Examples of numerical modelling of atmospheric aerosols and hydrological processes

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(with contributions of B. Cvetkovic and G. Pejanovic)
Republic Hydrometeorological Service of Serbia

EuroCC4SEE Workshop in Belgrade, 21-22 May 2025

Numerical Weather Prediction (NWP) and HPC

NWP one of the largest customers for HPC

Brief history

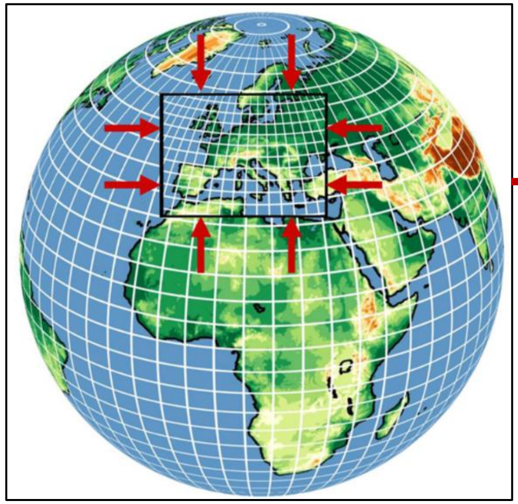
- Richardson 1924
  - Unsuccessful NWP attempt because of the short waves problem
- Charney at al., 1950
  - The Meteorology Project ran its first computerized weather forecast on the ENIAC in 1950.
- Arakawa:
  - Introducing conservation of energy and enstrophy in NWP systems

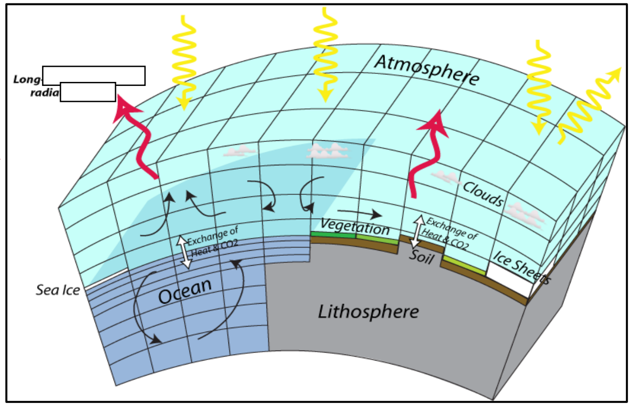
Increase 2X horizontal resolution ➔ computing time increases 8X (for the same number of processors) – Why?

Double the number of vertical levels ➔ **16X more CPU!**

Current ECMWF operational global model resolution ~ 10km

Among the most powerful computers in the world!



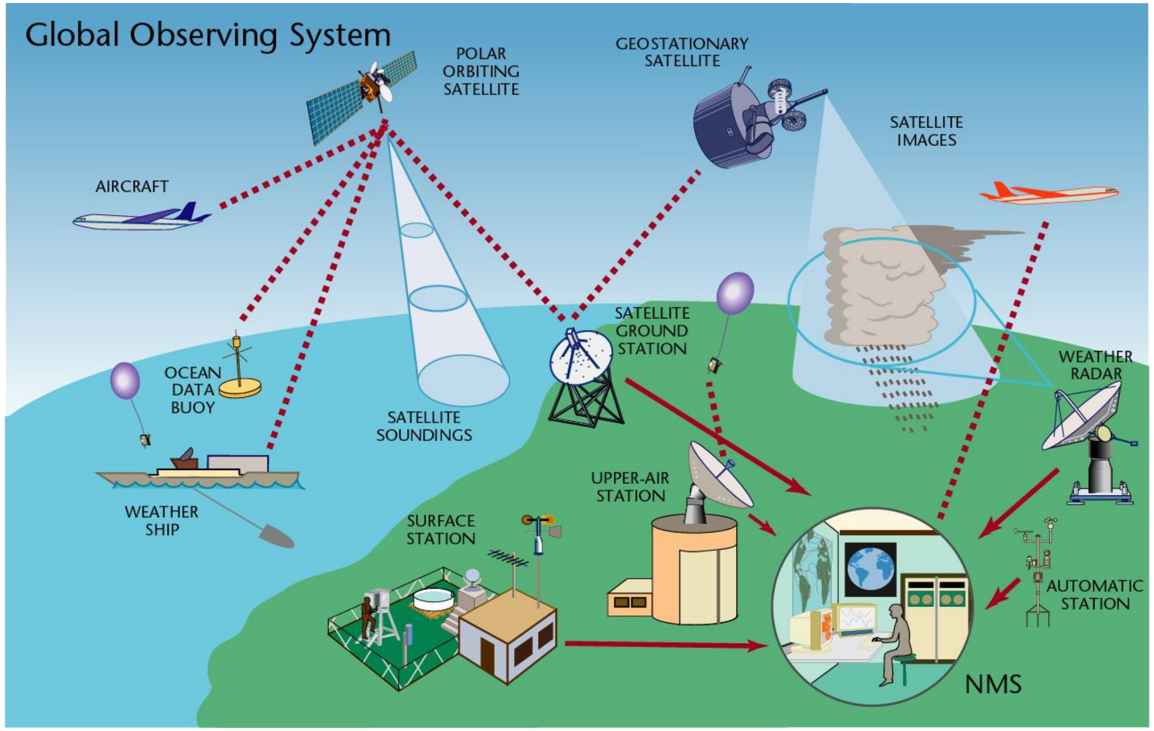


Model resolution – distance between grid points

Initial and boundary conditions – starting point for NWP

World Meteorological Organization
Weather • Climate • Water

World Meteorological Organization
Global Observing System

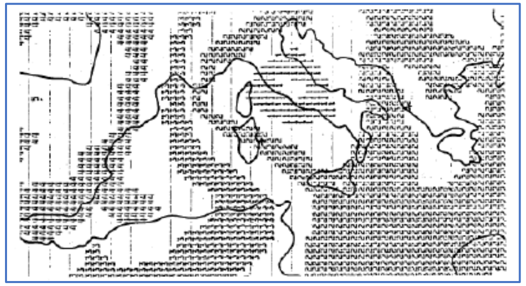


Actual atmosphere, ocean and land conditions

NWP in Serbia

Numerical weather prediction (Belgrade) – first steps in using HPC

- 1970: Arakawa NWP concept brought to Belgrade
- 1975: USA permitted export of IBM 370/135
- 1976: Yugoslav limited-area NWP HIBU model – Alpine cyclogenesis (Z. Janjic, F. Mesinger)
- 199ties- : The model became operational for NWP in USA NOAA



NWP Zebra maps (1979)

[IBM System/370]

MINERAL DUST

WORLD METEOROLOGICAL ORGANIZATION

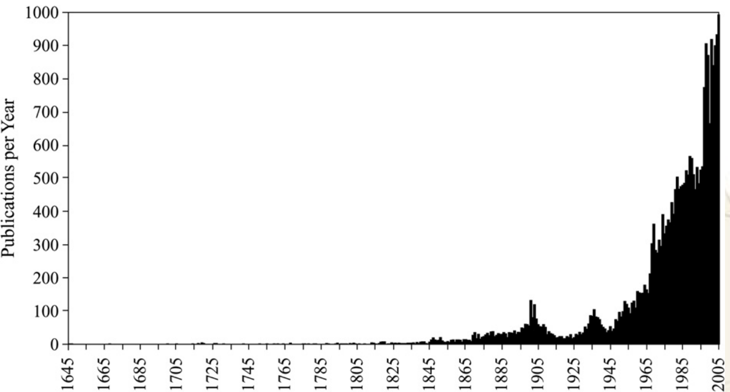
المركز الإقليمي للتحذير من العواصف الغبارية والرملية
Sand and Dust Storm Warning Regional Center

المركز الوطني للأرصاد
National Center for Meteorology

Mineral dust: an international issue

- **WMO SDS-WAS**
- **COST InDust**
- **UN Coalition to Combat Sand and Dust Storms**

dust publications



United Nations

General Assembly

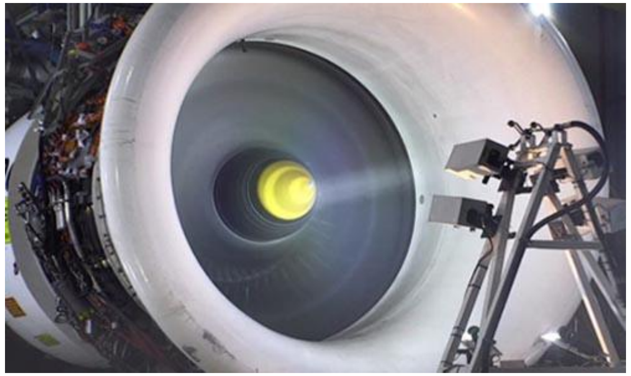
Resolution adopted by the General Assembly on 21 December 2020

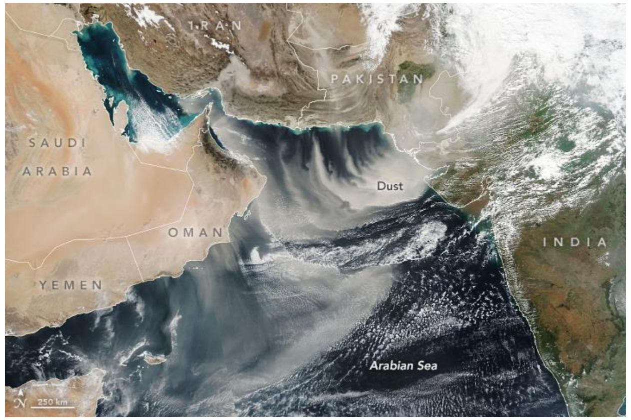
75/222. Combating sand and dust storms

Why Dust? Hazards, benefits…

Impacts

- Aviation
- Health
- Marine Environment
- Climate
- Energy
- Agriculture
- Weather

