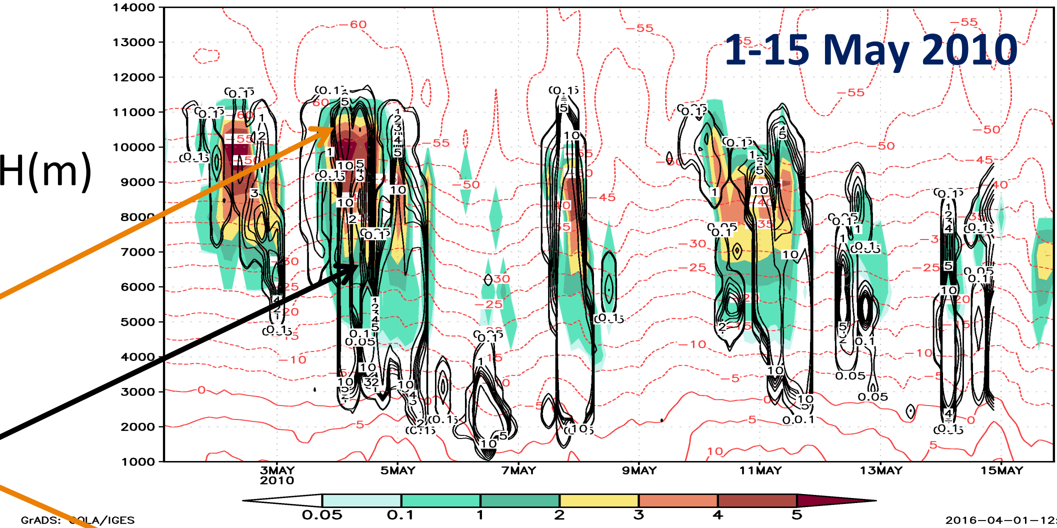
NMMB Thompson dust-friendly cold cloud micrphysics

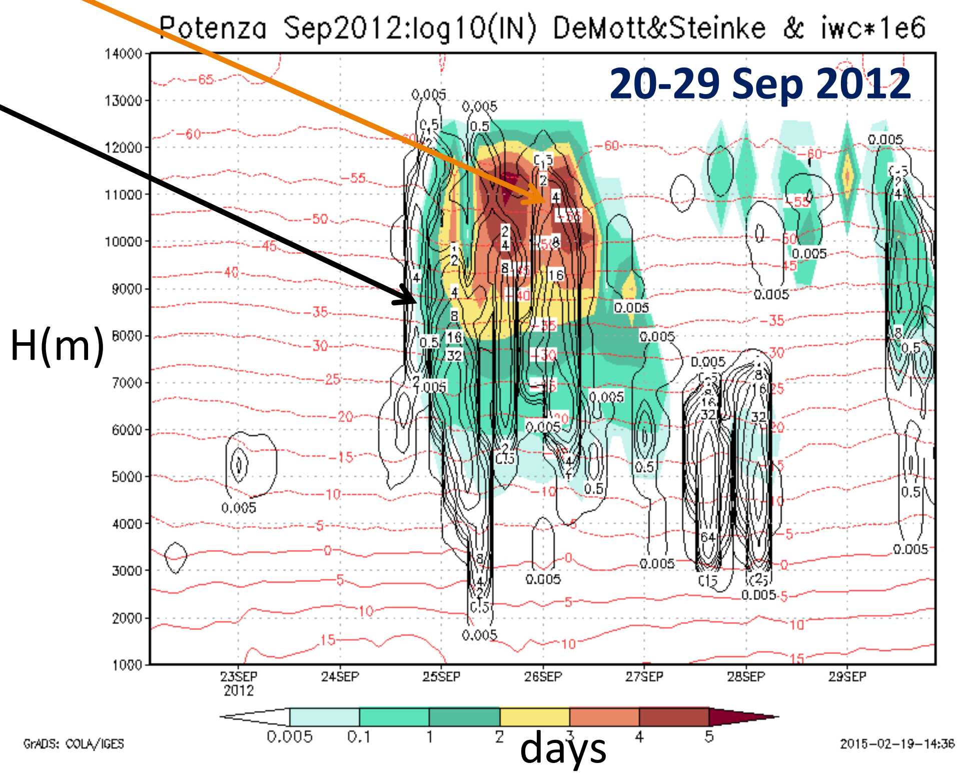
Nickovic et al, 2016, Atmos. Chem. Phys., 16, 11367–11378

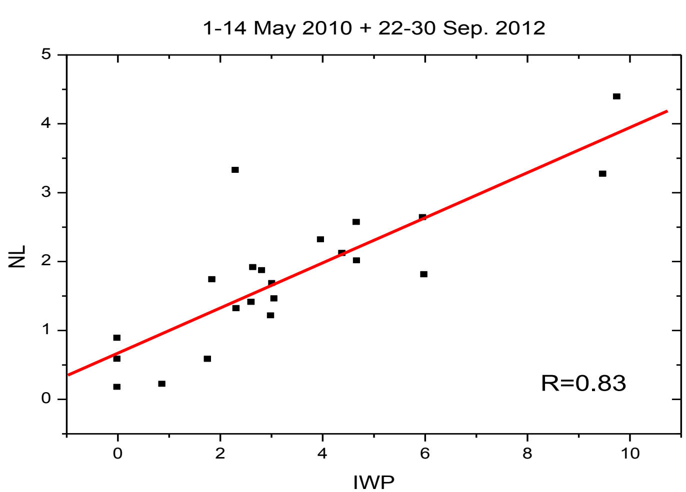
Model well reproduced timing, duration and position of #IN

