# ICAP 2023 : Met Office Update

8th November 2023

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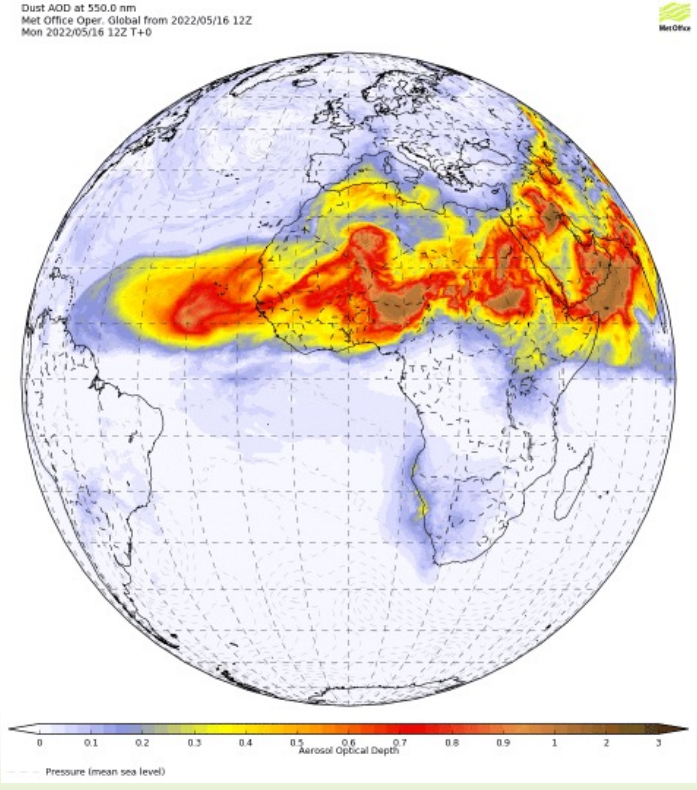
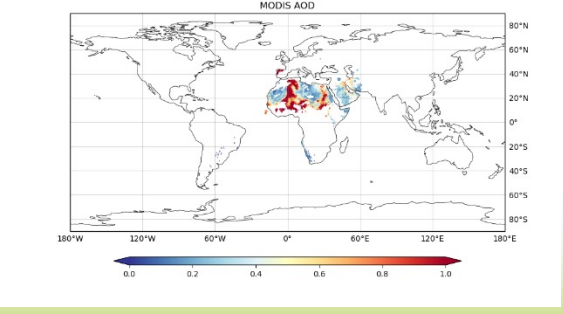
# Met Office Dust Forecasting




A Global to Regional scale system

- Our global model has ~10km resolution
- Wind/temperature/humidity etc. obs assimilated.
- Limited Dust observations assimilated
  - (MODIS satellites)



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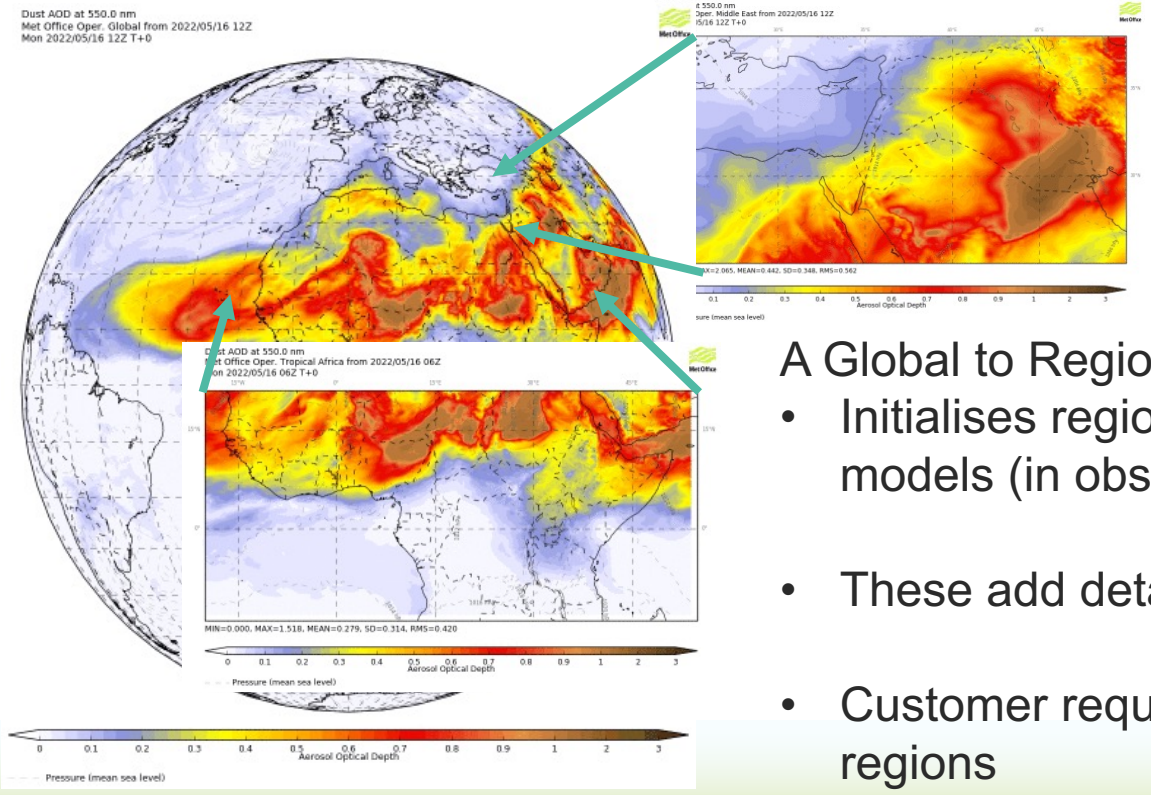
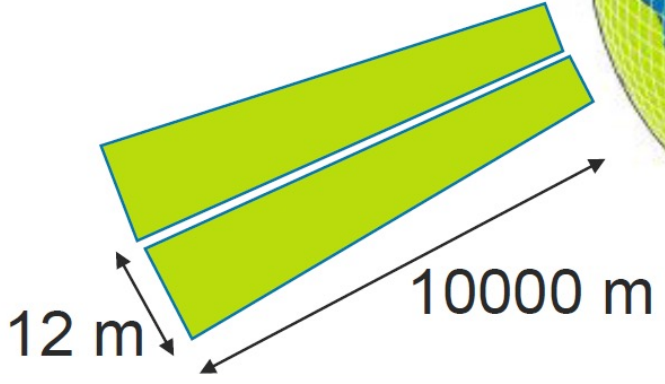


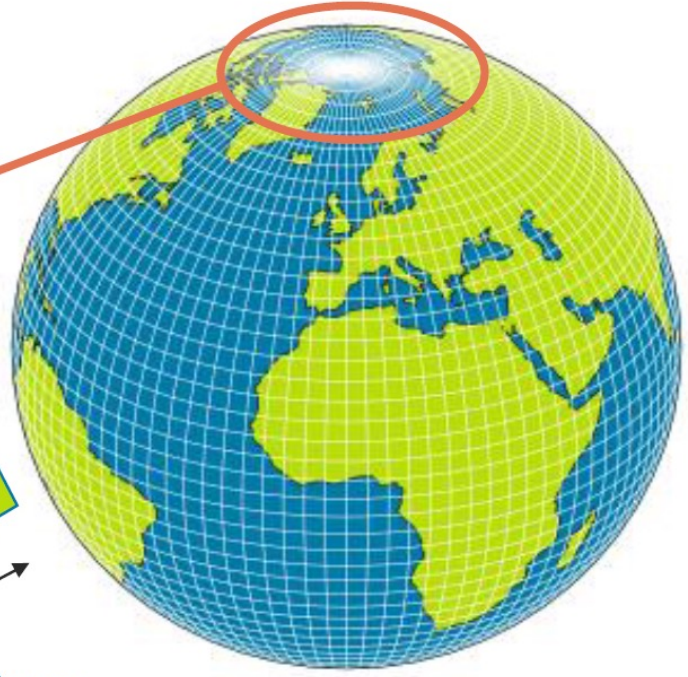

A Global to Regional scale system

- Initialises regional 4km and 1.5km models (in obs sparse regions)
- These add detail to the global start
- Customer requirements: UK and arid regions
  - Aerosols: Dust only, at high res

# 1. Met Office migration to LFRic - motivation

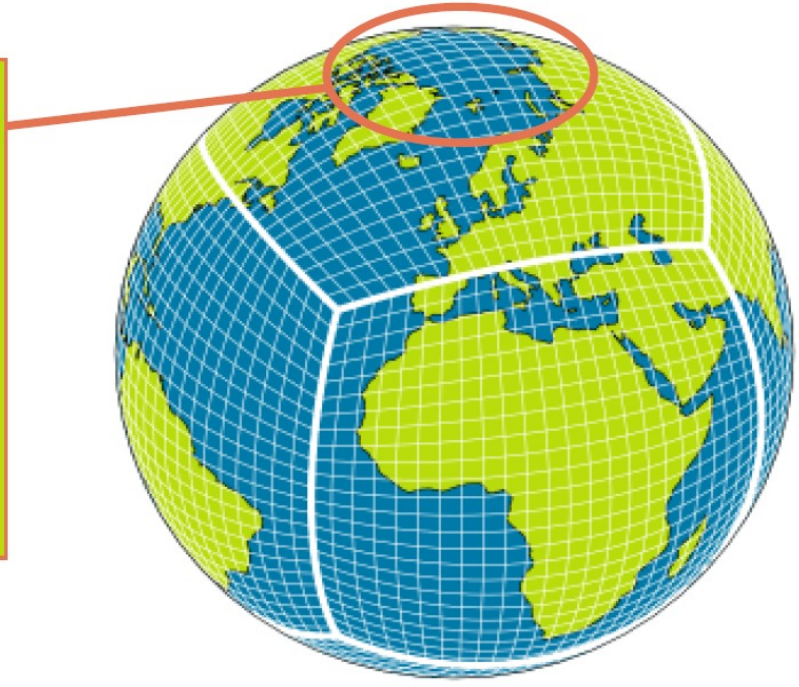
- At 25km resolution, grid spacing near poles = 75m
- At 10km reduces to 12m!



# 1. Met Office migration to LFRic - motivation

- A new grid is essential or any resolution increase
- Migration to a cubed-sphere
- New dynamical core: ‘GungHo’



| | ENDGame | GungHo |
|---|---|---|
| Grid | Lat-Long | Cubed-Sphere |
| Prognostic Variables | ρ, θ, Π, u, v, w | ρ, θ, Π, **u** |
| Prognostics Equations | Advective form | Flux/Advective/Vector Invariant form |
| Spatial Discretisation | 2nd Order FD | Mixed FEM |
| Temporal Discretisation | Iterative Semi-Implicit | Iterative Incremental Semi-Implicit |
| Advection | Semi-Lagrangian | COSMIC (Dimensionally split, Eulerian) |

# ENDGame (UM) vs GungHo

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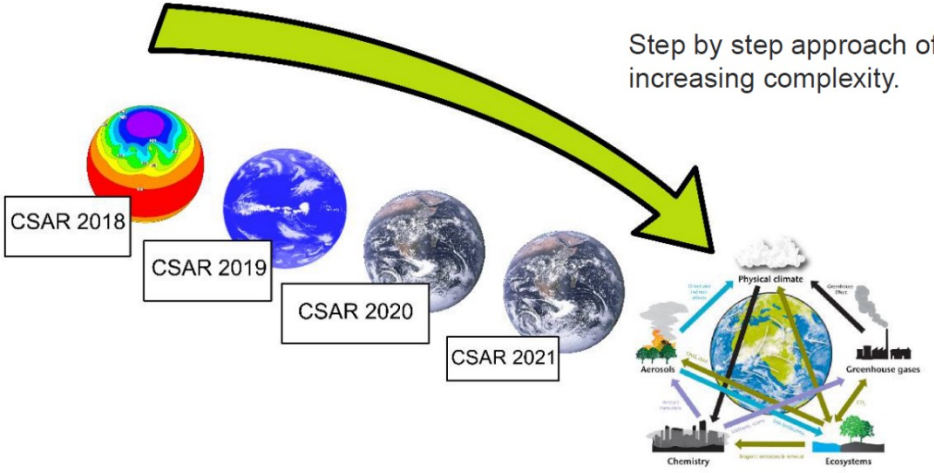
# Met Office Migration to LFRic - Progress