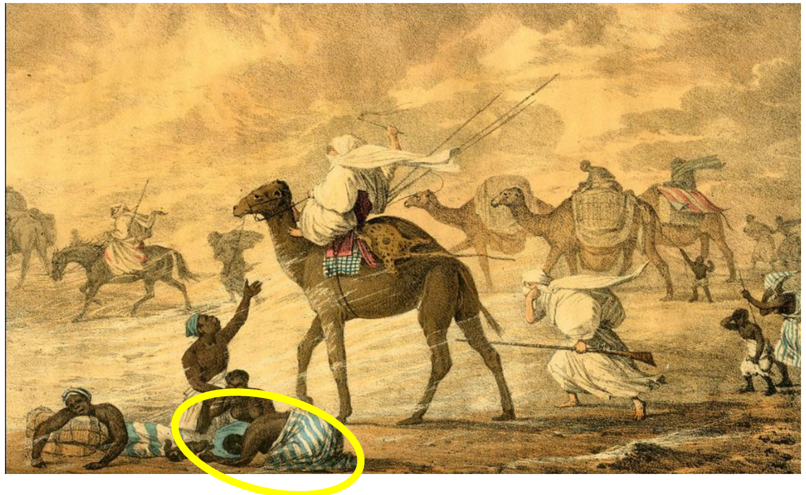




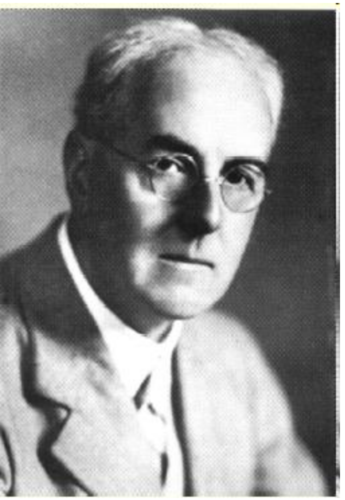
Ancient records on dust

Table 1. The records of dust events during the Three Kingdoms period (57 BC–AD 938) in Korea.				
Year	Month[a]	Kingdoms[b]	Original record[c]	Meaning
174	2	Silla	雨土	Dustfall
379	5	Baekje	雨土竟日	Dustfall for a day long
389	3	Silla	雨土	Dustfall
606	4	Baekje	王都雨土晝暗	The sky of Baekje's capital was darkened like night by dustfall
627	4	Silla	大風雨土過五日	Dust storm lingered over five days
644	11	Goguryeo	平壤雪色赤	Snow tinged with red in Pyongyang, Goguryeo's capital
770	4	Unified Silla	雨土	Dustfall
780	3	Unified Silla	雨土	Dustfall
850	2	Unified Silla	京都雨土	Dust fell in Gyeongju, Silla's capital

The records of dust events in Koraa (57 BC–AD 938)



Painter: George Francis Lyon



DUST MODELLING – first ideas

Richardson's "Forecast Factory“: a pioneering attempt to predict weather

In 1922, **Lewis Fry Richardson** developed the first numerical weather prediction (NWP) system. Richardson's method, based on simplified versions of Bjerknes' "primitive equations" of motion and state (and adding an eighth variable, for **atmospheric dust**) reduced the calculations required to a level where manual solution could be contemplated.

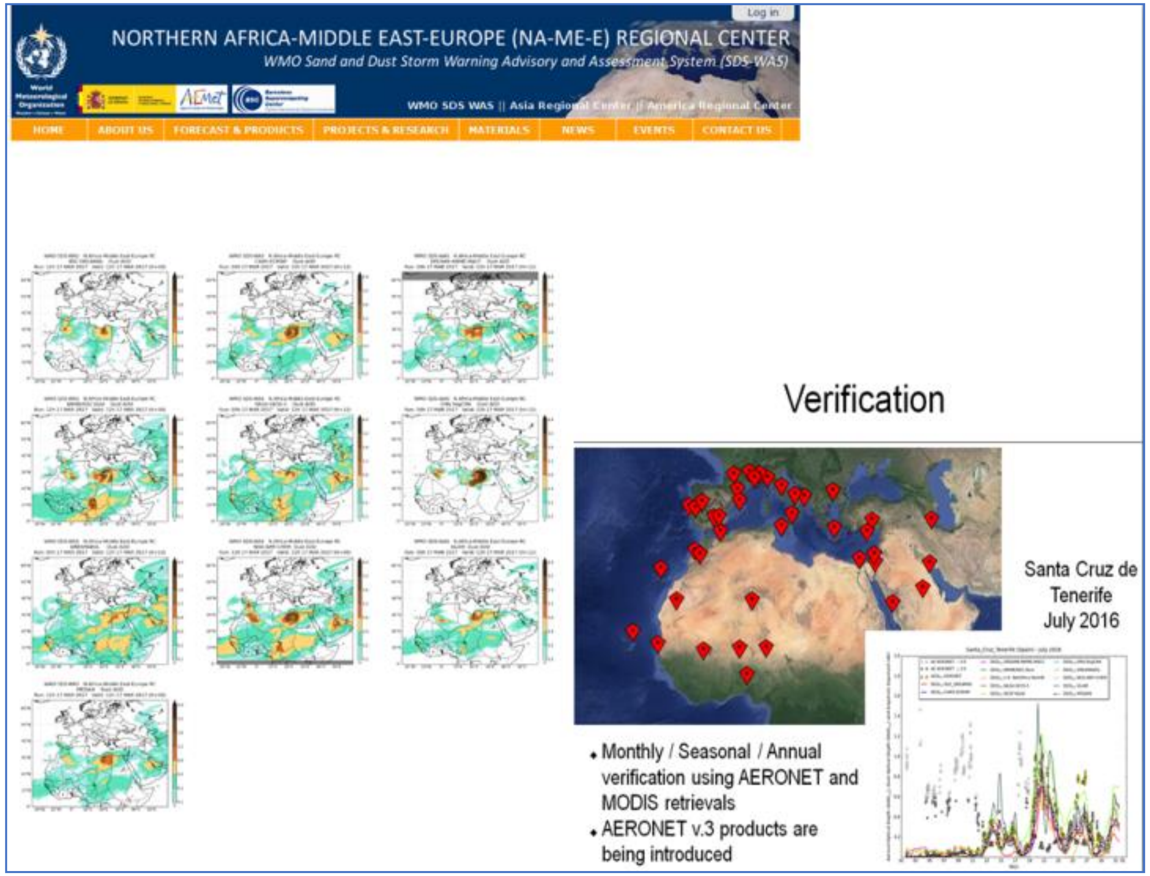
BRIEF HISTORY OF DUST MODELLING

- First dust models, late 1980ties
- online- vs. offline modelling
- First operational online dust model – **DREAM - Dust regional Atmospheric model)** (Nickovic, 1987)

WMO Sand and Dust Storm Warning Advisory and Assessment System SDS-WAS

SDS-WAS

- established 2005
- First such UN project



Mission:

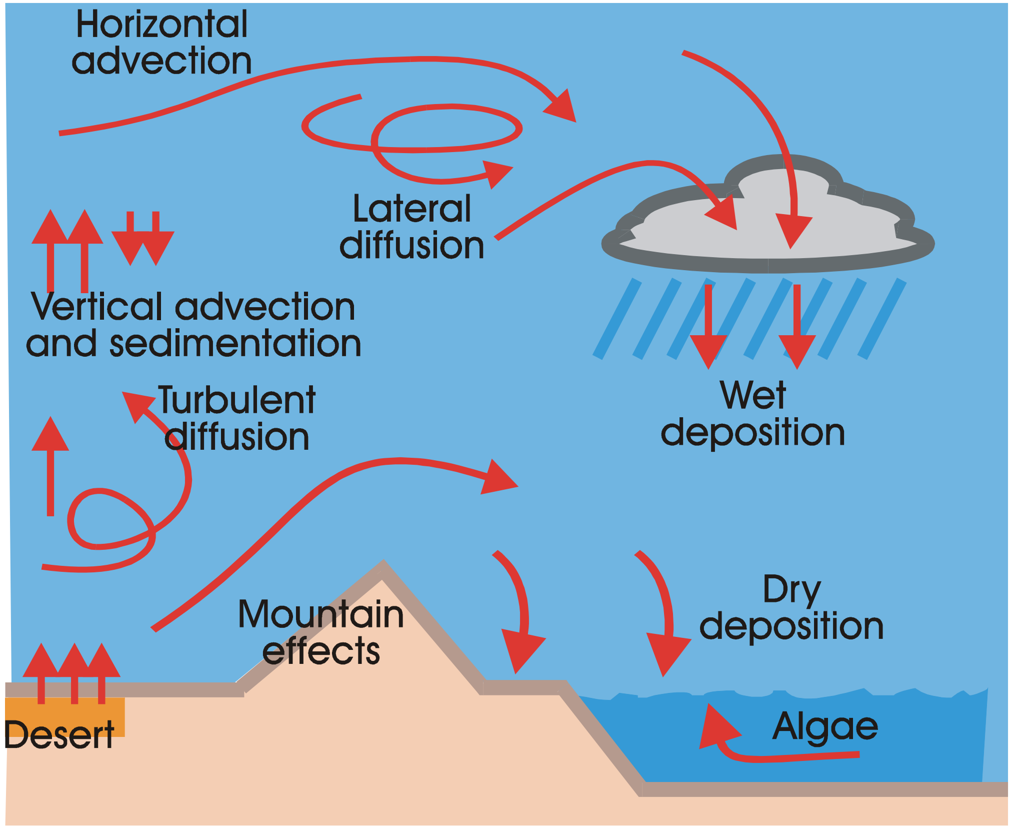
- Global network of SDS research & forecasting centers;
- Delivering SDS forecasts, observations and knowledge

Dust Regional Atmospheric Model (DREAM)

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

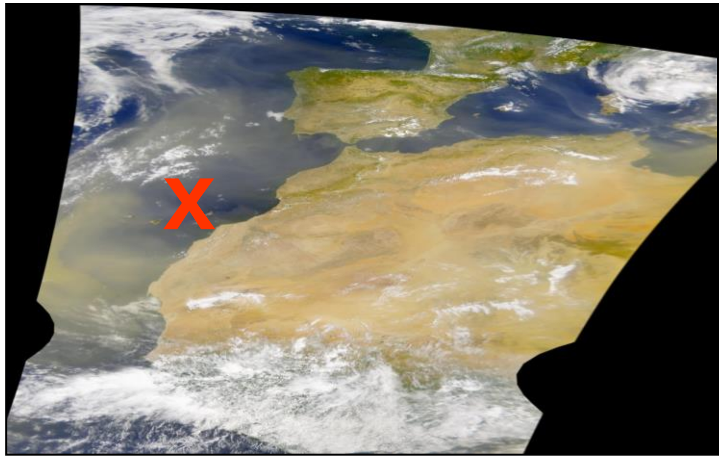
- **Dust component on-line driven by atmospheric models**
- **First prognostic dust model in the community (1994)**
- **Parameterization of all major atmospheric dust phases**
  - **Emission**
  - **Turbulent mixing**
  - **Long-range transport**
  - **Wet/dry deposition**