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)**





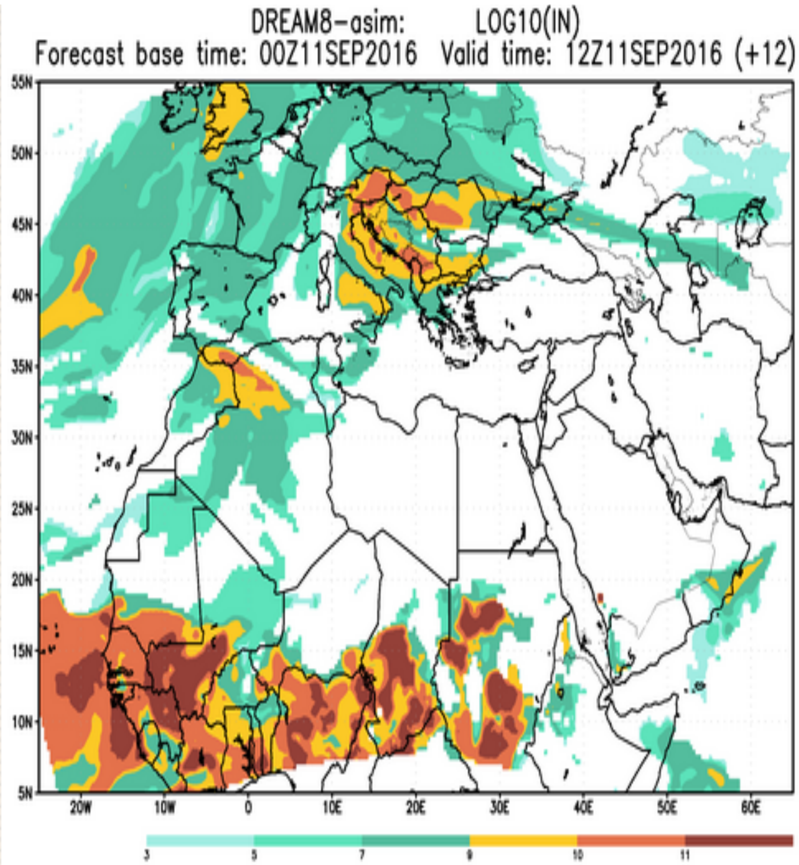


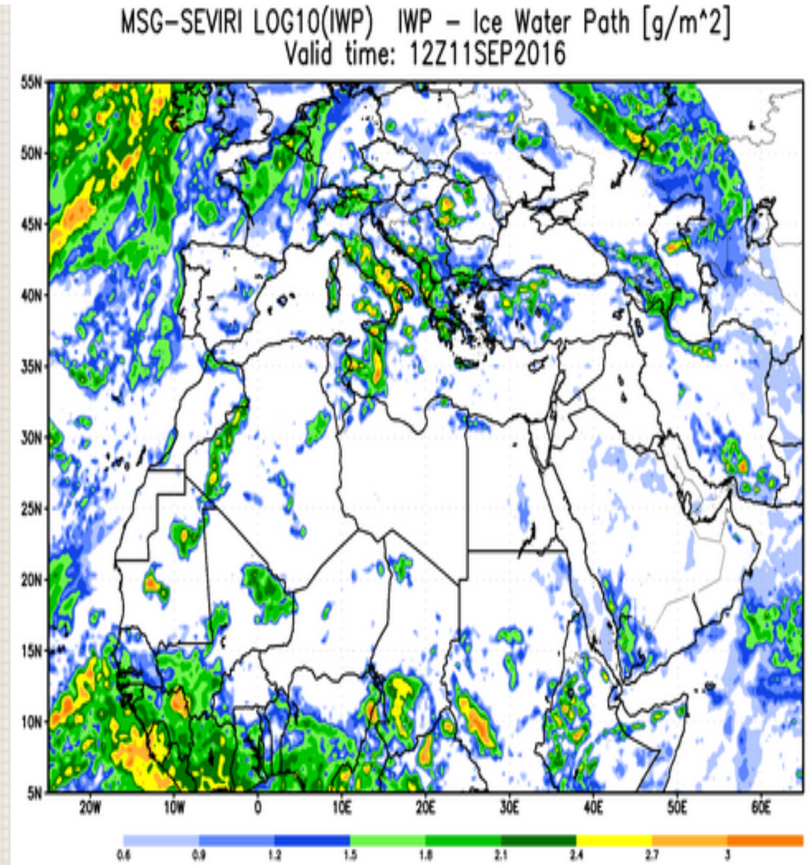
Daily averaged vertical loads
Potenza , May 2010 & Sep 2012

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 HYPOTHESYS ON DUST ROLE IN THE ACCIDENT

1st June 2009

Airbus A330-203 operated by Air France flight AF447

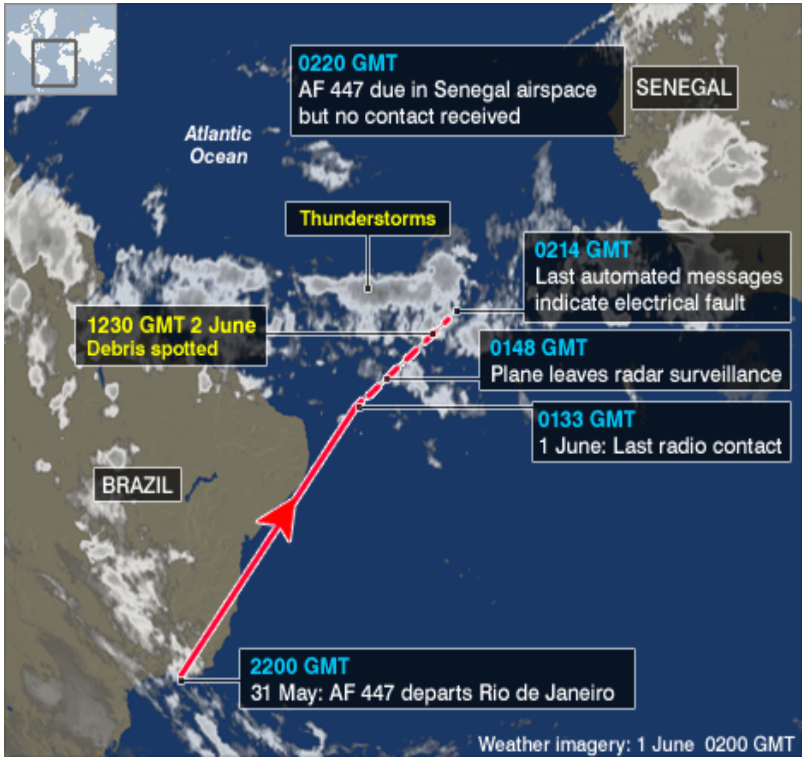
From Rio de Janeiro (Brasil) – Paris (France)