LFRic – a new model



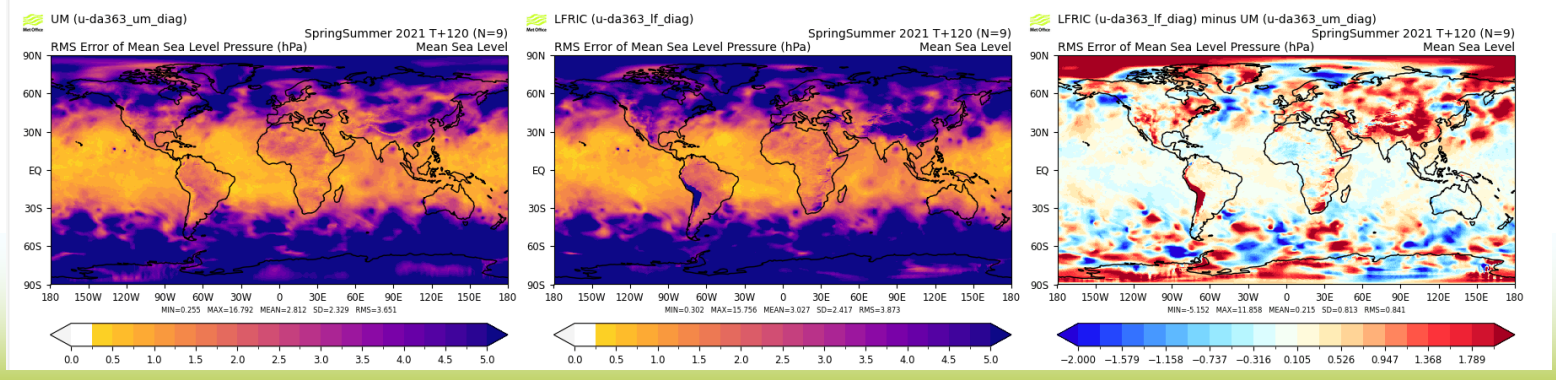

2023:

Near complete set of physics

Testing no longer idealised

Testing in climate model runs
and NWP case studies
Data assimilation trials imminent

Errors are comparable to UM!



# 2. Aerosols within LFRic

- The current UM has 2 aerosol models
  - CLASSIC: single moment, mass based. Operational NWP for dust. Research NRT for other aerosols.
  - GLOMAP MODE: 2 moment Used in climate model config, using full complexity

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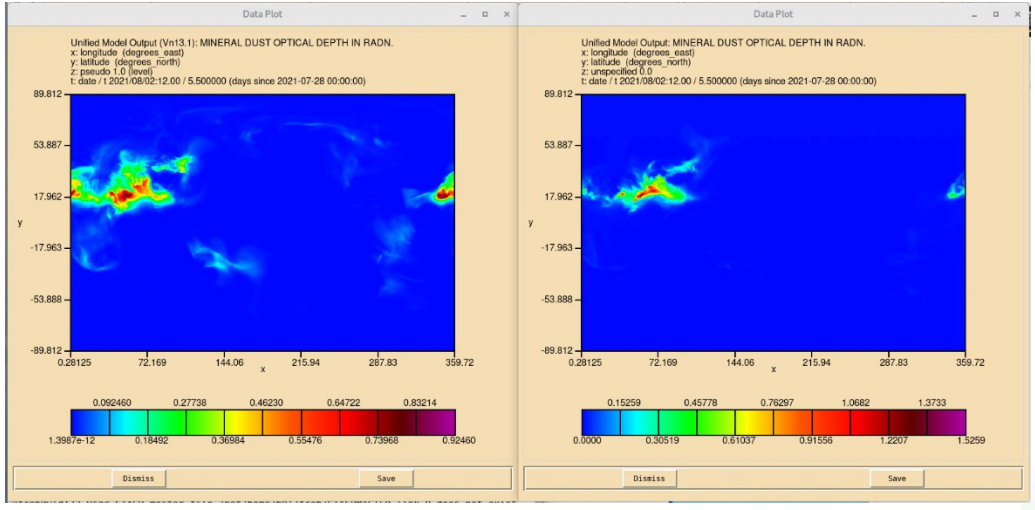
  - CLASSIC: single moment, mass based. Operational NWP for dust. Research NRT for other aerosols.
  - GLOMAP MODE: 2 moment Used in climate model config, using full complexity

For portability – only GLOMAP mode has been ported to LFRic

- Integration into LFRic technically completed
- Climate tests and simple NWP tests show good performance.
- TODO: Include in evaluation software
- Needs tuning!



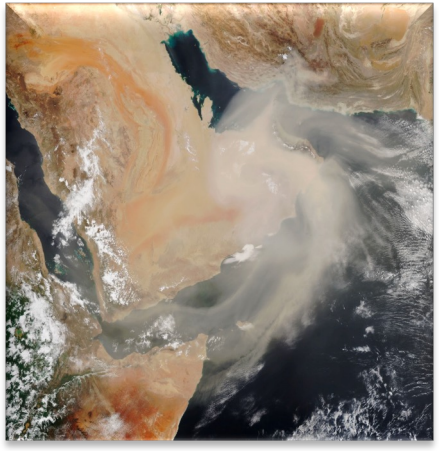

UM Dust AOD

LFRic Dust AOD

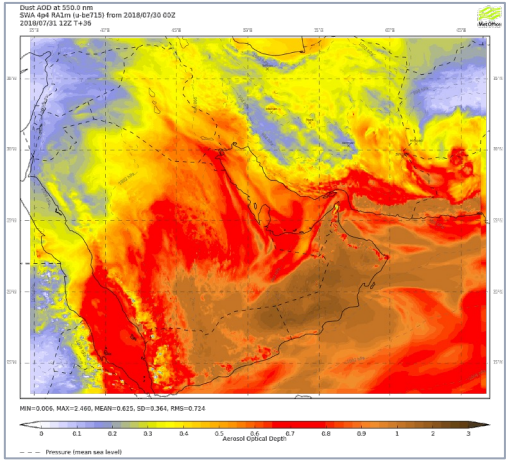
# Dust Capability Gap

ERDC-GEO

- The Unified Model **(UM)** is our core of our Numerical Weather Prediction system.
- **Current UM** dust emission configuration **struggles to simulate individual dust events**
- Especially:
  - Significant dust outbreaks
  - Miss lowest surface visibility events
  - Location/time specific extinction coefficients
- UM dust code **originally designed for** large scale atmospheric patterns and **climate applications**
- Surface specification produces **widespread dust emission** to achieve atmospheric aerosol loads on regional scales



*July 30, 2018 VIIRS true color satellite image of a strong dust storm over the Arabian Peninsula, Arabian Sea, and Persian Gulf.*



*36 hour 4.4 km 550 nm **Aerosol Optical Depth (AOD)** forecast generated via the current UM configuration. Model produces widespread dust with "excessive tails."*

**GOAL: Better represent major high impact dust events in theatre.**

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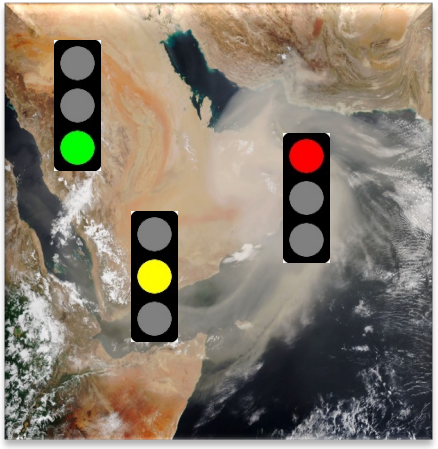

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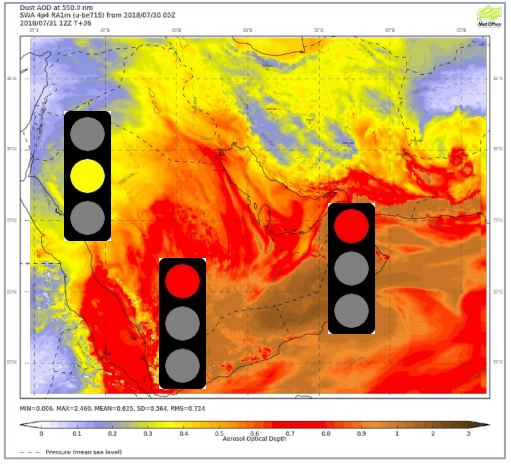

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# How can we fix this?

ERDC-Geo

## ERDC Geomorphic (ERDC-Geo) Surface Erodibility Parameterization

Mathematically **links geomorphic landscape traits (landforms)** to soil erodibility and **dust emission potential**

Incorporates the effects of **material supply** on dust emission into dust models

**Scales dust emission** in the model to account for emission features on all scales

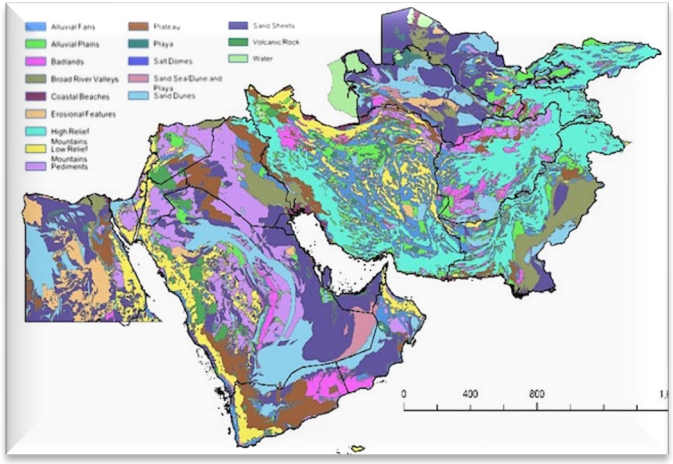
**TEAM**

UK Met Office, UK Ministry of Defence,
US Army Engineer Research and Development Center (ERDC),
US Air Force Life Cycle Management Center (AFLCMC),
US Air Force 557th Weather Wing, US Dept. of Agriculture,
Desert Research Institute, Uni. of California Los Angeles, New Mexico State University

Method is **simple to apply** and **portable** across dust models

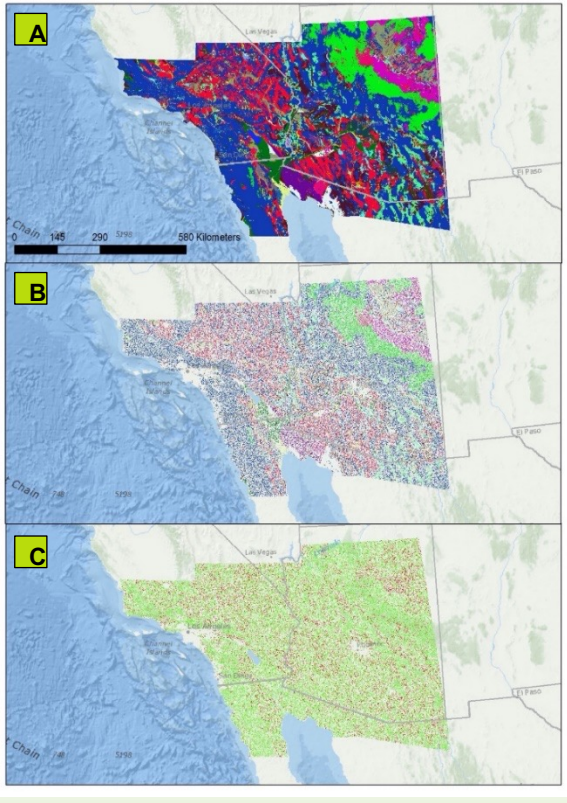
# A Machine learning approach

Extending ERDC-Geo




Previous maps:

- Meticulously hand drawn by trained analysts
- Expensive / time consuming (~ £3M over 6+ years)



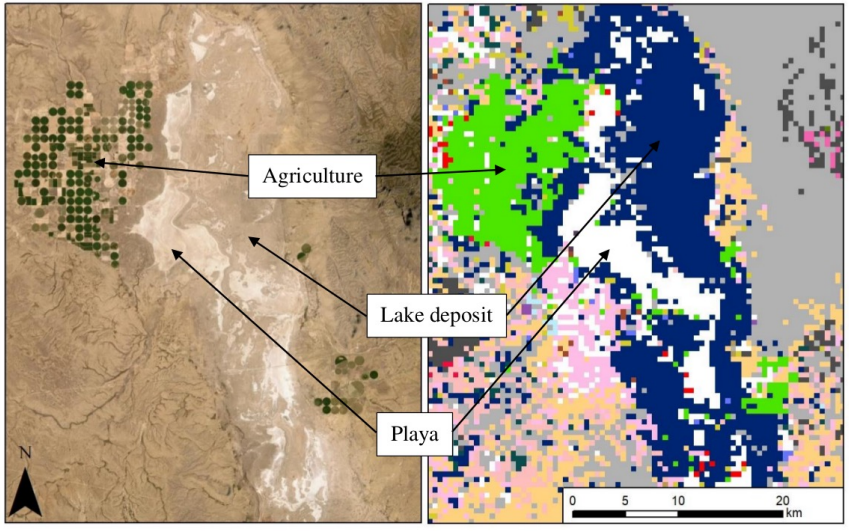

Maps used as training dataset:

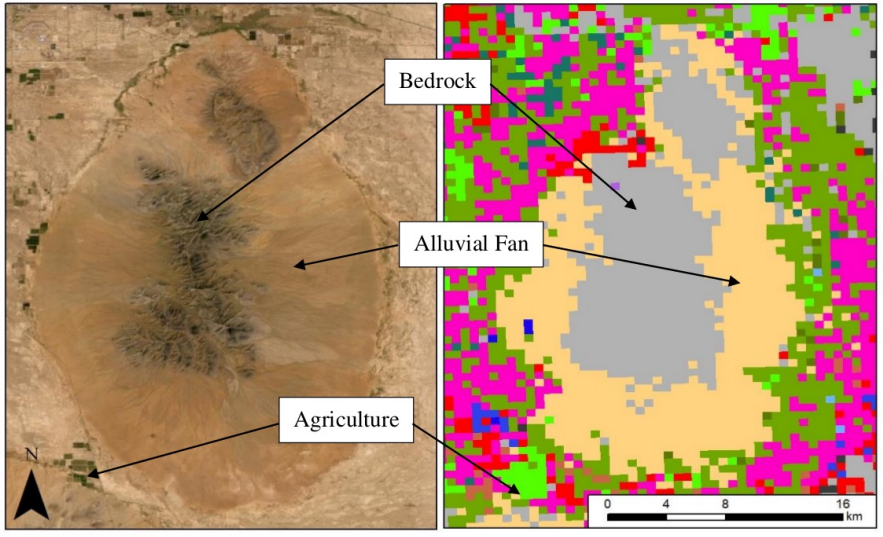
- With satellite retrievals and geospatial dataset.
- A Machine Learning algorithm can learn to classify landforms

Using a ML algorithm, the **ERDC-Geo** surface data can be gathered in a **scalable** way to achieve **global coverage**.

# Testing the ML

Extending ERDC-Geo



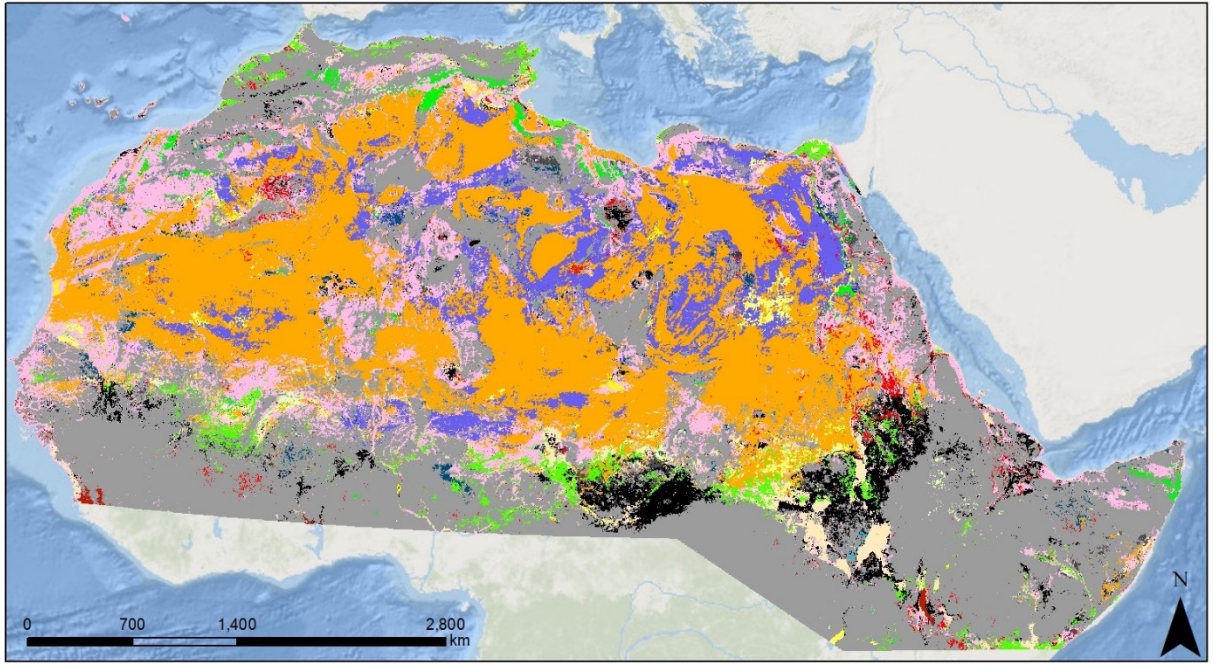




Sand Dune
Bedrock
Plateau
Alluvial Fan
Badlands
Active Wash
Sand on Bedrock
Fluvial Terrace
Urban
Agriculture
Wet Playa
Water
Sand Sheet
Recent Volcanics
Dry Playa
Pediments
Fine Grained Deposits
Landslide Features
Plateau/Sand Sheet
Surficial Deposits
Sand Sea
Broad River Valley
Alluvial Fan & Sand Sheet
Pluvial Lake

The ML algorithm produces a good map in an independent desert region.

# Phase 1 Output – N. Africa Maps

N. Africa Region



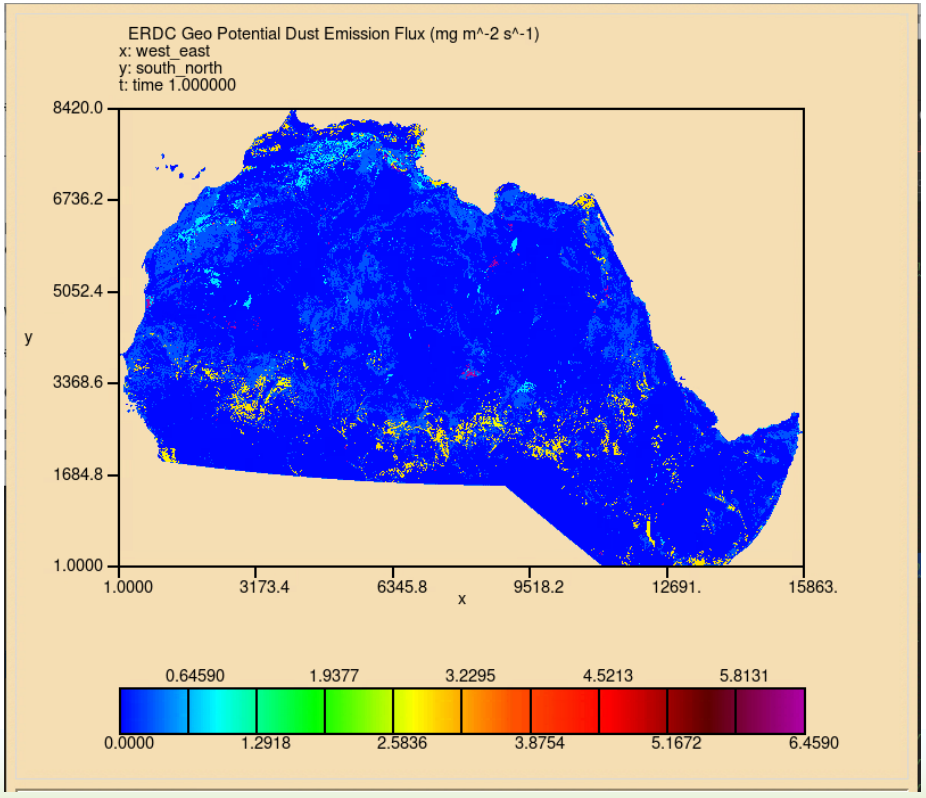

Alluvial Fan
Alluvial Plain
Badlands
Broad River Valley
Coastal Features
High Relief Mountains
Low Relief Mountains
Pediments
Plateau
Playa
Recent Volcanics
Sand Dunes and Playa
Sand Sea/Dunes
Sand Sheets
Water
Wind Eroision Features
Urban
Agriculture

- ML algorithm applied to a domain in North Africa

# First Look – N. Africa Preliminary Results

N. Africa Region

- Landform type converted to dust emission potential
- Via a lookup table, derived from wind tunnel in-situ obs for each landform type.

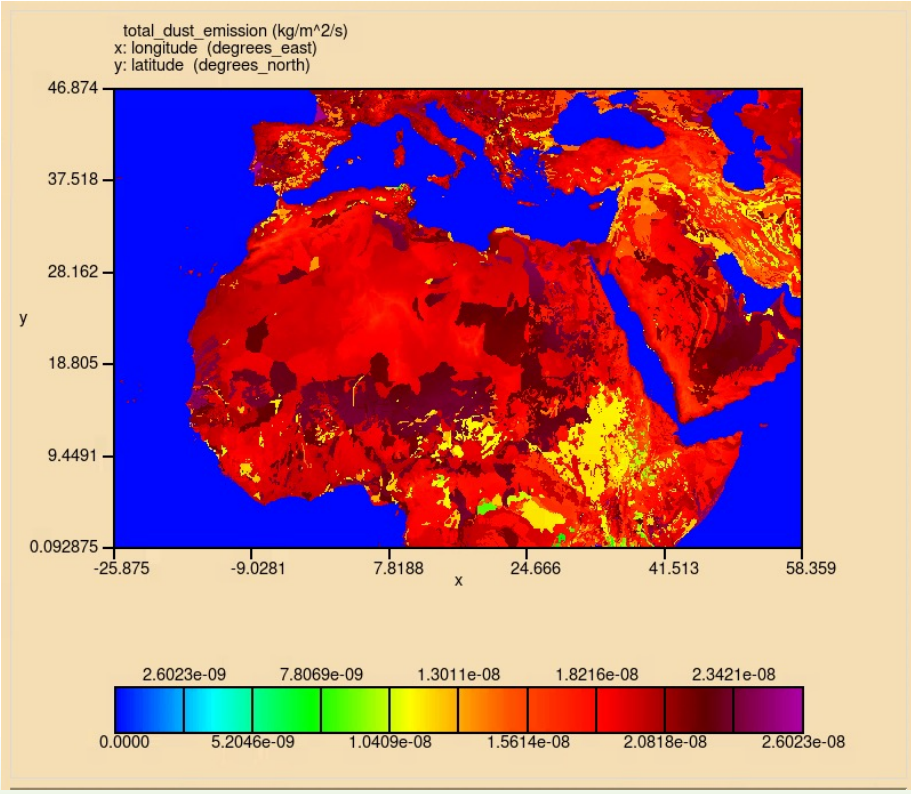


# First Look – N. Africa Preliminary Results

N. Africa Region

Average this to the model grid, and divide by the model output of the dust emission under idealised conditions to match the obs