(*Nickovic et al., 1996*)



DUST AND OCEAN

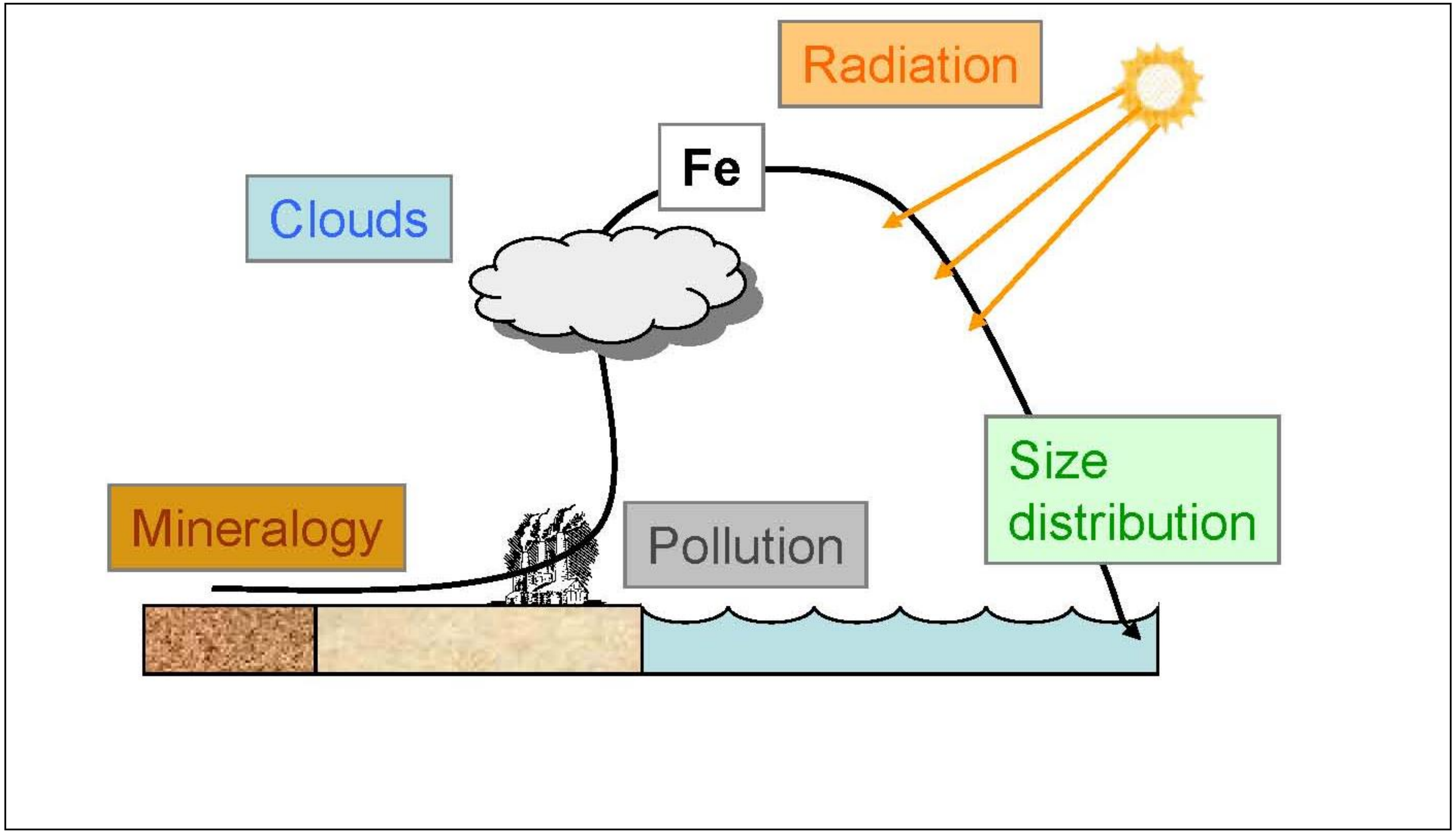
ATMOSPHERIC IRON



Algae Bloom Canary Islands, August 2004

- Dust is a carrier of nutrients such as Fe oxides
- In remote oceans, Fe oxides in dust dominates other inputs
- Soluble iron is an essential micronutrient in marine environments

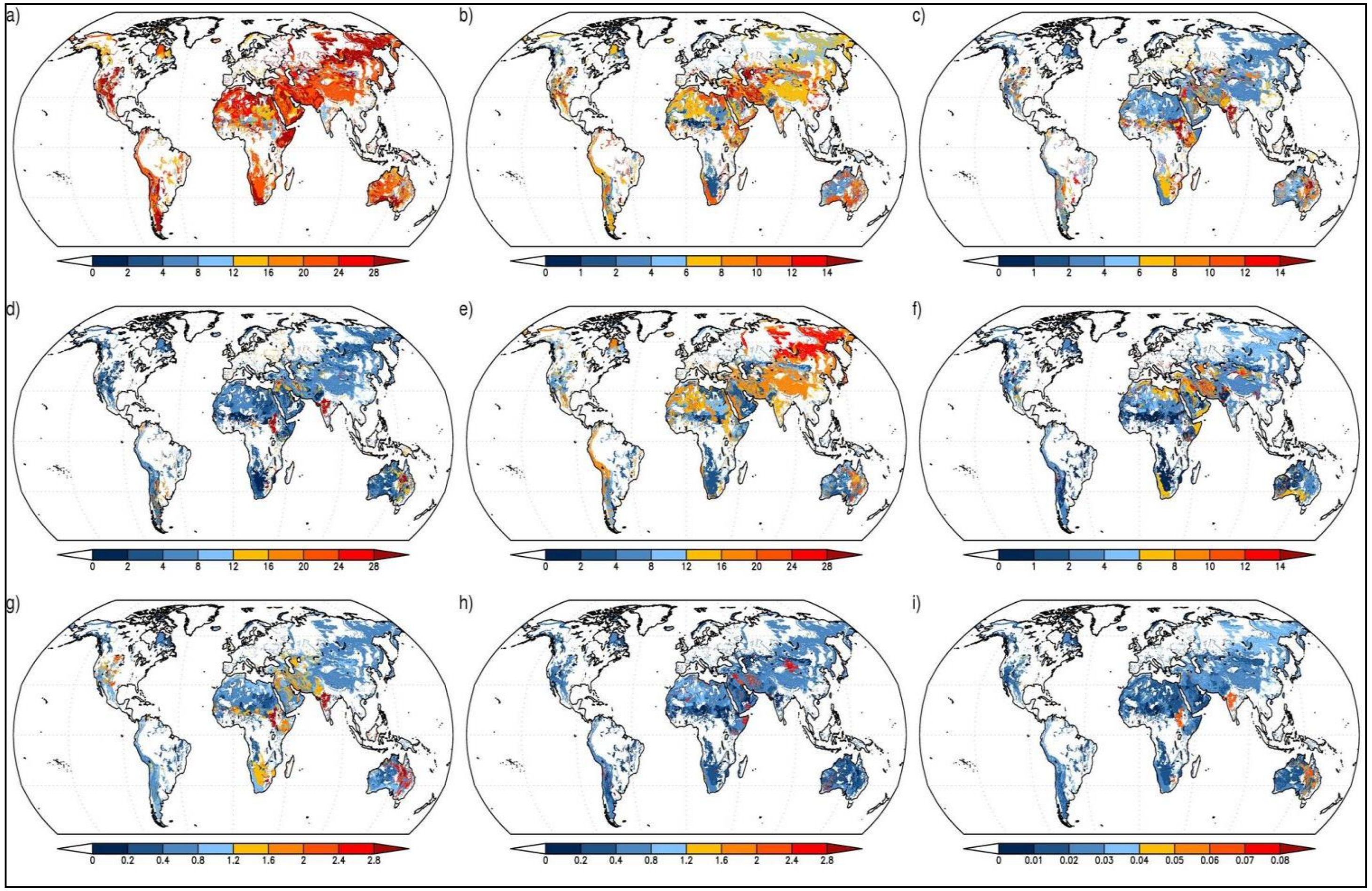
ATMOSPHERIC IRON PROCESSING AND OCEAN PRODUCTIVITY



(*Nickovic et al., 2012*)

Dust mineralogy 1km maps

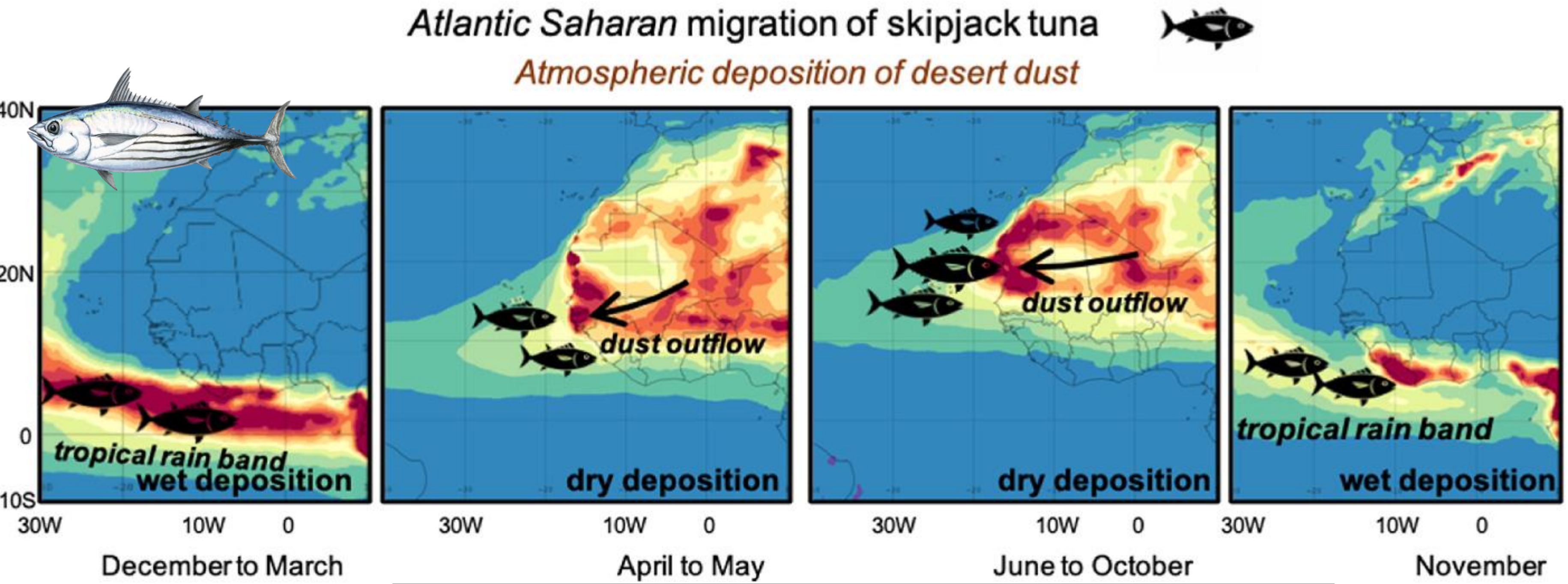
(*Nickovic et al., 2012*)