AIR FRANCE AF477 ACCIDENT REPORT

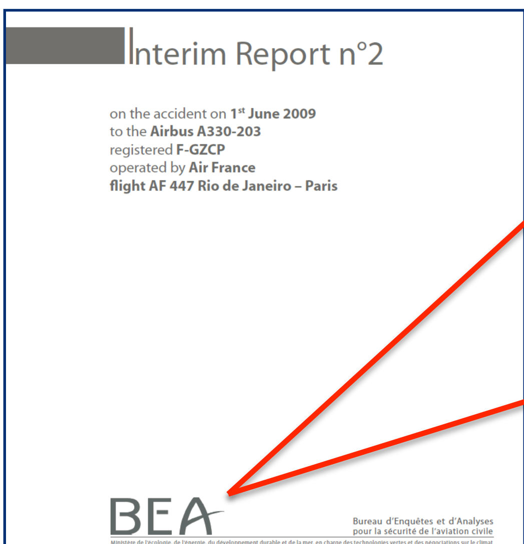
Air France Flight 447

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 TASIL[1]: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

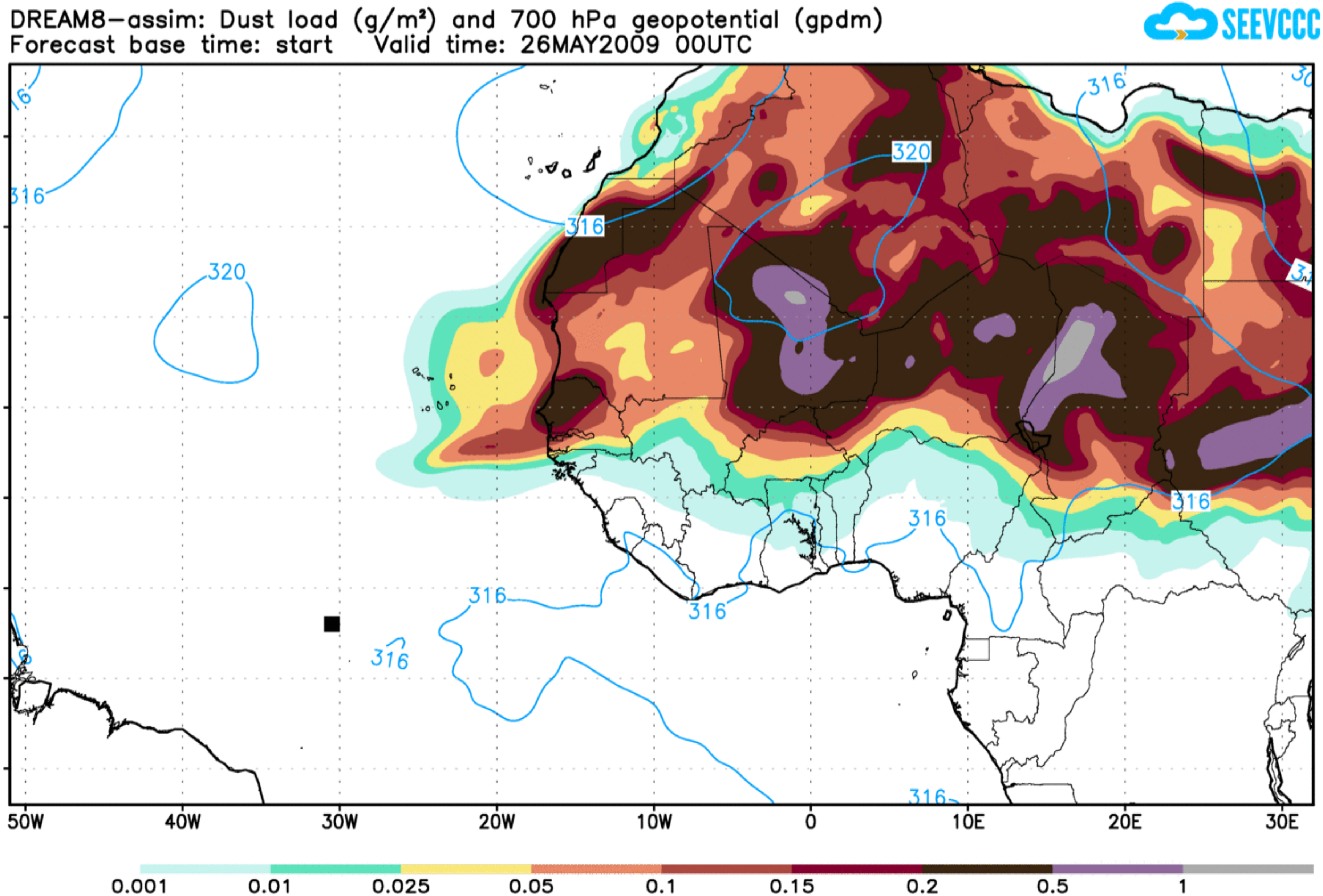
on the accident on 1st June 2009
to the Airbus A330-203
registered F-GZCP
operated by Air France
flight AF 447 Rio de Janeiro – Paris