* dry soil
* a surface friction velocity of 0.69 ms-1



# First Look – N. Africa Preliminary Results

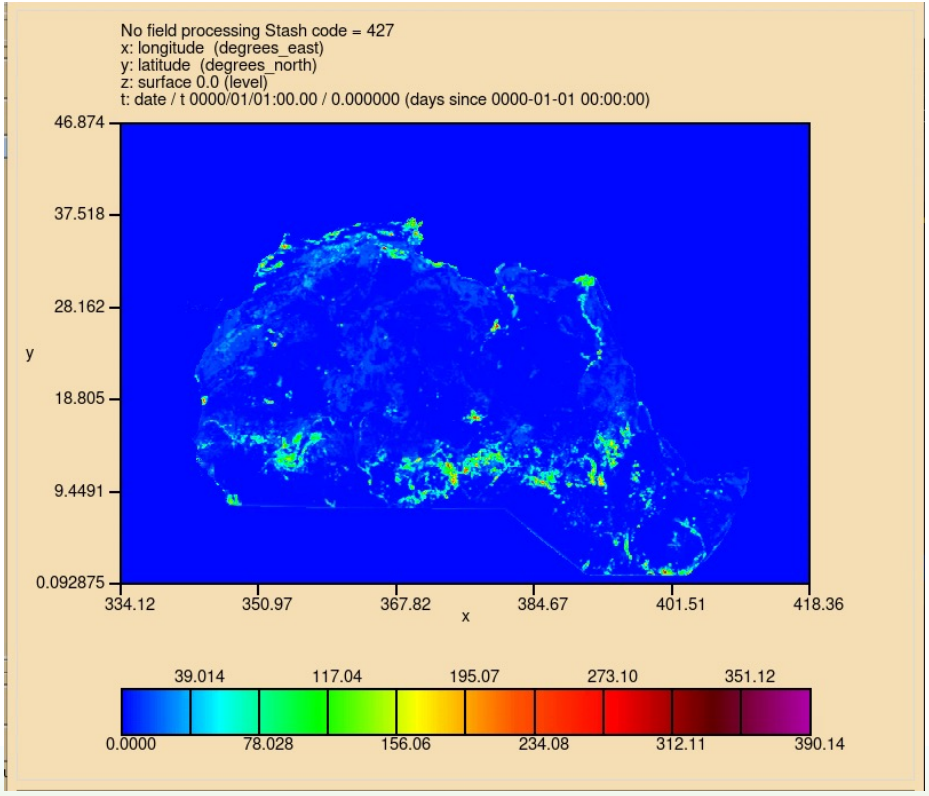
N. Africa Region

- That gives a scaling factor:

- A lot of zeros and values < 1.0
- Regions of moderate scaling
- Active dust sources are enhanced by factor > 100!

- Applied before vegetation and soil moisture masks.

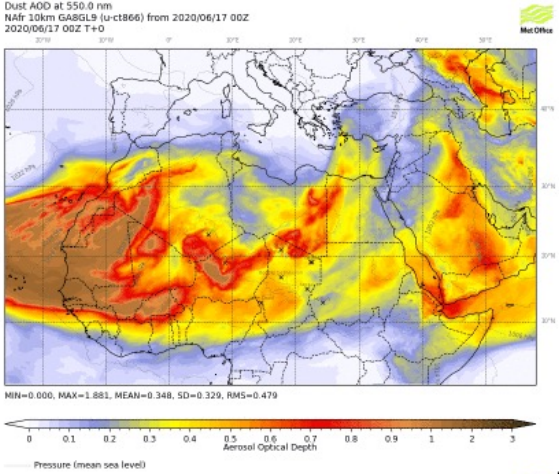
- Dust emissions are being constrained and localised to the geographically correct locations.

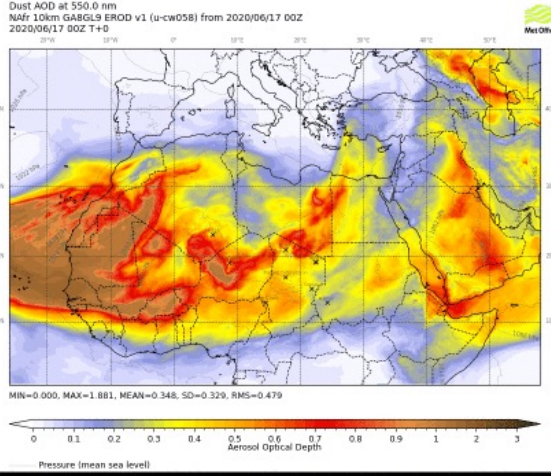


# Phase 1 Output – North Africa Sim

N. Africa Region

Standard

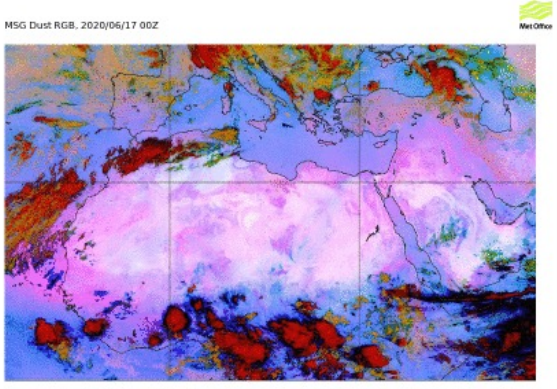


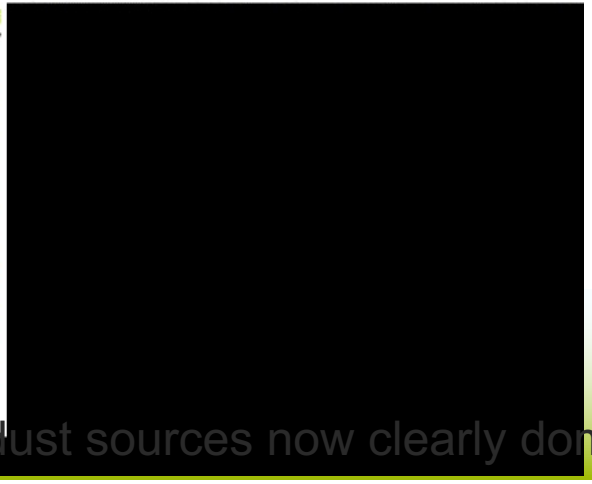




+ ERDC-GEO

DUST RGB
'pink' sat img

(daytime
thermal
contrast)



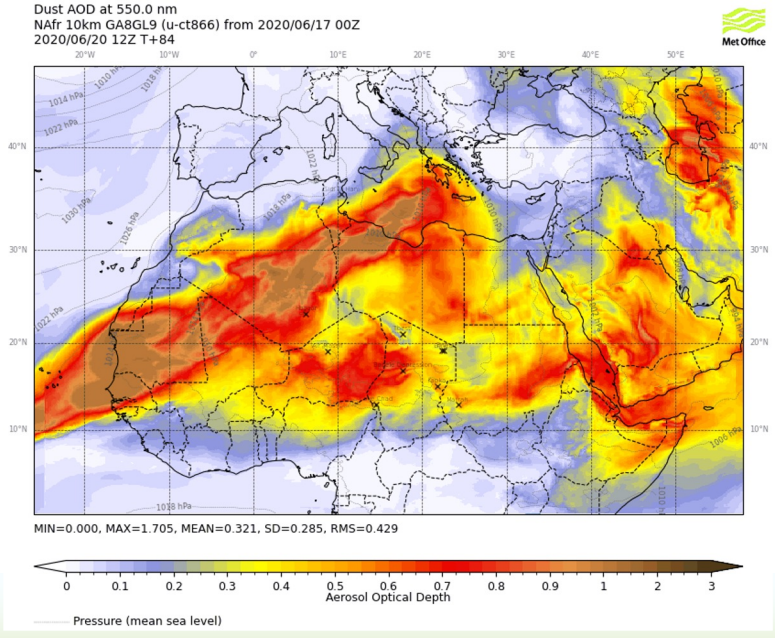
Model variability more realistic – primary dust sources now clearly dominant.

# Phase 1 Output – North Africa Sim

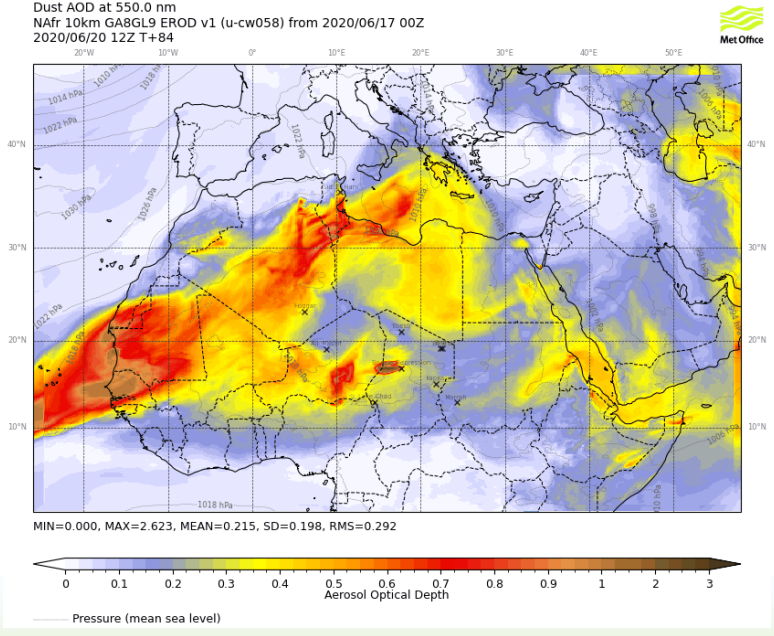
N. Africa Region

- ERDC-GEO increases dust emission in known sources – adding structure as intended

## Standard




## + ERDC-GEO

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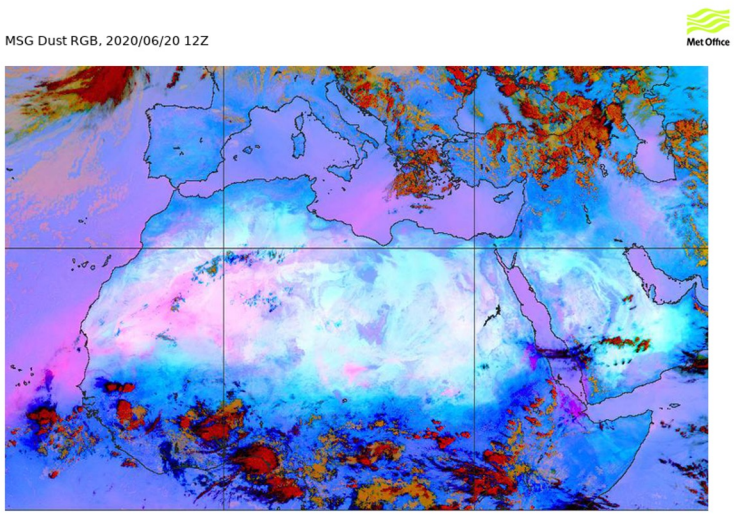
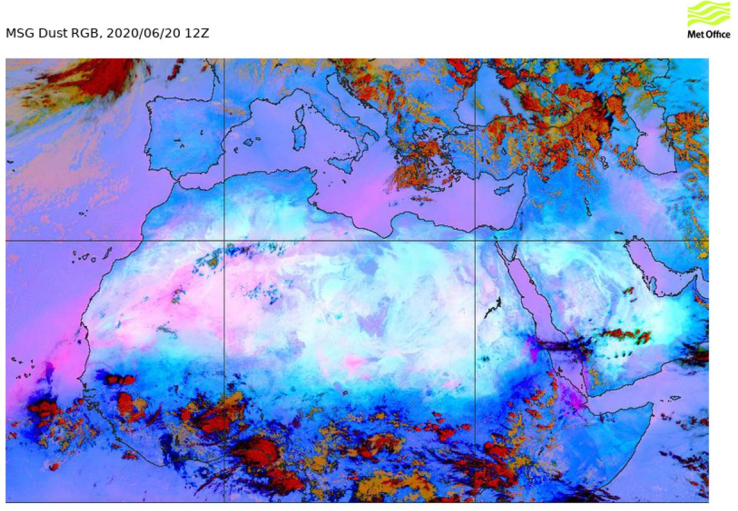



+ ERDC-GEO



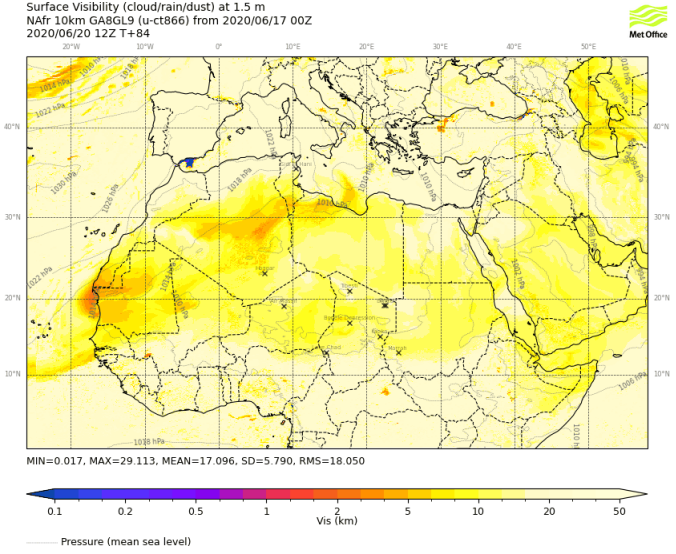

Individual sources correctly and precisely located!