Global maps of:

a) Quartz, b) Illite, c) Kaolinite, d) Smectite, e) Feldspar, f) Calcite, g) Hematite, h) Gypsum, i) Phosphorus

Skipjack-tuna migrations



African desert dust influences migrations and fisheries of the Atlantic skipjack-tuna

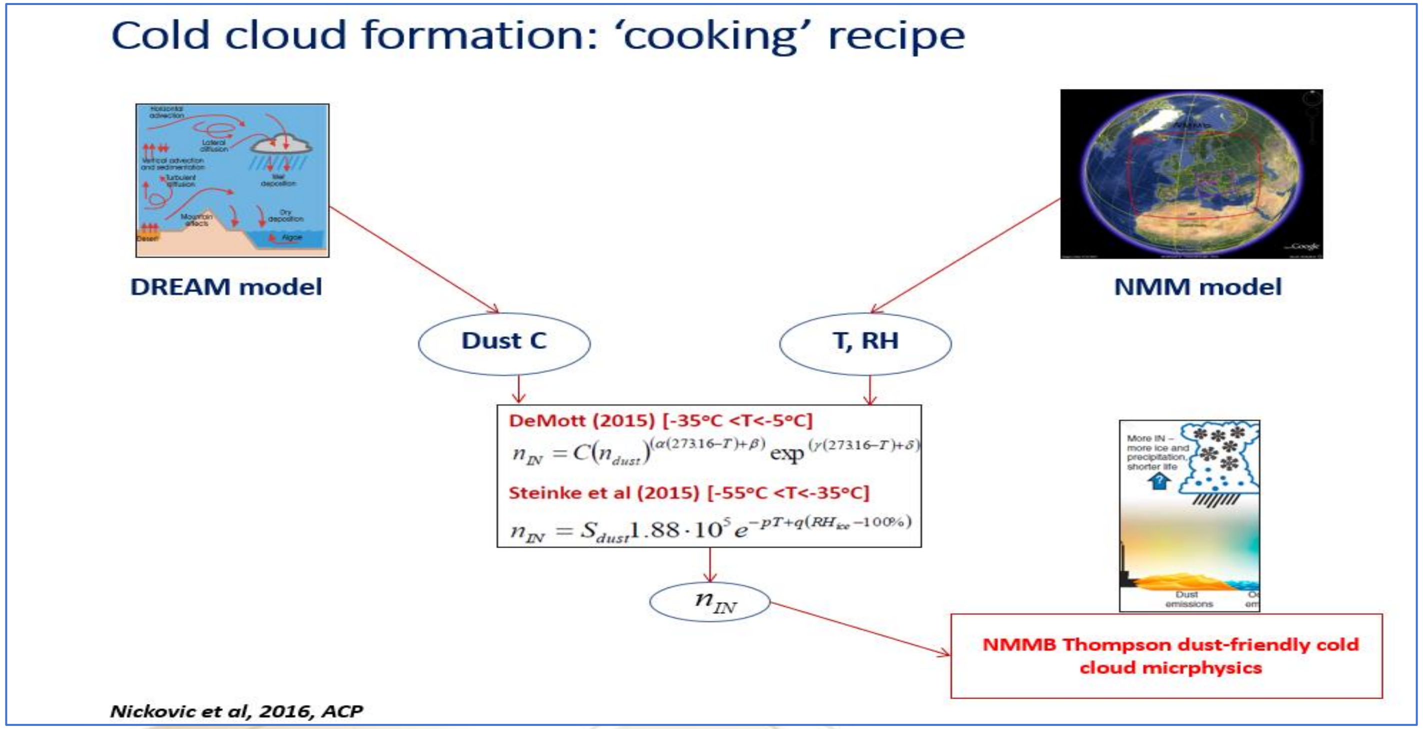
Sergio Rodríguez [a,b,*], Rodrigo Riera [c,d], Alain Fonteneau [e], Silvia Alonso-Pérez [f,g], Jessica López-Darias [a,h]

DUST AND CLOUDS

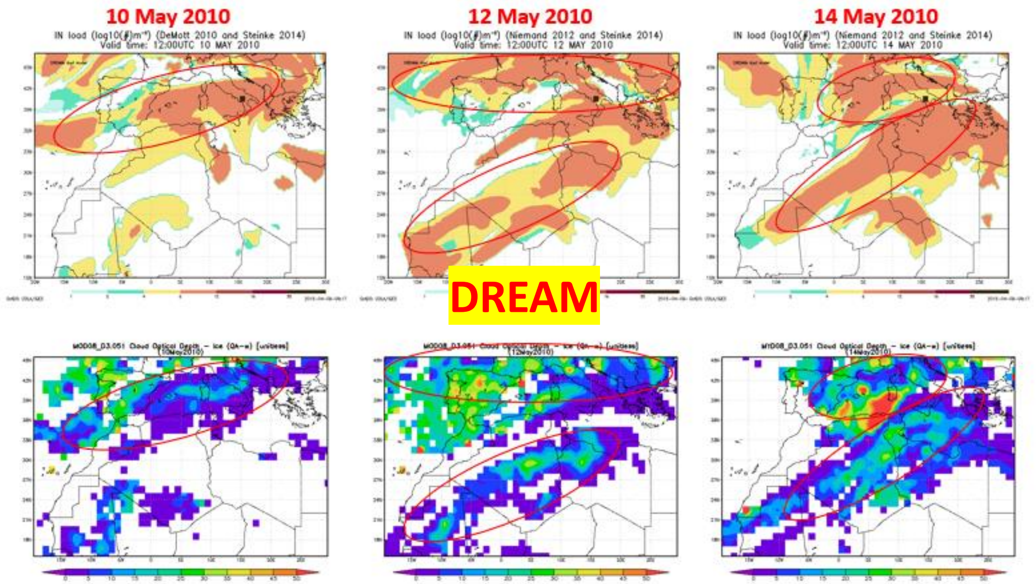
المركز الإقليمي للتحذير من العواصف الغبارية والرملية
Sand and Dust Storm Warning Regional Center
المركز الوطني للأرصاد
National Center for Meteorology

Dust particles: more than 60% than other aerosols generate ice clouds

Modelling dust-generated ice nucleation



Ice nucleation predicted vs, observed



DUST AND AVIATION

Impact to aviation – dust cloud ice

AF477 – June 2009 – 228 deaths
Atlantic, near Brazil

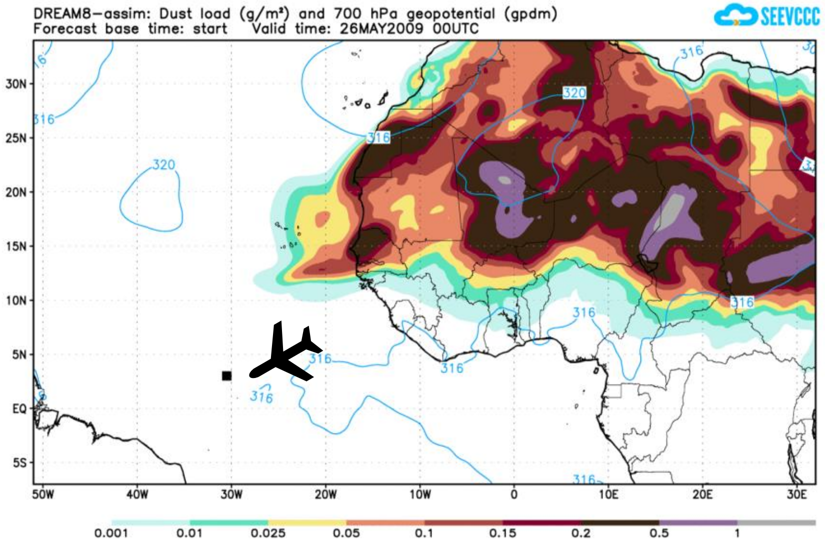
BEA Report
… *Pitot probes* ***obstructed by ice*** → *automatic systems failed by* ***ice crystals formed by dust***

AH5017 – July 2014 – 116 deaths
Mali

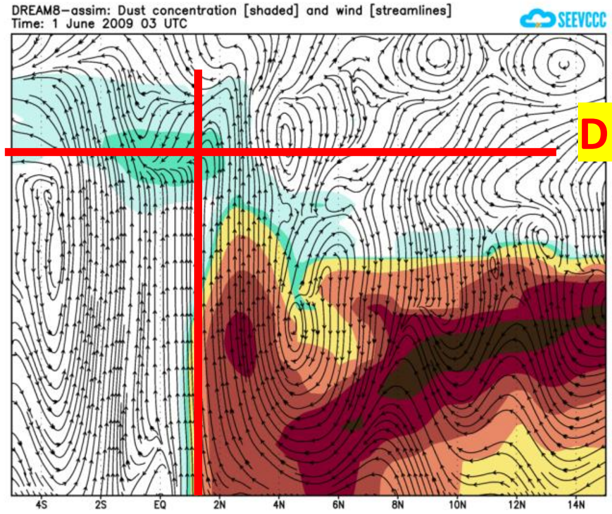
BEA Report
ice crystals caused by dust *within the anvil cloud was very likely cause for catasthophe…*