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

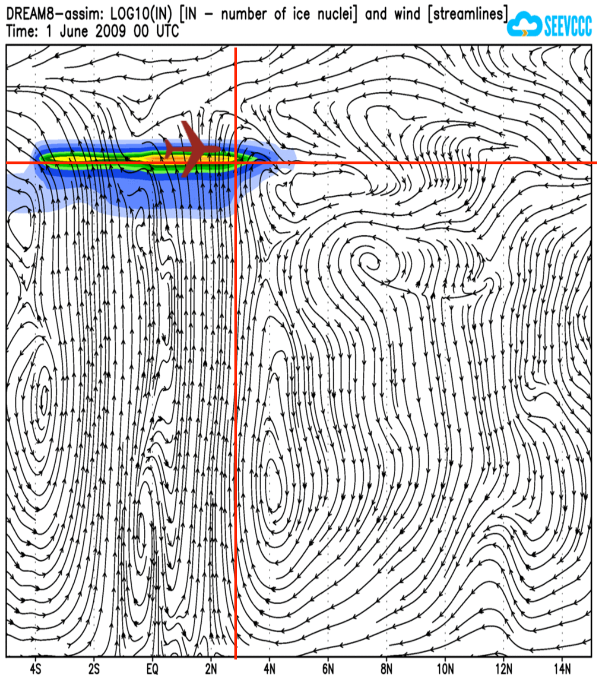
As of 3 November 2009, Airbus had identified thirty-two events that had occurred between 12 November 2003 and 1st June 2009[18]. According to Airbus these events are attributable to the possible destruction of at least two Pitot probes by ice. Eleven of these events occurred in 2008 and ten during the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

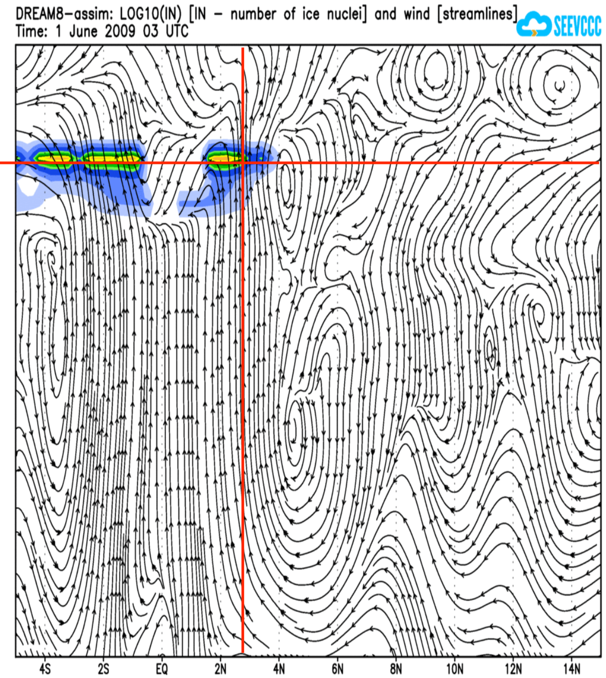
Goodrich 0851GR probes either with Goodrich type 0851HL or by Thales type C16195AA probes before 31 December 2003. According to the analysis carried out at the time, the most likely cause of the problem was the presence of ice crystals and/or water in the Goodrich 0851GR type Pitot probes within the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

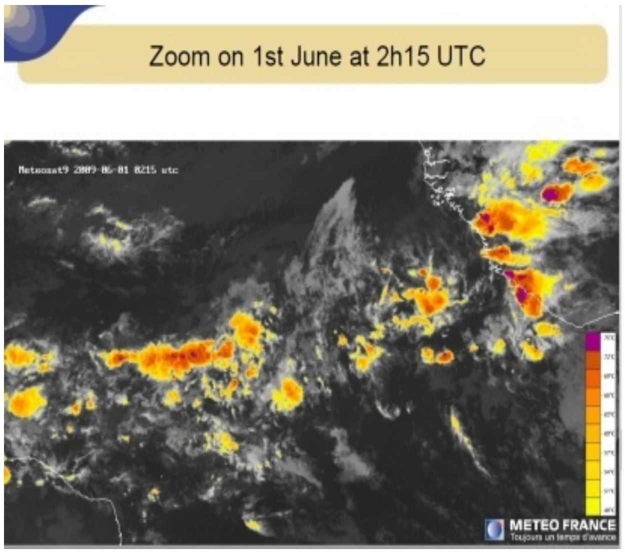
INTENSIVE LONG-RANGE TRANSPORT OF AFRICAN DUST TOWARDS EQUATORIAL MID-ATLANTIC REGION



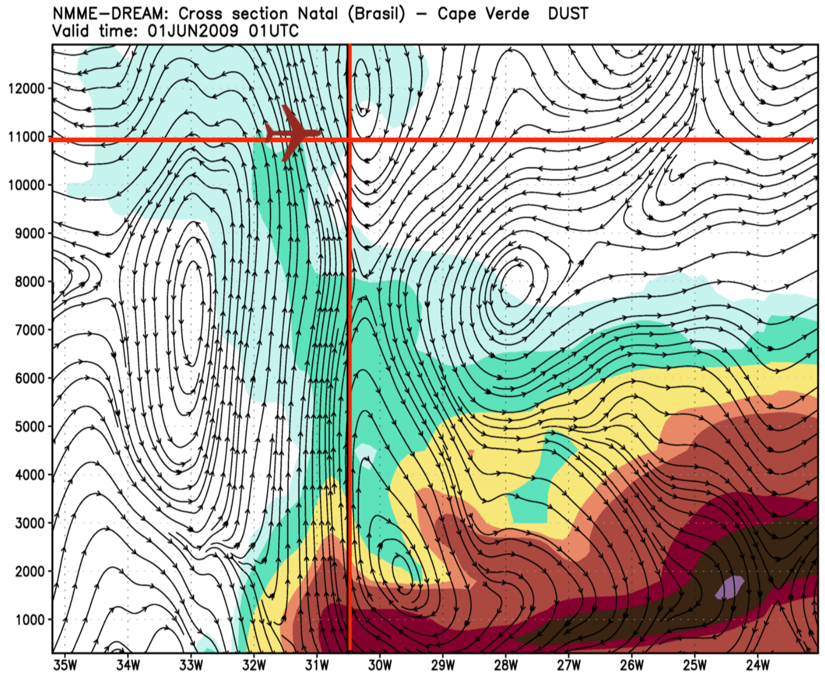
Cross at LON 30W; LAT 5S-15N, FL330







Satellite picture of the storm cloud top temperature



Ice nucleation induced by the dust particles

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

AIR ALGERIE AH5017

A HYPOTHESYS 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)