# North Africa Modelling

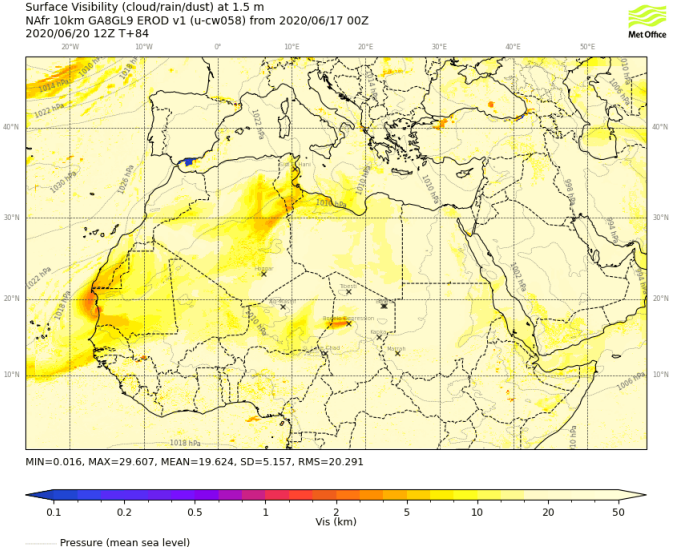
N. Africa Region

- ERDC-GEO does pull that into theatre-relevant fields, ie. Low visibility events

## Standard




## + ERDC-GEO

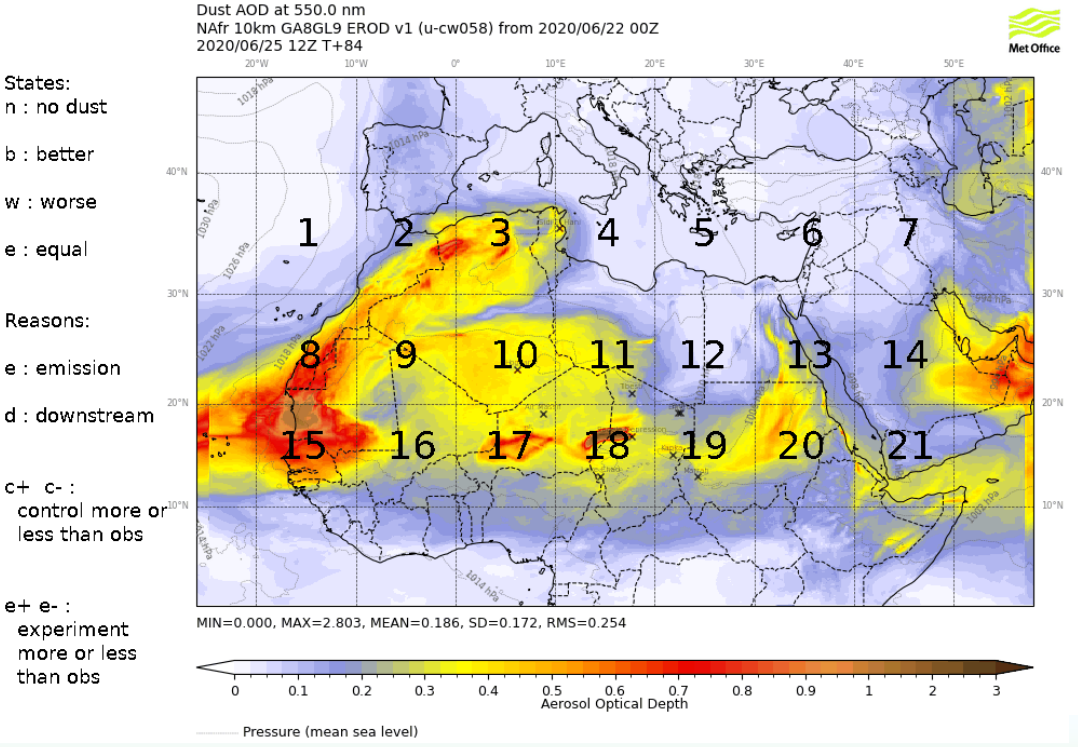



ERDC-GEO appears to be working as intended/expected in North Africa

# North Africa Modelling

N. Africa Region

- ERDC_GEO Forecast performance evaluation:
  - Dust events are located in obs sparse regions.
  - Surface observations are present but coverage is poor.
  - Exact co-location of forecast and satellite imagery allows for subjective comparisons.
  - These can be aggregated into hits/misses, false alarms and correct rejections
    - Hit: ERDC-Geo forecasts dust the control does not.
    - Miss: misses dust the control has
    - Correct Rejection: correctly dust-free when the control is dusty
    - False Alarm: incorrectly dusty when the control is clear.



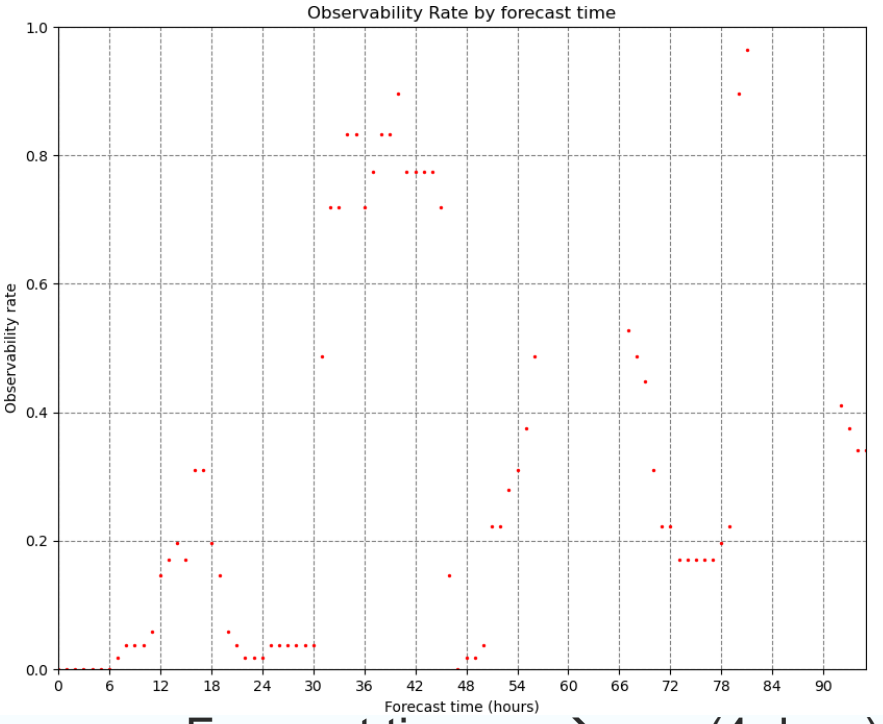

Contingency skill scores can give a metric of ERDC-GEO performance

# North Africa Modelling

N. Africa Region

- ERDC_GEO Forecast performance evaluation:

- '**Observability Rate**': how often we can discern improvement or not:
- Diurnal cycle from observations
- Starts low as the forecast difference needs to spin up from common initial conditions.




Forecast time ----→ (4 days)

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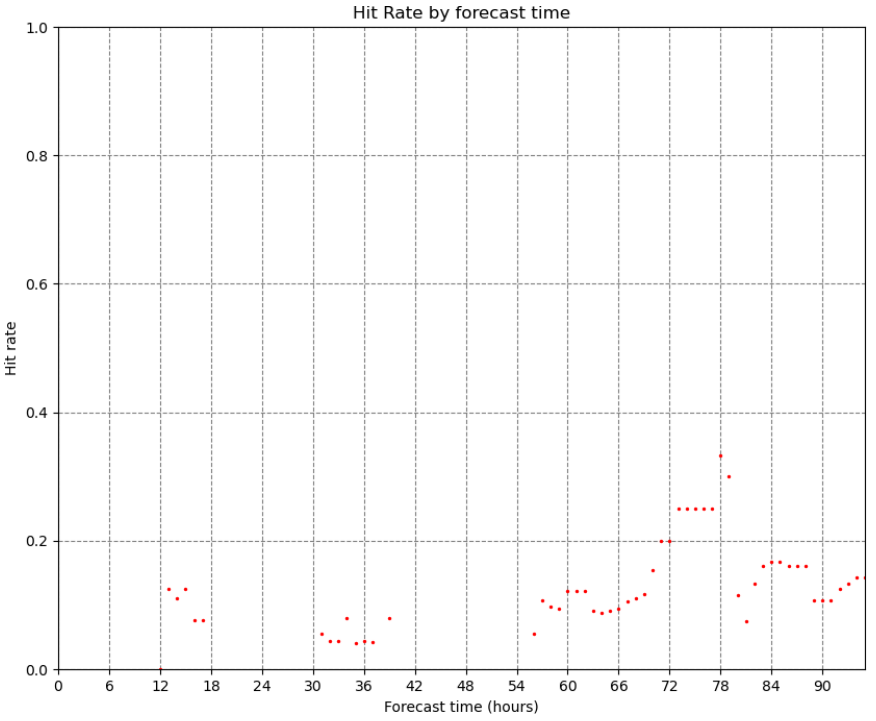
# North Africa Modelling

N. Africa Region

- ERDC_GEO Forecast performance evaluation:
- **'Hit rate':** the proportion of forecasts which are better due to ERDC-GEO
- 10% to 20% of the time, peaking to 30% of the time.



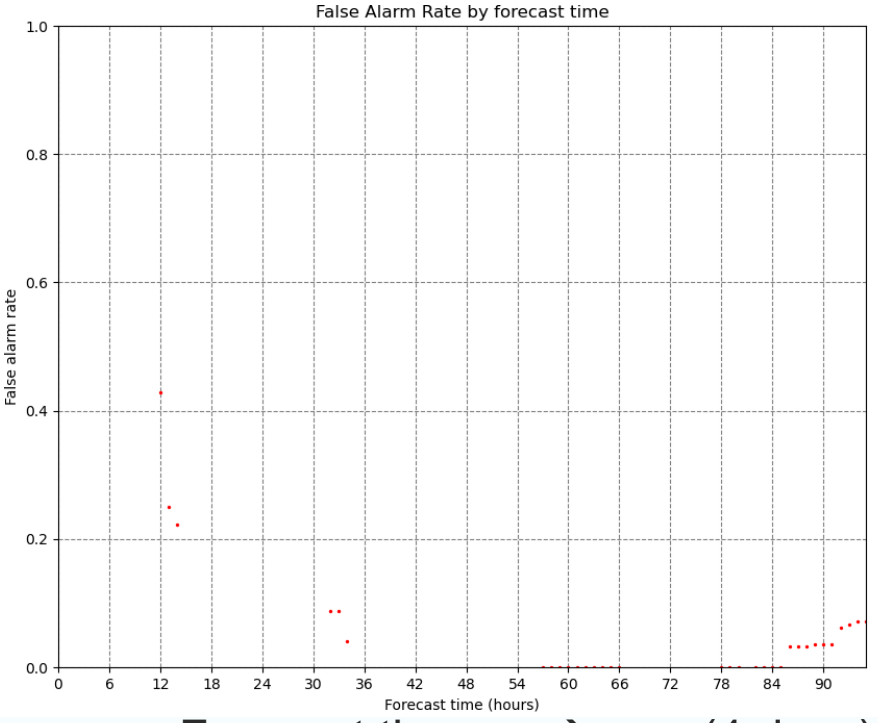

Forecast time ----→ (4 days)

ERDC-GEO appears to be working as intended/expected in North Africa

# North Africa Modelling

N. Africa Region

- ERDC_GEO Forecast performance evaluation:
- **'False Alarm Rate'**: the proportion of forecasts where ERDC-GEO has excessive dust.
- Starts high – 40%, drops to < 5%.
  - High start is spin up issue where observability is low.