Both accidents related to presence of dust and consequent icing

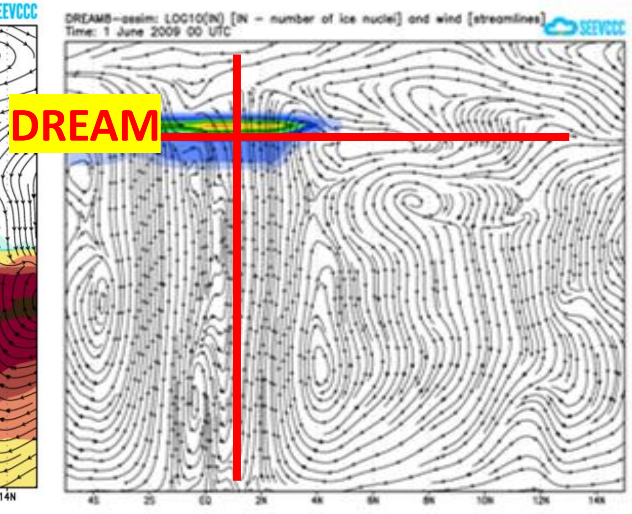
AF477 dust prediction



AF477 dust prediction



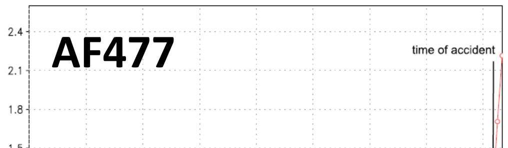
AF477 IN prediction



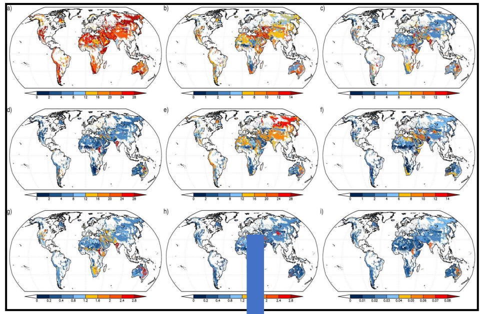
Nickovic et al, 2022, Nature SR

Satellite observation AF477

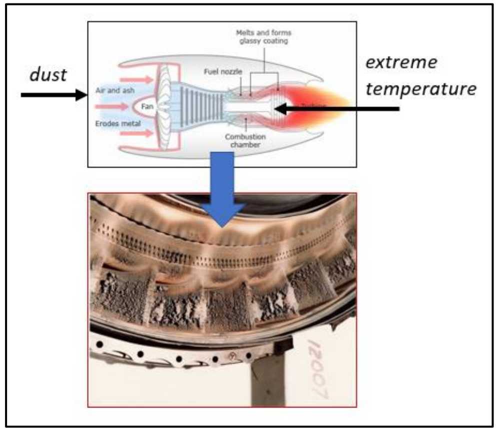
Predicted Dust Icing Index



Melting dust in aircraft turbines



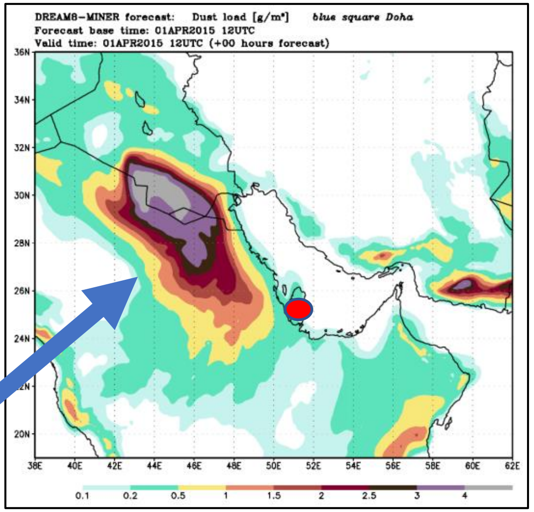
Melting
- **starts at approx. 2500 C deg**
- **depends on the dust minerals mixture**
- **DREAM used to predict dust melting**



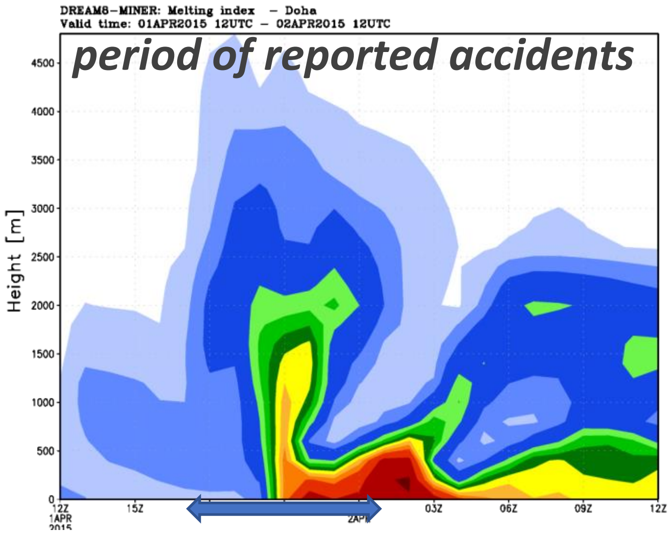
Doha April 2015 case

❖ Flight operations badly affected
❖ Dust melted in several aircrafts' turbines
❖ Economic loss – 3 mil USD in one day

Predicted Doha dust storm



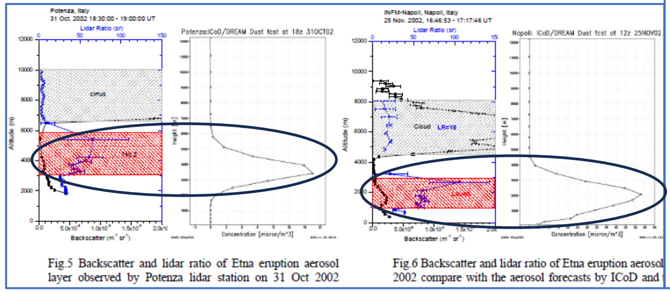
Predicted melting index (Doha)