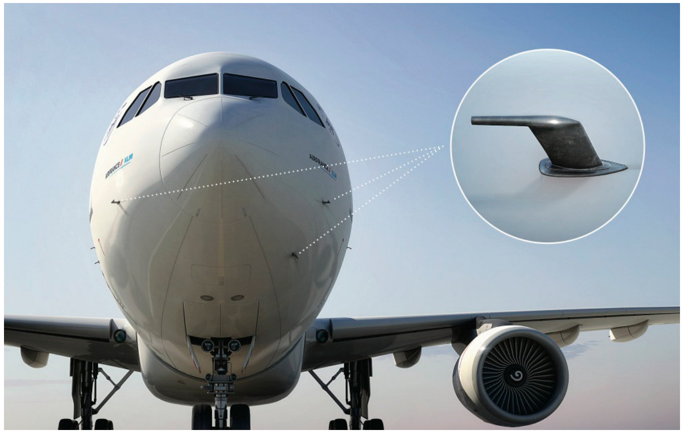
AIR ALGERIE AH5017 ACCIDENT REPORT

Air Algérie Flight 5017

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

Pitot tube



MINISTERE DE L'EQUIPEMENT, DES TRANSPORTS ET DU DESENCLAVEMENT

COMMISSION D'ENQUETE 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

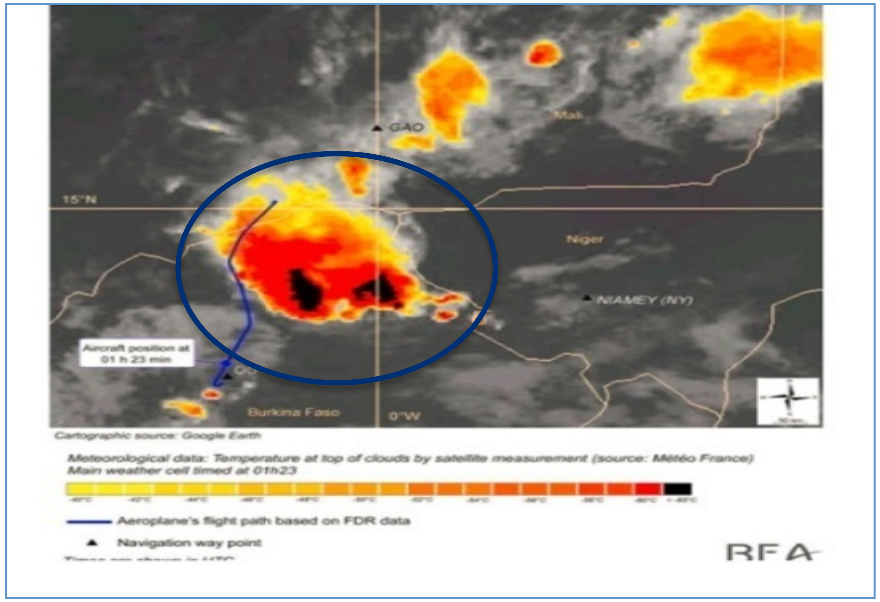
The accident resulted from a combination of the following events:

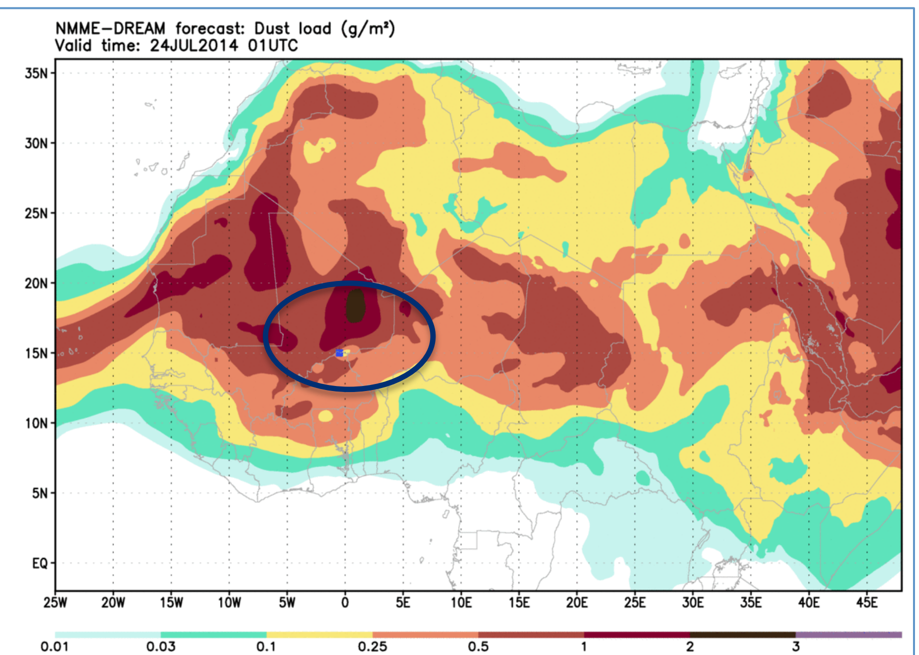
- non-activation by the crew of the engine's anti-icing system ;
- obstruction of the PT2 pressure sensors, likely by ice crystals, leading to erroneous EPR values that caused the autothrottle to limit the thrust delivered by the engines below the level of thrust required to maintain FL310 ;
- the crew's 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.