Forecast time ----→ (4 days)

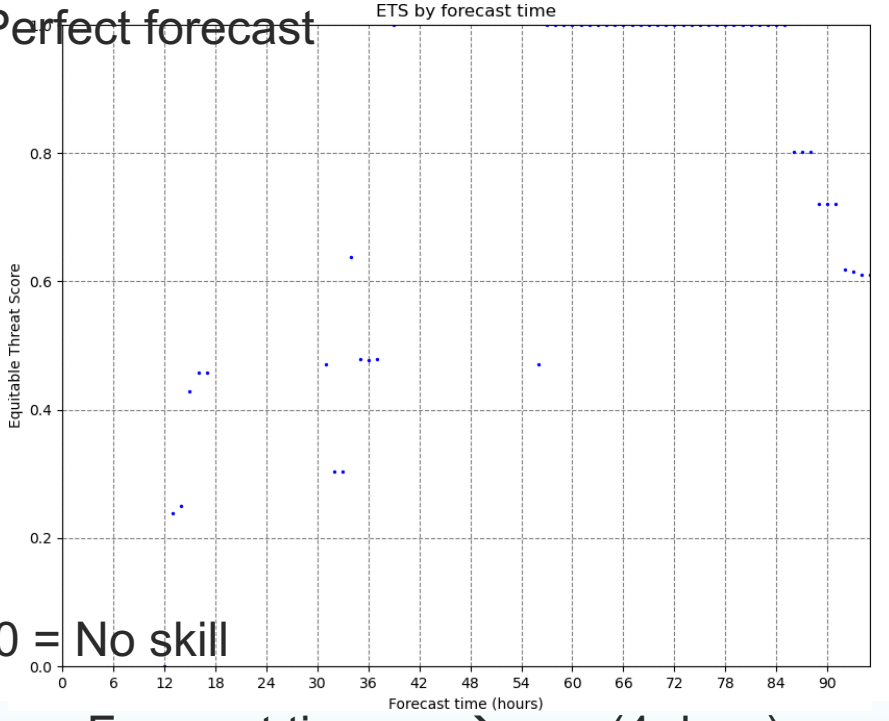
ERDC-GEO appears to be working as intended/expected in North Africa

# North Africa Modelling

N. Africa Region

- ERDC_GEO Forecast performance evaluation:
- **'Equitable Threat Score'** is a balanced skill score
- combines hits and false alarms and accounts for chance forecasts.
- Always +ve, starts out at ~0.3,builds to ~0.7

1 = Perfect forecast



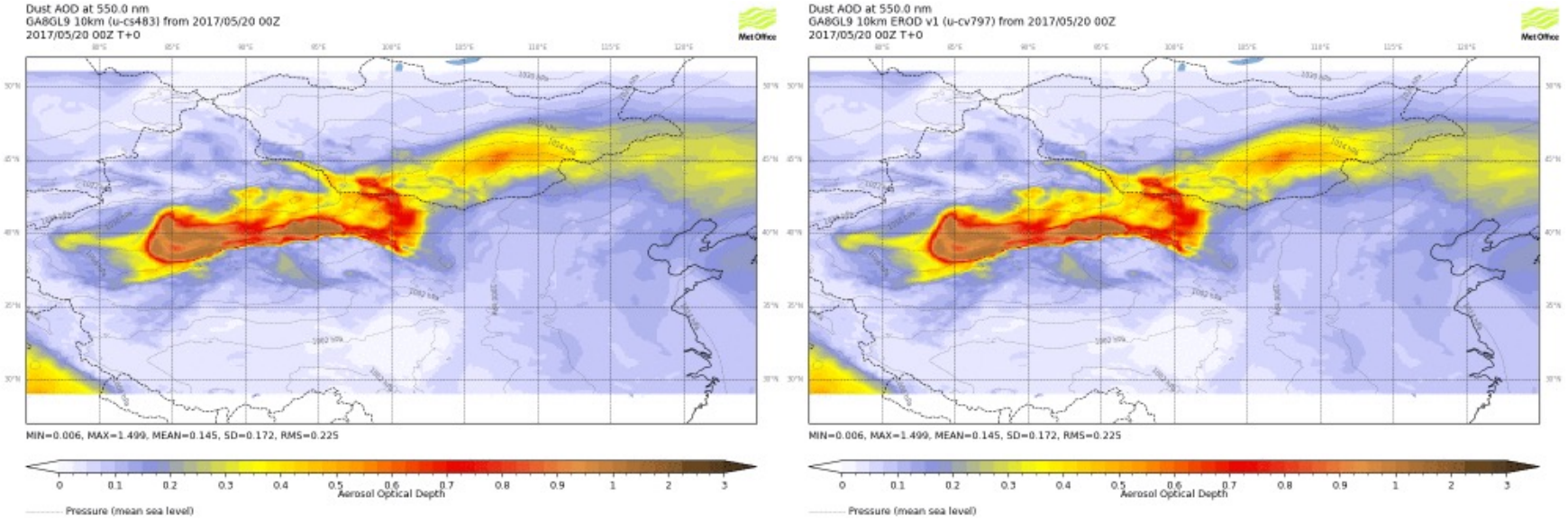

0 = No skill

Forecast time ----→ (4 days)

More data is needed but ERDC-GEO appears to be working very well

# Other regions:

Beyond The Sahara

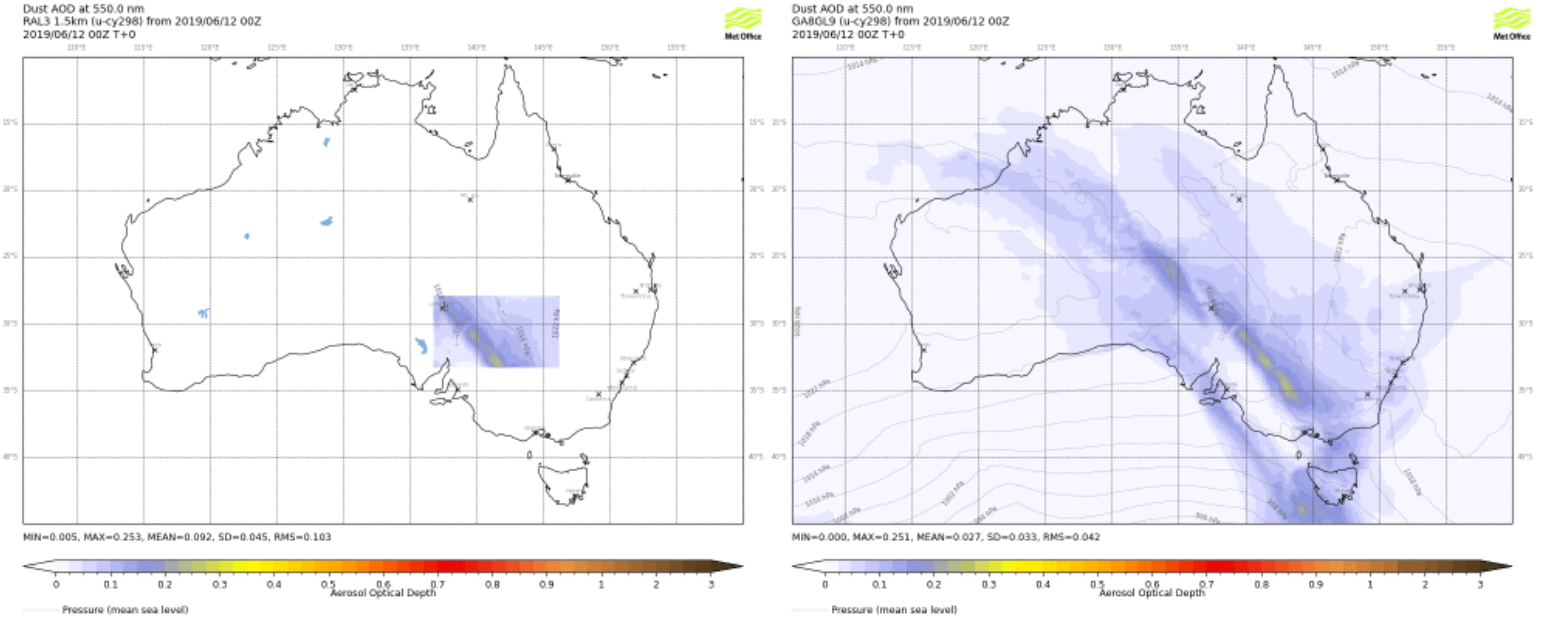



Control and ERDC-GEOP test cases run for Northern Asia

Evaluation of these runs is underway…

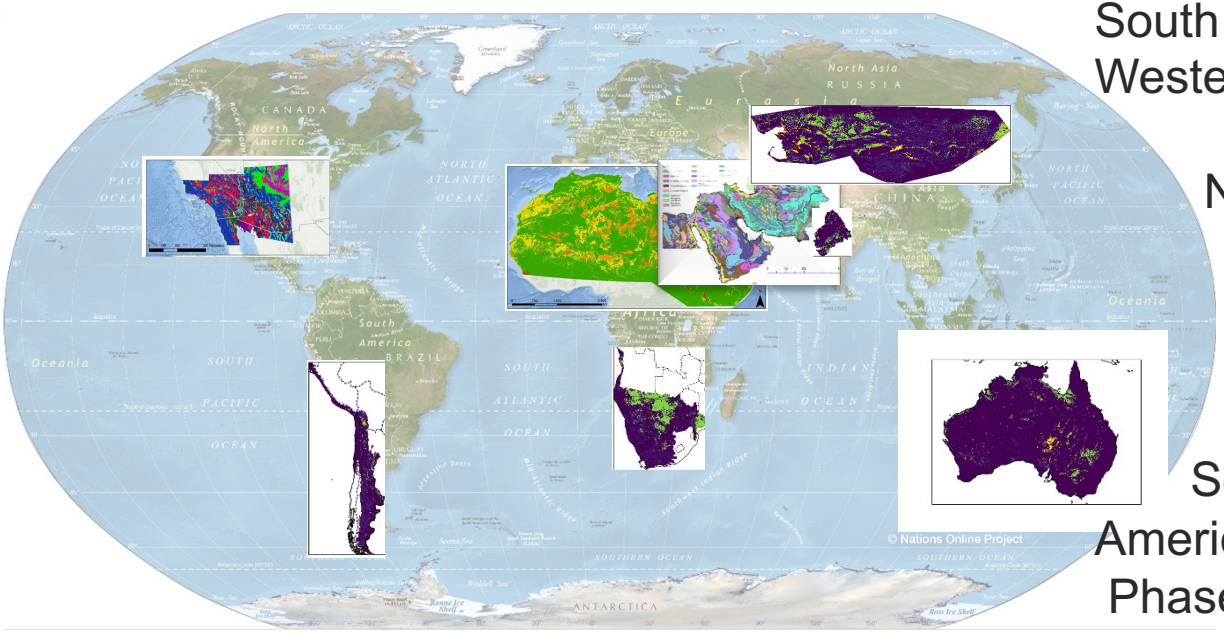
# Other regions:

Beyond The Sahara




Simulations over Australia underway for the ERDC-Geo test cases…

# Global landform maps




South East Asia and Western USA: training data

North Africa: Phase 1

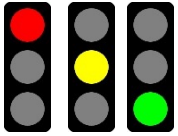
Asia and Australia: Phase 2

South Africa, Sourth America, and Thar deserts: Phase 3 – just in!