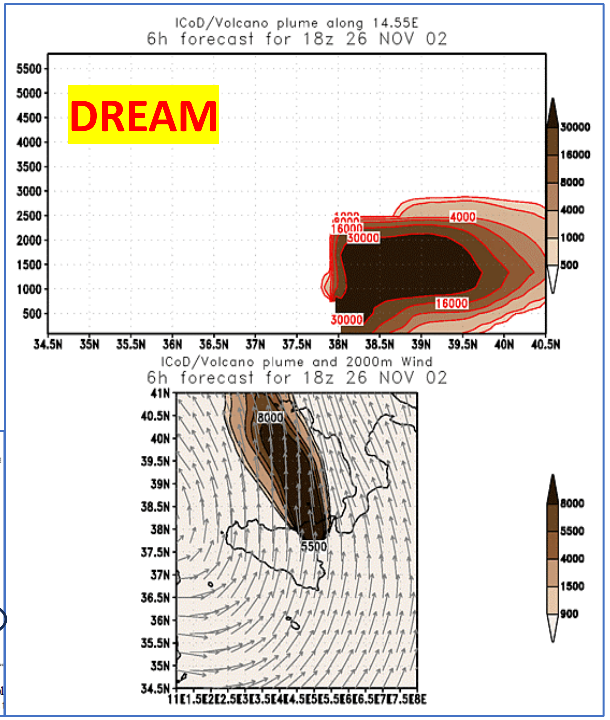


Nickovic & Cvetkovic, 2019

VOLCANIC ASH

Etna eruption 2002

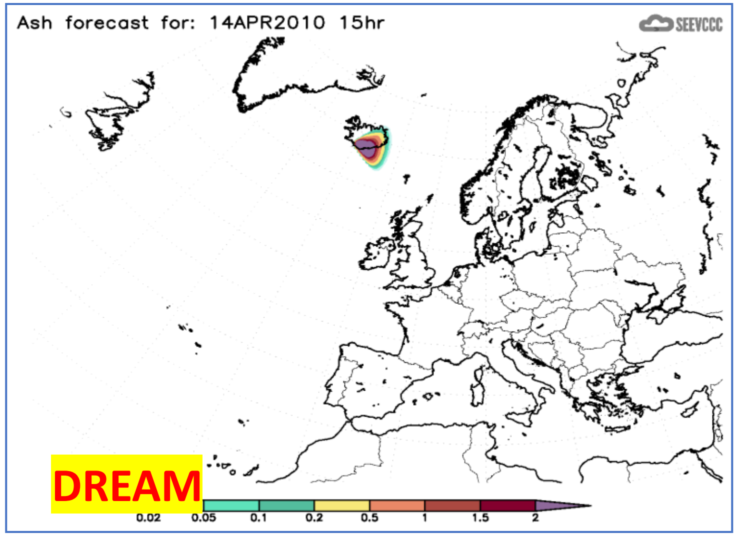




Volcanic dust characterization by EARLINET during Etna's eruptions in 2001–2002

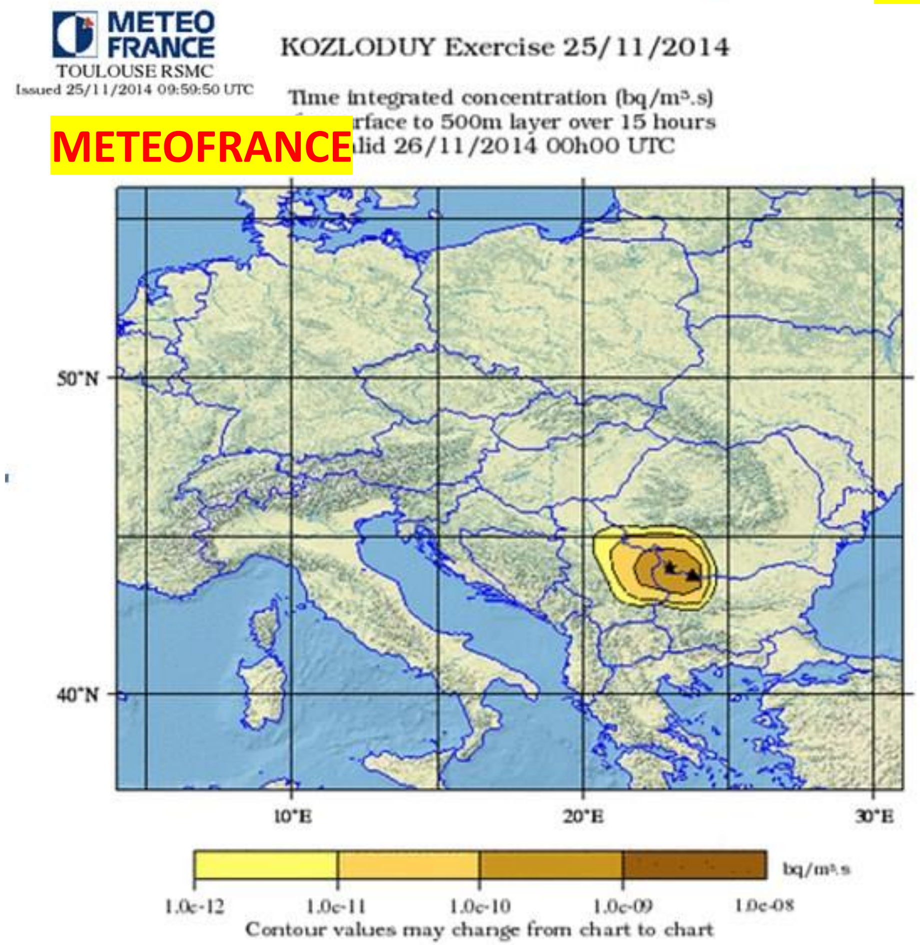
X. Wang[a,b,*], A. Boselli[c], L. D'Avino[a], G. Pisani[a], N. Spinelli[a], A. Amodeo[c], A. Chaikovsky[d], M. Wiegner[e], S. Nickovic[f,1], A. Papayannis[g], M.R. Perrone[h], V. Rizi[i], L. Sauvage[j], A. Stohl[k]

Iceland eruption 2010

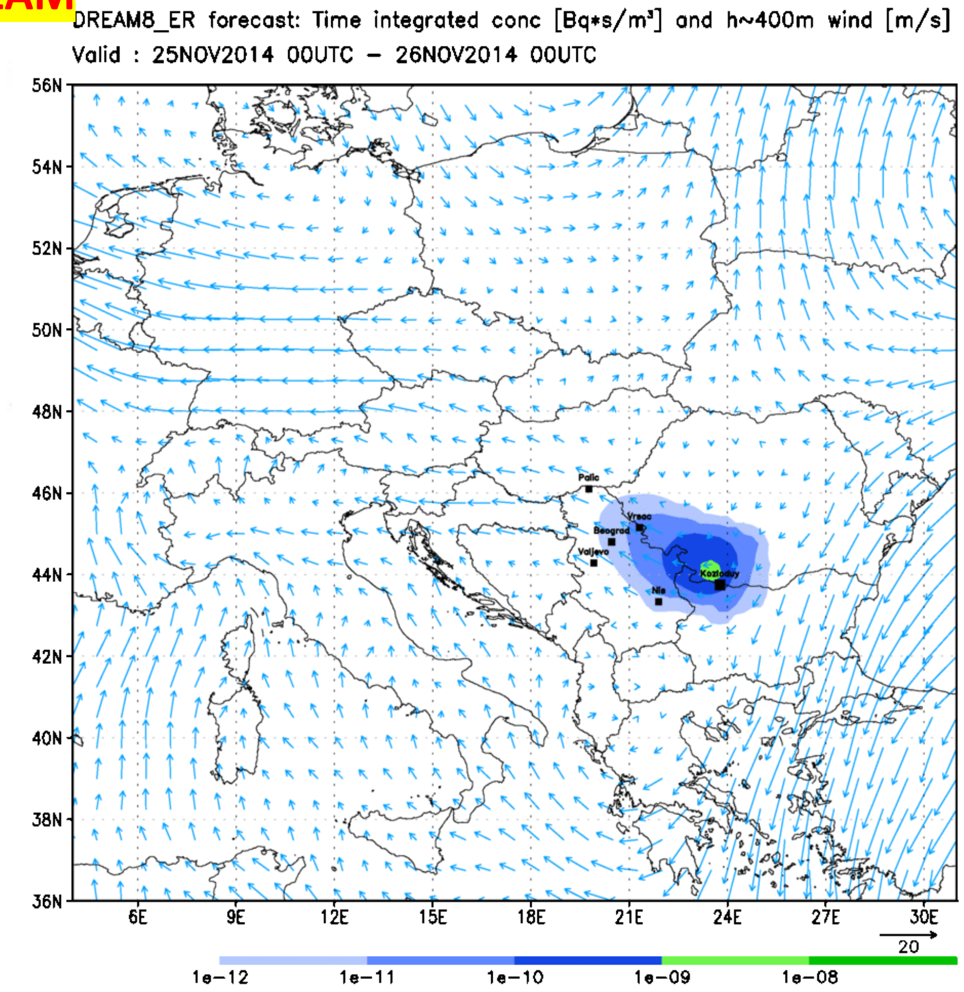


NUCLEAR ACCIDENT AEROSOL

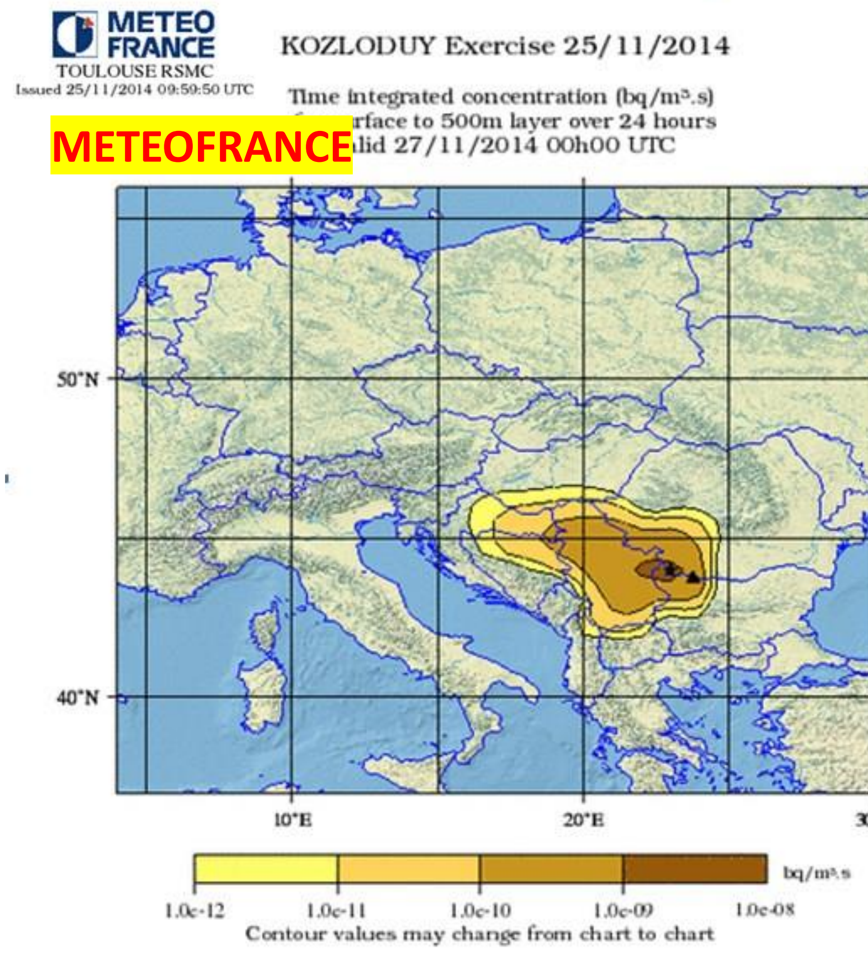
Kozloduj nuclear power station (Bulgaria) . concentration
Synthetic experiment 25-26 Nov 2014 proposed by
International Atomic Energy Agency (IAEA)