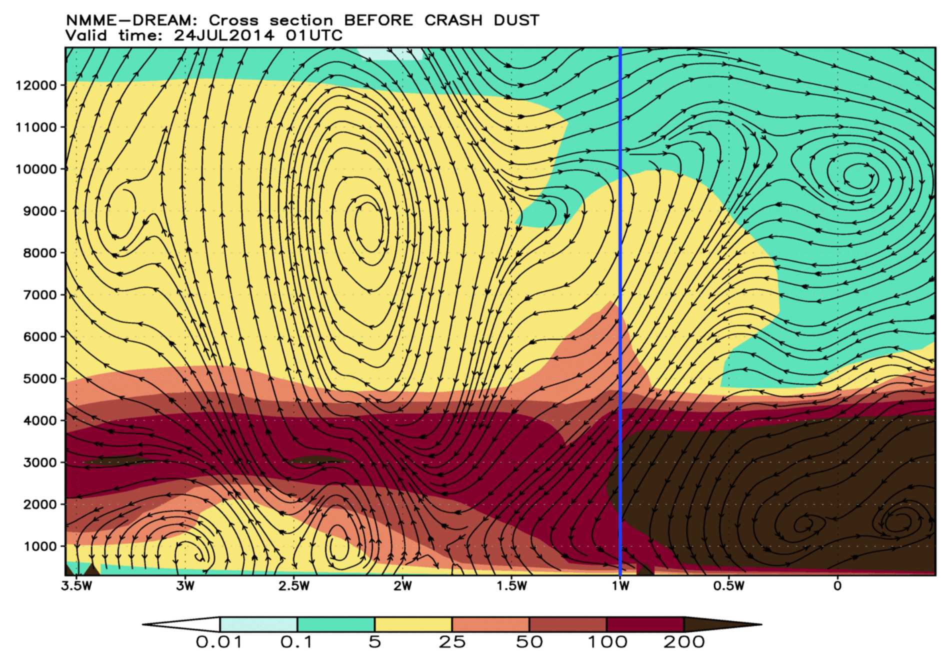
The presence of a storm cell close to the aeroplane's flight path, as well as the absence of activation of the engine anti-ice systems (see 1.16.4) at the time the phenomenon occurred, makes more likely an obstruction of the P_{t2} pressure sensors on the right engine, then on the left engine, resulting 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.

AIR ALGERIE AH5017

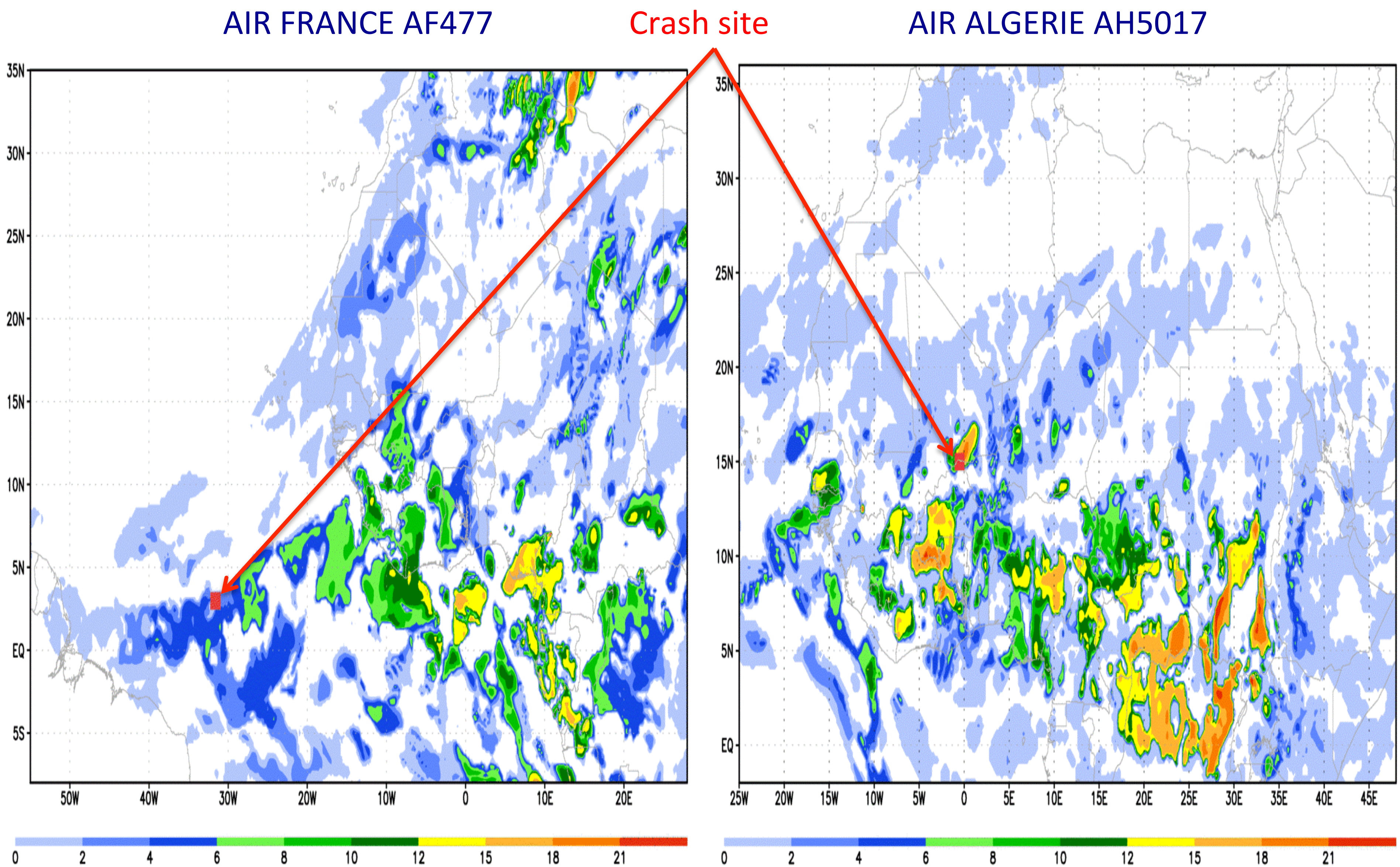
Satellite picture of the storm - cloud top temperature