ERDC-Geo: project

# Summary

- Dust emission problem: good on regional scale, lack surface details



  - Leads to inaccurate details in dust forecasts
  - Especially for high impact dust events.
- ERDC-Geo method gives details of surface erodibility to dust models.
- Uses a **M**achine **L**earning approach to extend current data scalably!

- Initial tests show a significant improvement in dust forecast skill.

- Global coverage
  - More testing underway and planned
  - Implementation in 2025? Coinciding with LFRic and other changes may delay this.

# Dust Assimilation Scheme

## NASA MODIS C6 Deep Blue/Dark Target 10 km

- Observation errors R = 0.222, no thinning
- Four 6 hourly assimilation windows

Filter AOD for **dust only aerosols** using secondary retrieval parameters (+ **Global dust belt filter** over ocean)

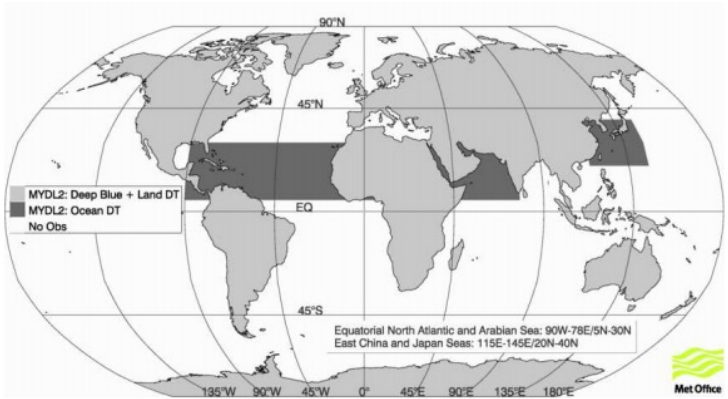
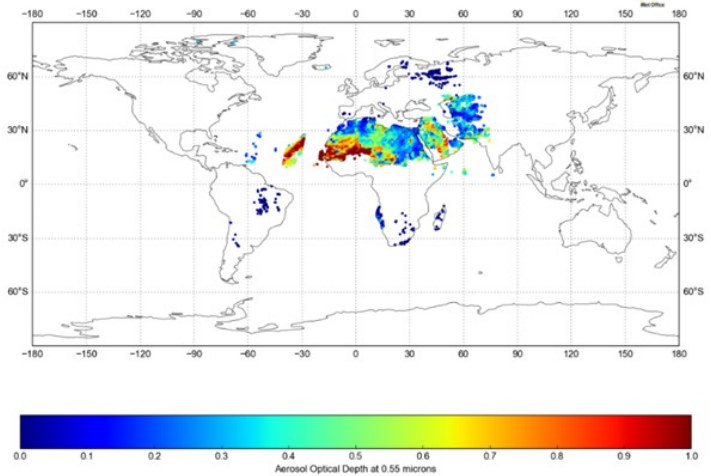
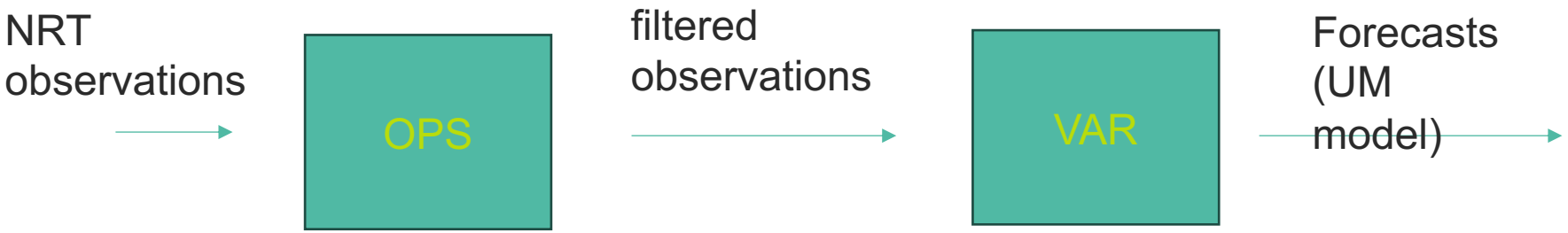



Figure 1: Geographic mask for MODIS dust AOD over ocean.



# Next Generation modelling: Data Assimilation

# Current Operational System




Observation Pre-processing System:

- Quality control (dust filtering)
- 1-D Var (MW, IR, GPSRO..)

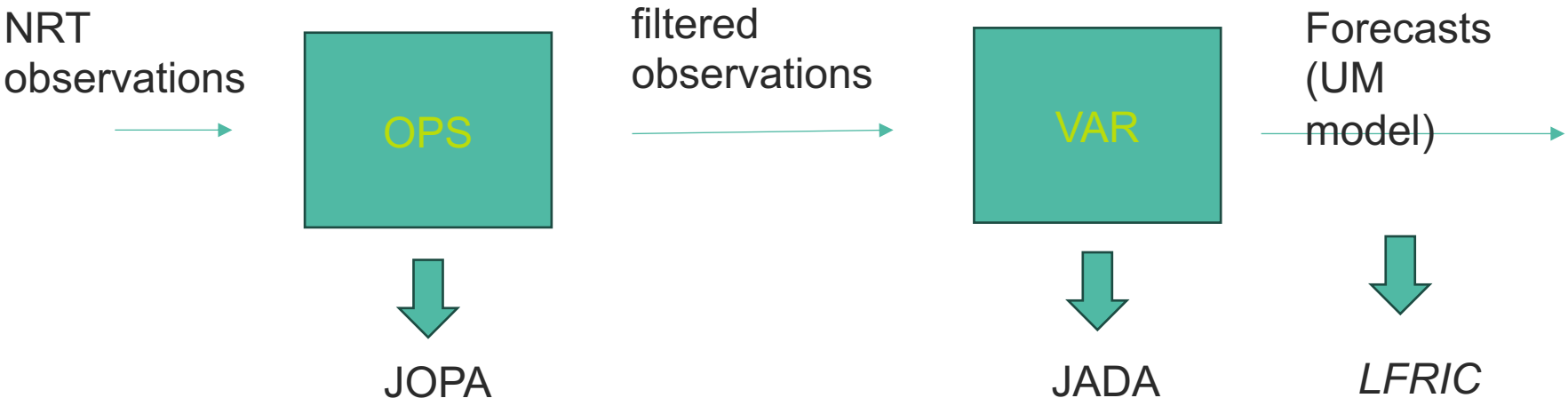
4-D Var Minimisation:

- Temperature, wind, humidity
- Dust mass concentration

# New System: NG-PAO (JOPA + JADA+ LFRIC)

NG-PAO will:

- Ensure readiness for next-generation HPC
- Allow collaborative and agile development in the JEDI framework

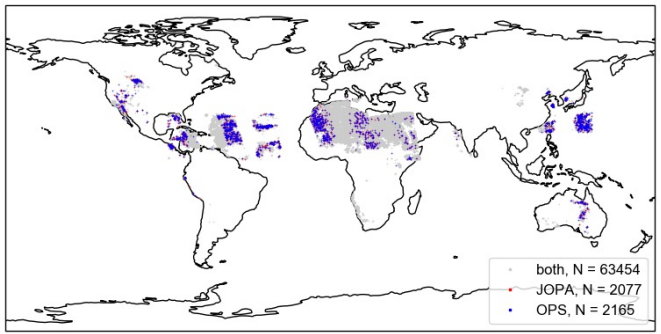


# Porting to NG-PAO

## Stage 1: JOPA porting (summer 2024)

- Match the current operational system (as close as possible)

e.g. Dust filtering & QC (MODIS & VIIRS)




- **VIIRS included for testing (future DA)**
- **Same number of observations selected by both JOPA and OPS**
- **Some (random) differences in selection due to VIIRS thinning**

## Stages 2 (JOPA/LFRIC) and 3 (JADA) porting ongoing

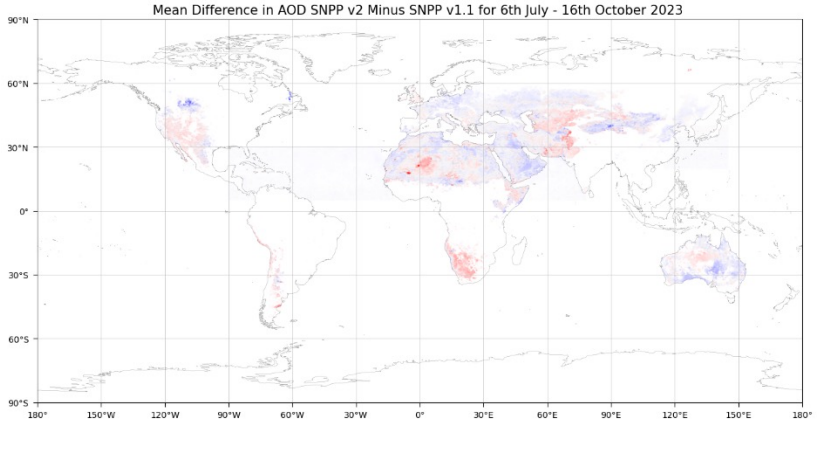
- Aim: include new science e.g. through LFRIC
- Testing 2025, operations 2027

Heather Lawrence

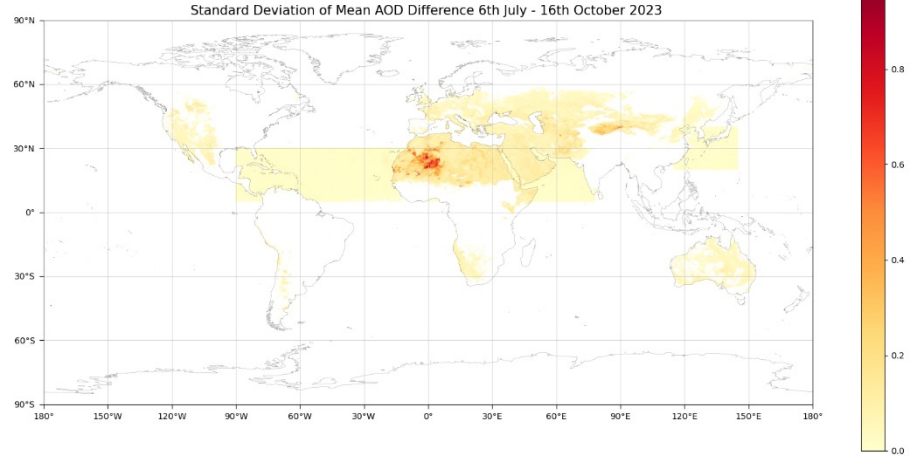
# Update on Assimilating Deep Blue VIIRS AOD

- SNPP v1.1 trialled for assimilation but now looking at v2 SNPP and NOAA-20
- Preliminary investigation show differences in dust over land >> re-evaluate for DA
- Match-up of total AOD (NRT) 6th July 2023 – 16th October 2023 + our own dust filtering