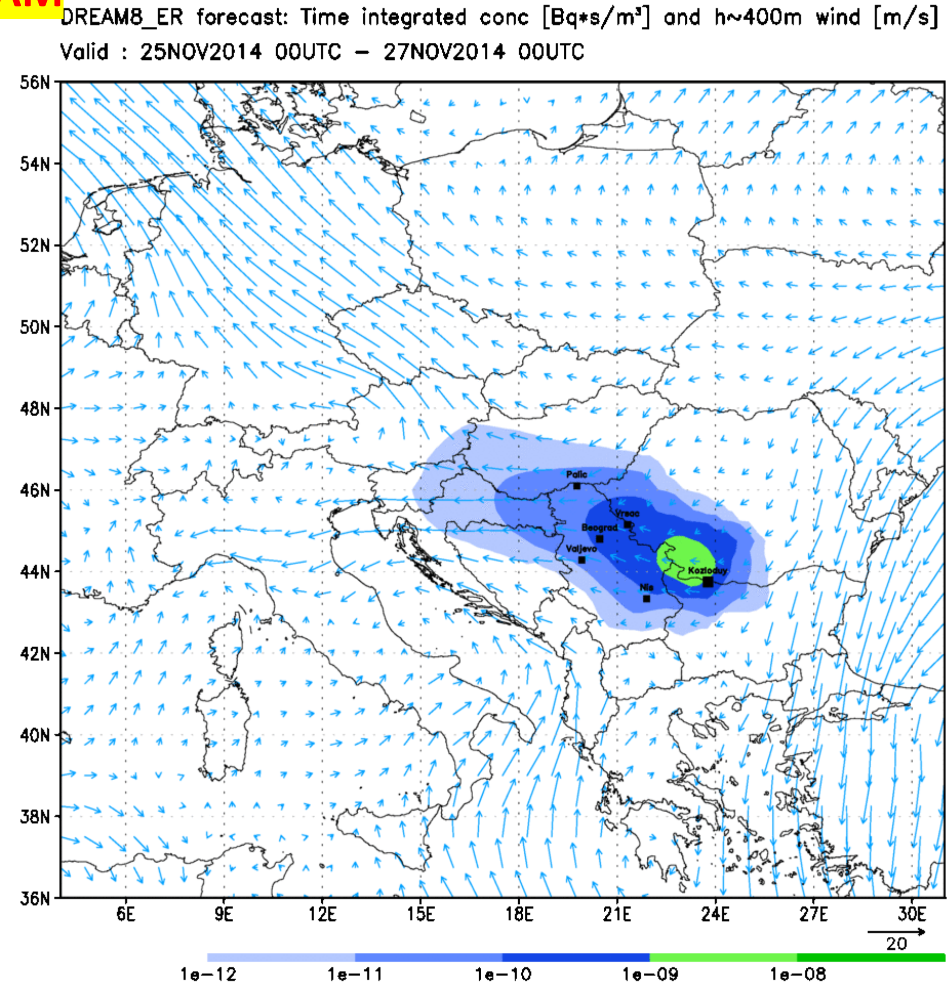
DREAM



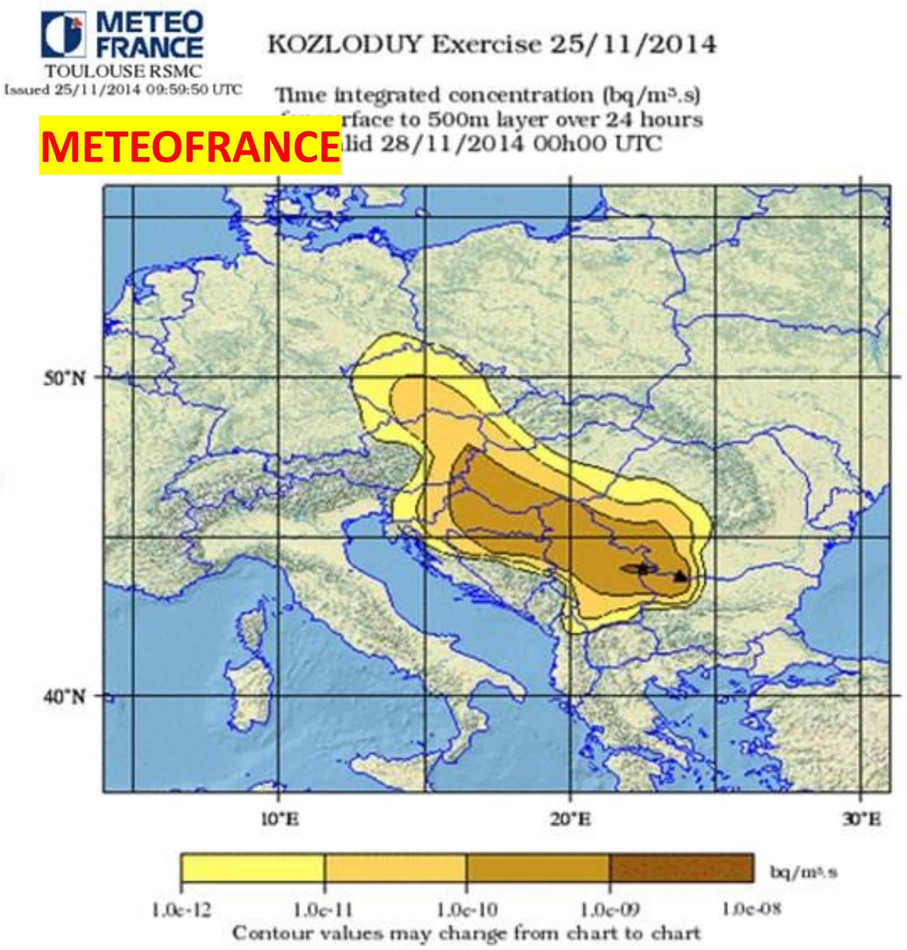
METEOFRANCE



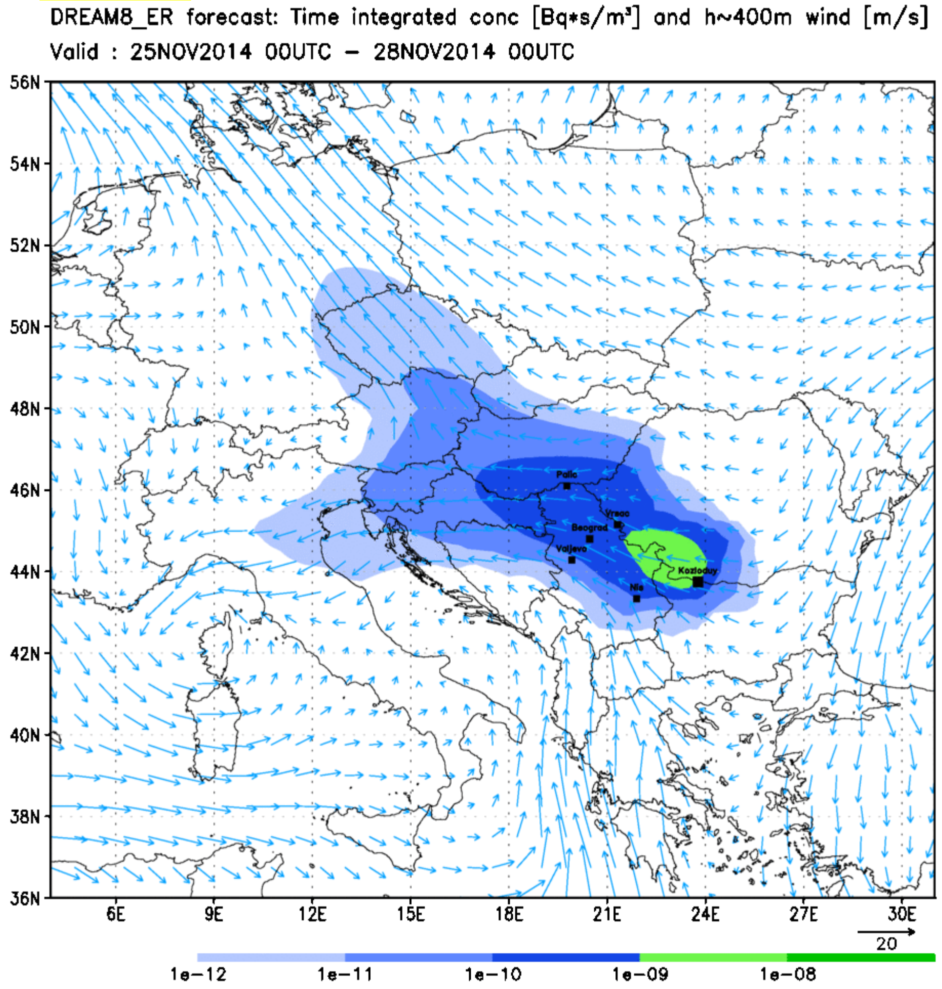
DREAM



METEOFRANCE



DREAM

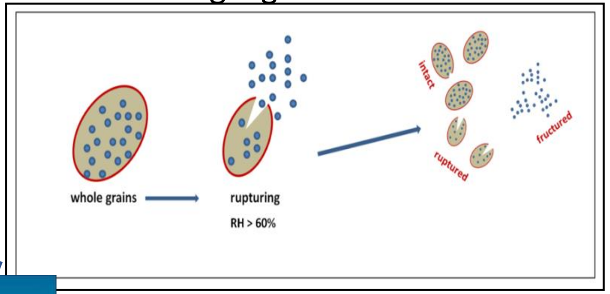


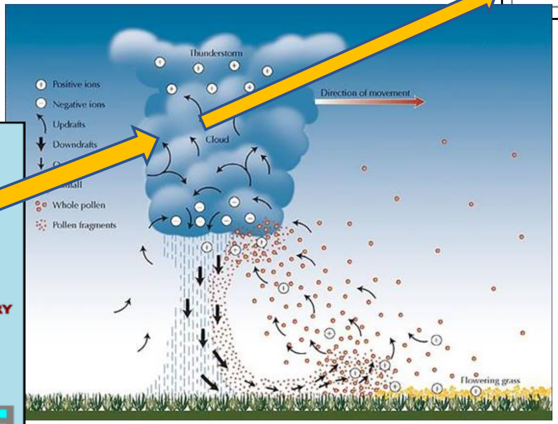
POLLEN

Sub-pollen fragments and thunderstorm asthma – DREAM-POLL

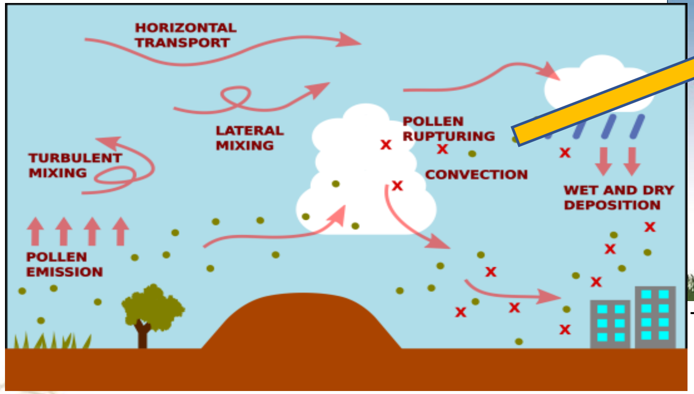
- Sub-pollen particles (SSPs) – intacts broken by thunderstorm forces
  - Electric force
  - High moisture osmotic force
  - Mechanic wind force
- SSPs supposed to be the major cause of Thunderstorm Asthma events
- **SSPs added in DREAM-POLL**