Vertically integrated log10 IN

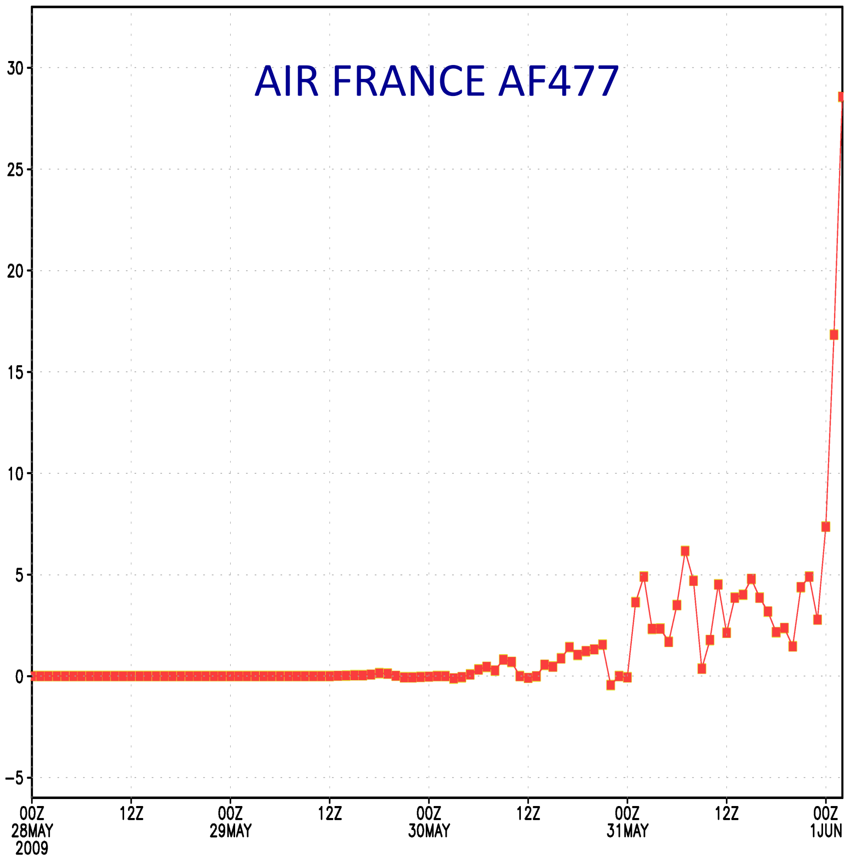


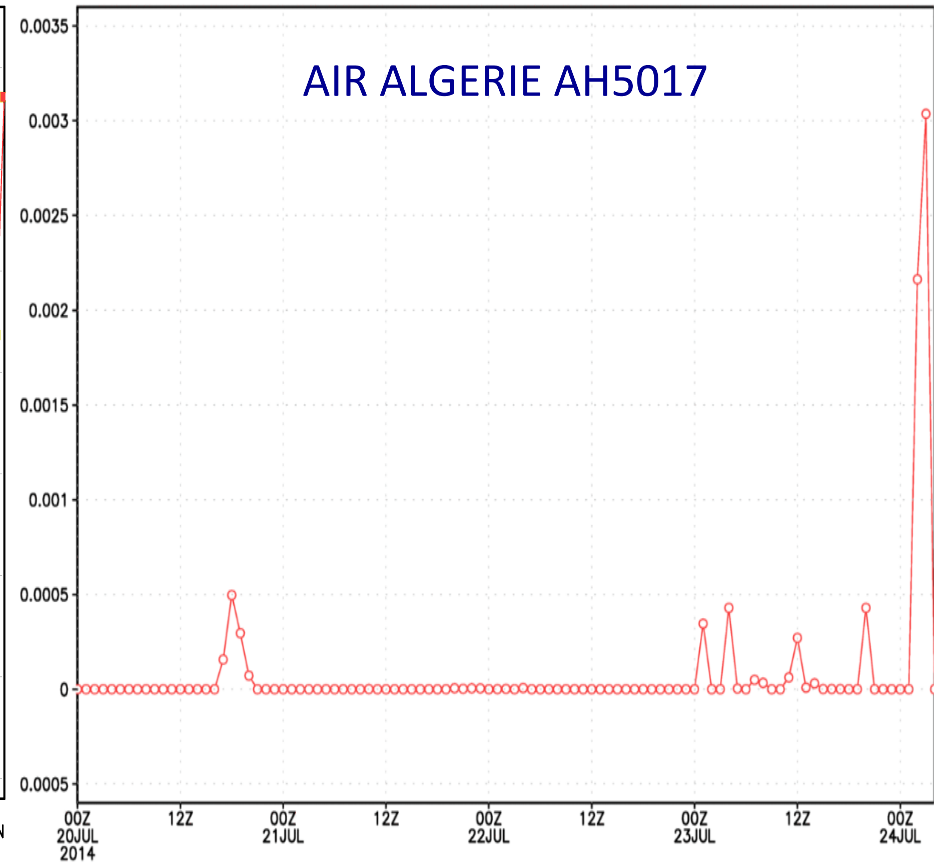
ICING INDEX

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

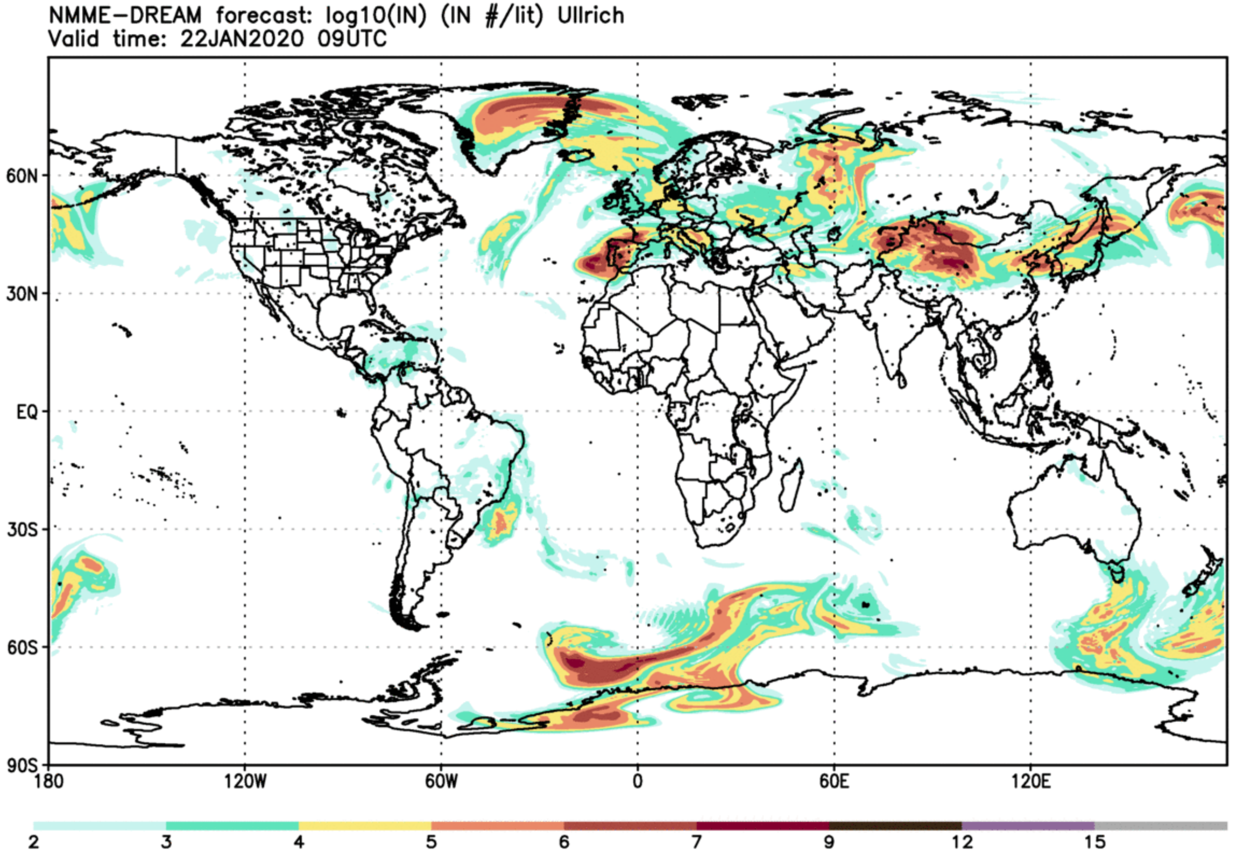
IN depends on dust concentration, temperature and relative humidity