**Mean Difference**




**Standard Deviation of Difference**



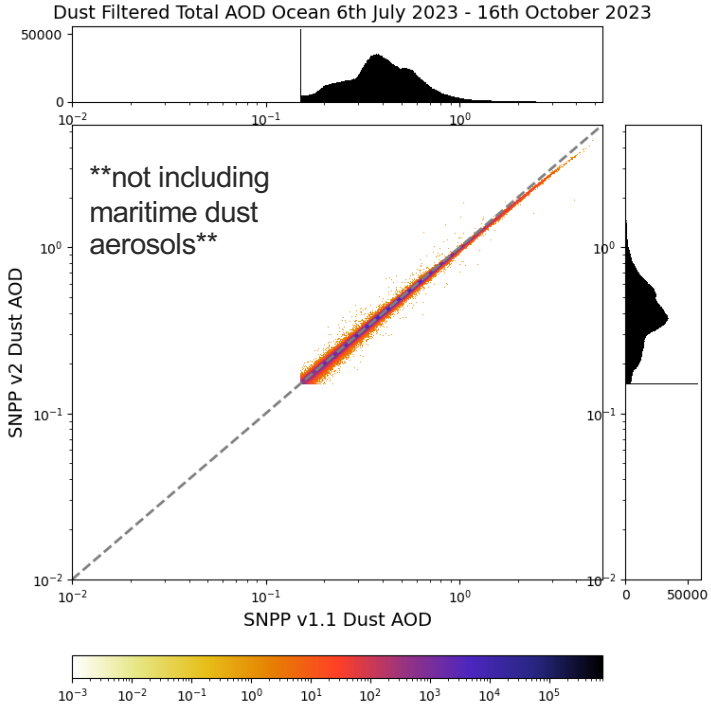
## Dust Filtered Ocean (AOD > 0.15)

**Ocean:**

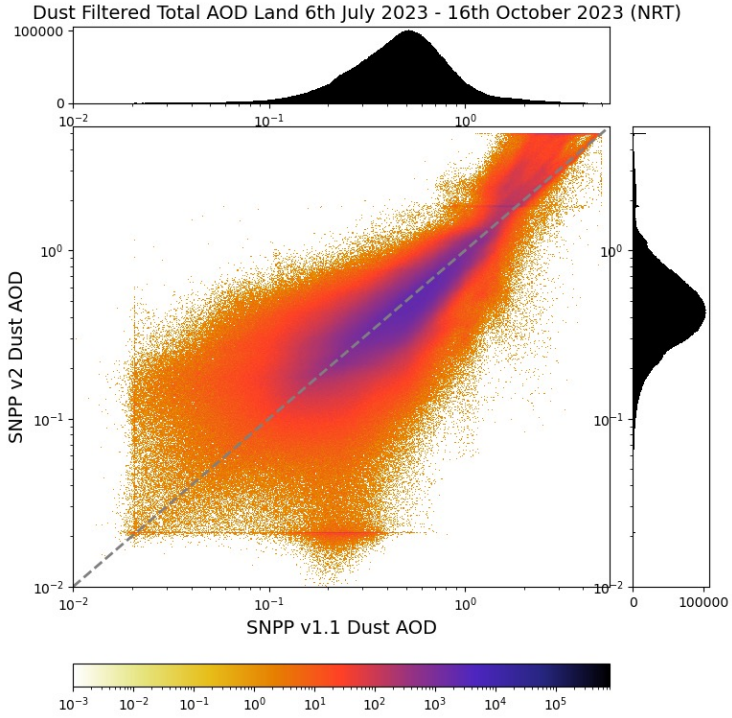
- DB Ocean Dust Flag
- AE <=0.5, FMF <= 0.4
- Dust belt geo filter
- AOD > 0.15

**Land:**

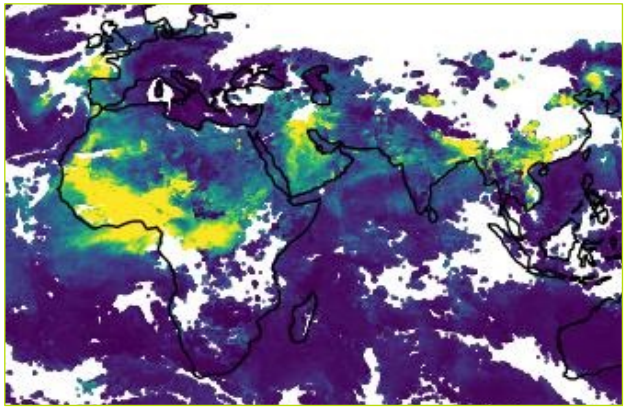
- 0.878 < SSA < 0.995
- AE < 0.6
- NOT smoke (DB Smoke Flag)




## Dust Filtered Land



Met Office



**MODIS AOD Total 2021-03-31**

Study on dust transport event (**29th March 2021**) by ECMWF - significant impact on HRES 2m ST forecast over **Iberian Peninsula.**

A SDS also occurred in Mongolia.

Source: https://www.ecmwf.int/en/newsletter/168/news/saharan-dust-events-spring-2021

Newsletter

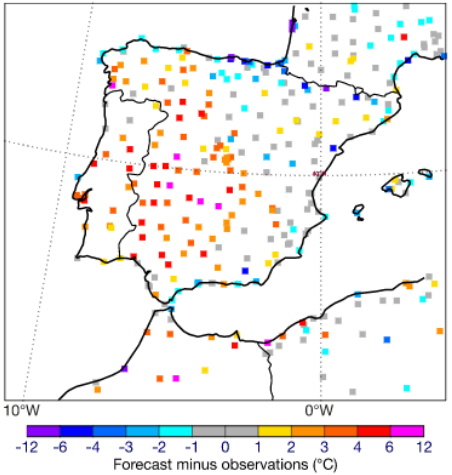
Number 168 - Summer 2021

Published in July 2021

◄ View all Newsletters

NEWS Saharan dust events in the spring of 2021

Linus Magnusson, Ivan Tsonevsky, Mark Parrington, Richard Forbes, Johannes Flemming



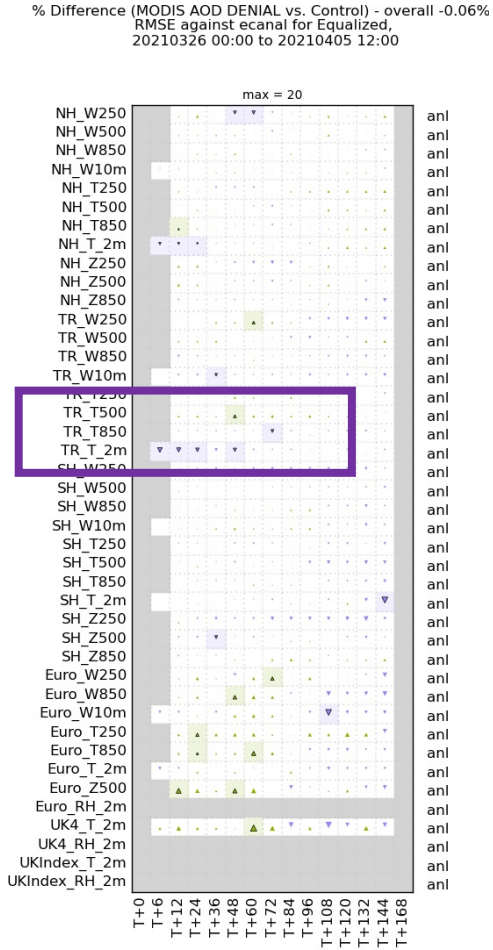

**Temperature forecast errors.** Two-metre temperature forecast errors (forecast minus observations) for the 12-hour HRES forecast issued on 30 March 00 UTC.

During this episode, ECMWF's high-resolution forecast (HRES) experienced large temperature errors over the dust-affected areas of the Iberian Peninsula. Even in the short-range 12-hour forecast for 2-metre temperature, the model was 2 to 7°C warmer than the observations (see the figure on temperature forecast errors).

# Short Dust DA Denial Trial

- 2-week denial trial 26th March to the 5th of April
- **Control** (Prognostic Dust in DA) – Standard GM set-up (lower resolution, Atmosphere only)
- **MODIS AOD Denial** – Standard GM set-up without MODIS AOD data assimilation

- RMSE error differences against *ECMWF analysis*
- Purple = MODIS Denial experiment shows a small degradation in 2m Surface Temperature forecast
- Next step: compare to our climatology (static dust)

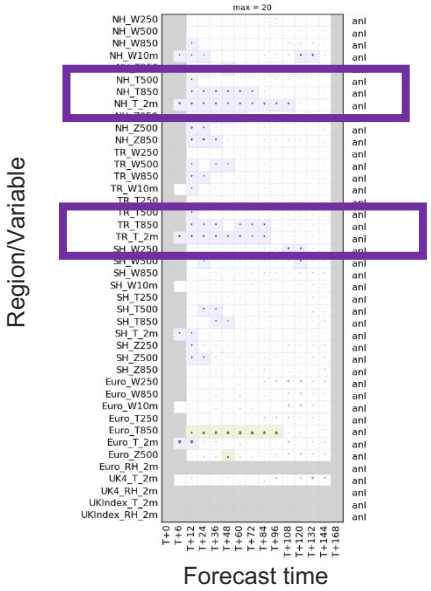


# Longer trials: Impact of MODIS on 2-metre temperature

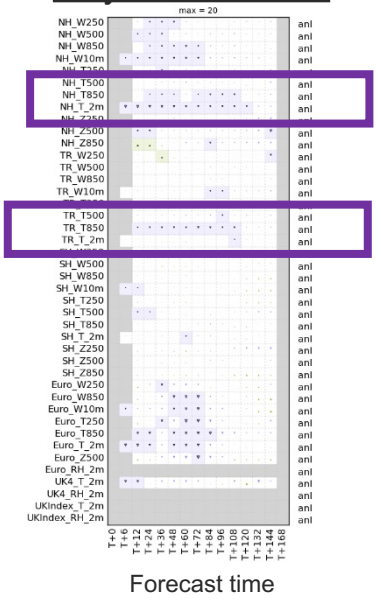
Heather Lawrence

MODIS denial vs Prognostic Dust in DA forecast scores:

Dec – Feb 2019/2020




May – June 2020




**2-metre temperature**
**Tropics & NH impacts**

*Verified against ECMWF analysis*

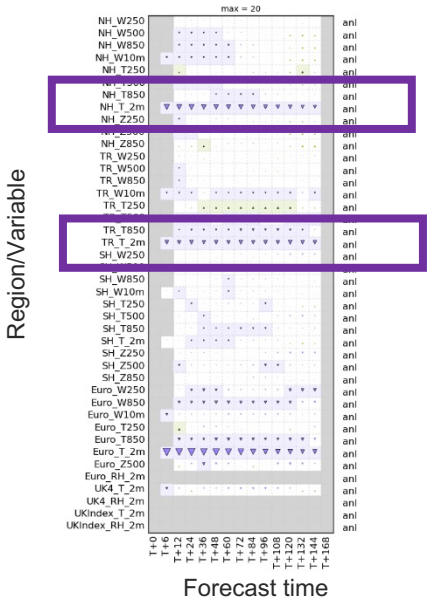
**MODIS AOD has a positive impact on near-surface temperature forecasts**

# Longer trials: comparison to climatology

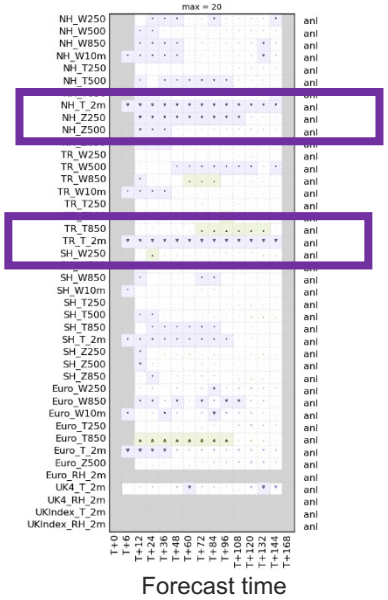
Prognostic dust in DA vs Climatology
Forecast scores:

Heather Lawrence

Dec – Feb 2019/2020




May – June 2020




*Verified against ECMWF analysis*

**The dust DA system has a positive impact on forecasts compared to climatology**

# Future Plans

## Modelling plans

- Migration to LFRic (GLOMAP Mode) 2025/2026
- ERDC-GEO implemented globally and regionally around LFRic
- Exploring including non-dust aerosols

## DA plans

- Assess and implement assimilation of Deep Blue VIIRS version 2 (S-NPP, NOAA-20, NOAA-21)
- Develop assimilation method using LFRIC for JADA (change of control variables, background errors…)
- Explore more use of IR data e.g. SEVIRI 1D-Var retrievals, IASI MAPIR dust product