From a single grain → >700 SPPs





Taylor & Jonsson (2004) conceptual TA model

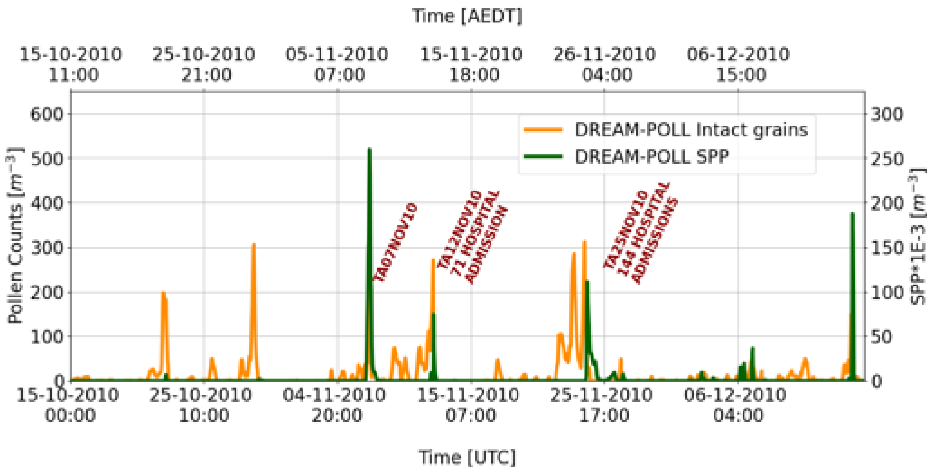


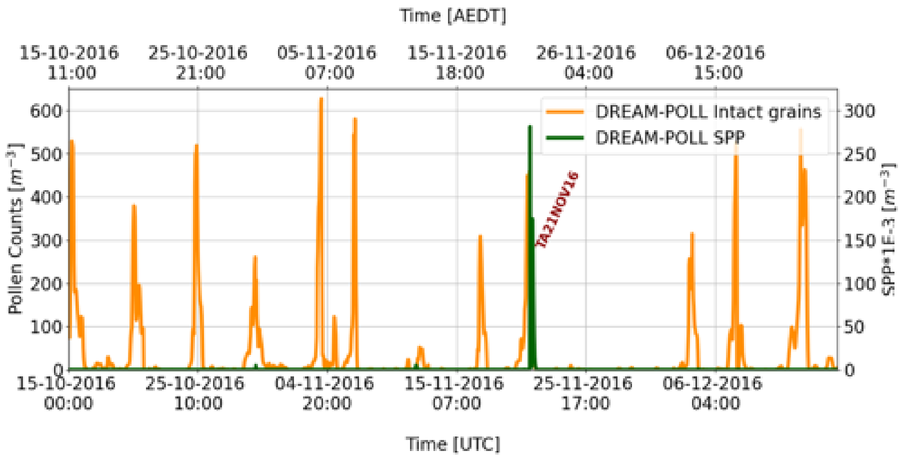
Melbourne pollen thunderstorm asthma (TA) events

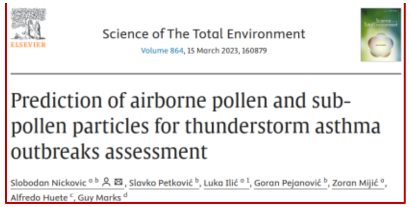
- Rare events
- false alarms to the public if only whole grains predicted
- DREAM-POLL designed and available for operational public warnings
- Pollen seasons 2010 and 2016 caused 4 extreme medical TA events
  - All cases successfully predicted by DREAM-POLL

Results

DREAM-POLL






ELSEVIER

Science of The Total Environment
Volume 864, 15 March 2023, 160879

Prediction of airborne pollen and sub-pollen particles for thunderstorm asthma outbreaks assessment

Slobodan Nickovic [a, b], Slavko Petković [b], Luka Ilić [a, 1], Goran Pejanović [b], Zoran Mijić [a], Alfredo Huete [c], Guy Marks [d]

HYDROLOGY

HYPROM governing equations:

refference

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\left[\frac{\partial h}{\partial x}+S_{fx}-S_{0x}\right]=0$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+g\left[\frac{\partial h}{\partial y}+S_{fy}-S_{0y}\right]=0$$

$$\frac{\partial h}{\partial t}+\frac{\partial (hu)}{\partial x}+\frac{\partial (hv)}{\partial y}+\dot{H}=0$$

○ h - points

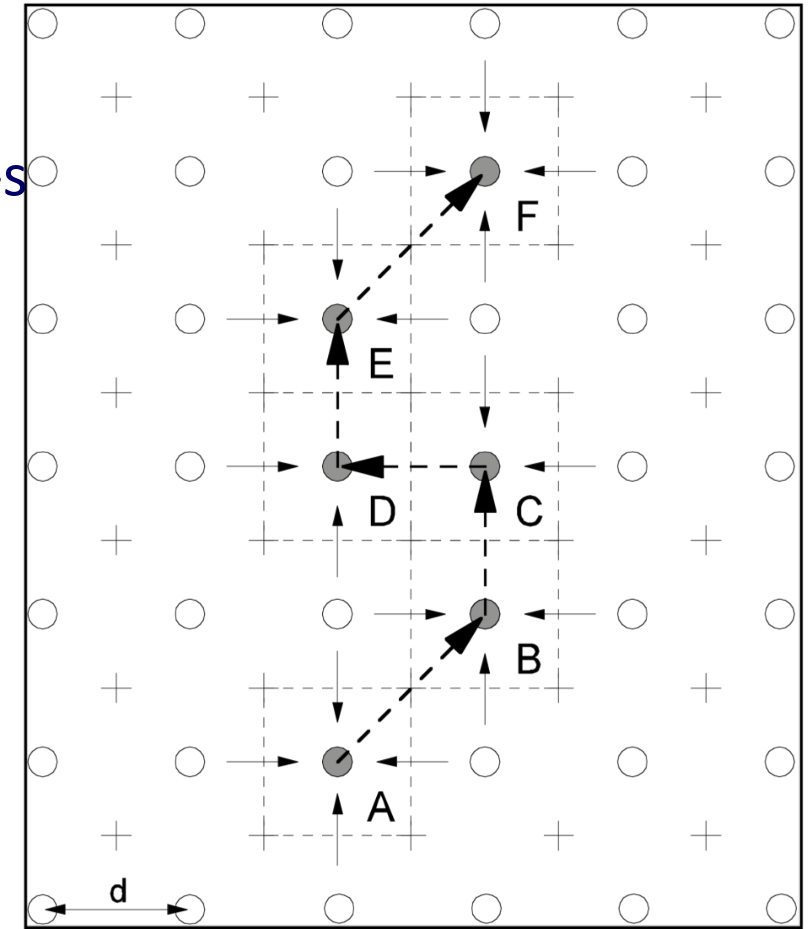
✦ u,v -points

A-B-C-D-E-F river points

river routing

Novel components in HYPROM

- NO approximation in the governing eq-s
- numerically stabile numerics
- new numerical technique for preventing grid decoupling noise
- suitable for scales ranging from local (flash floods) to climate (large rivers, e.g. Danube)



Possible instability in most hydro models due to vanishing water heights

Friction slope term

$$S_{fs} = \frac{n^2\sqrt{u^2+v^2}}{\boxed{h^{4/3}}}U$$

Potential source of model instability when $h \to 0$

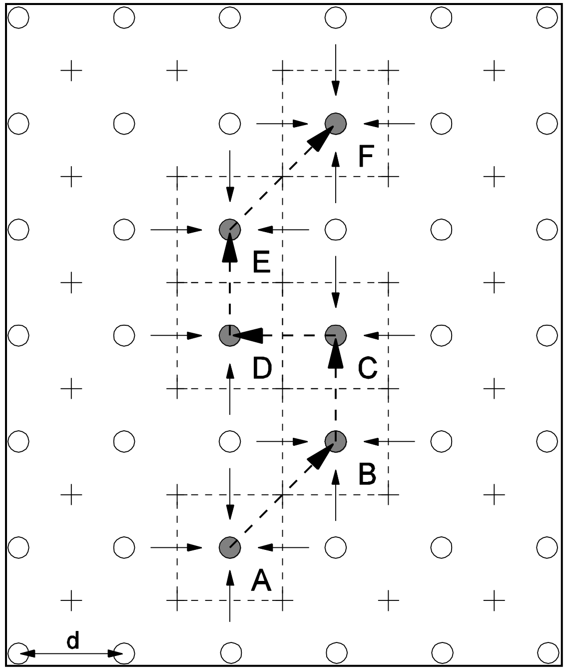
HYPROM solves it by physically correct approach

River routing

$$\frac{\partial U}{\partial t}+U\delta_s\overline{U}^{s}+g\delta_s\left(R+h_s\right)+\frac{n^2\left|U\right|}{\overline{R^{4/3}}^{s}}U=0$$

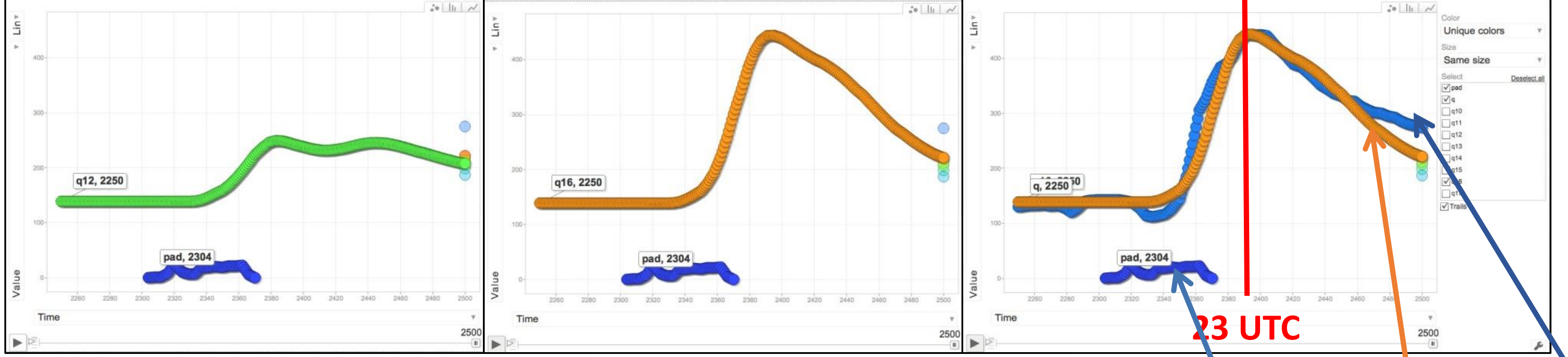
$$\frac{\partial R}{\partial t}+\delta_s\left(\overline{R}^{s}U\right)+\dot{R}=0$$

s – river direction



River path:
A-B-C-D-E-F

- River – a water collector from surrounding points
- Same numerics as for non-river points



12UTC 14UTC 16UTC

S. Morava River flash flood case
23 Jan 2015
disasterous consequences

HYPROM run
Driven by radar precipitation

Predicted correctly the max discharge 7 hours in advance

Observed Q

Predicted Q

Radar P

THANK YOU