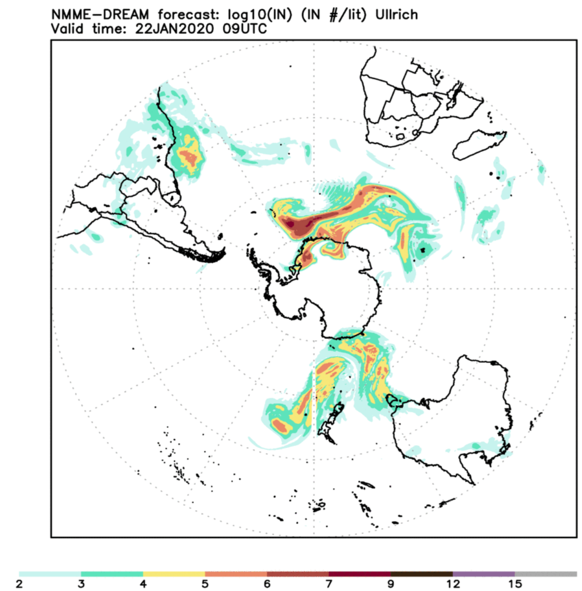
More details you will find soon when we publish the paper

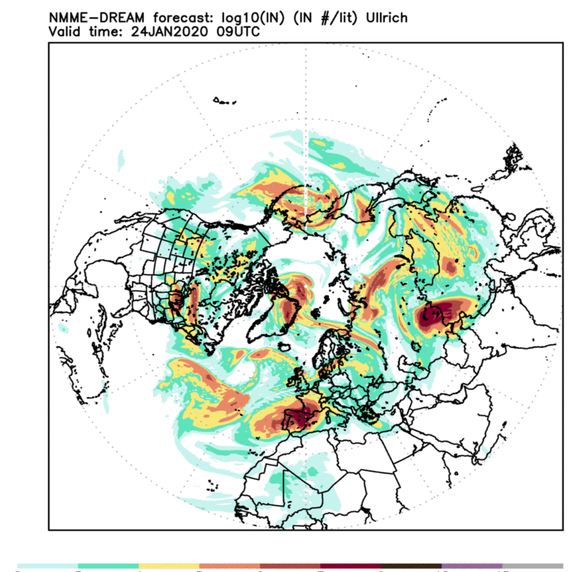




We developed methodology to forecast/predict Icing index globally
Global NMMB-DREAM model Belgrade







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!