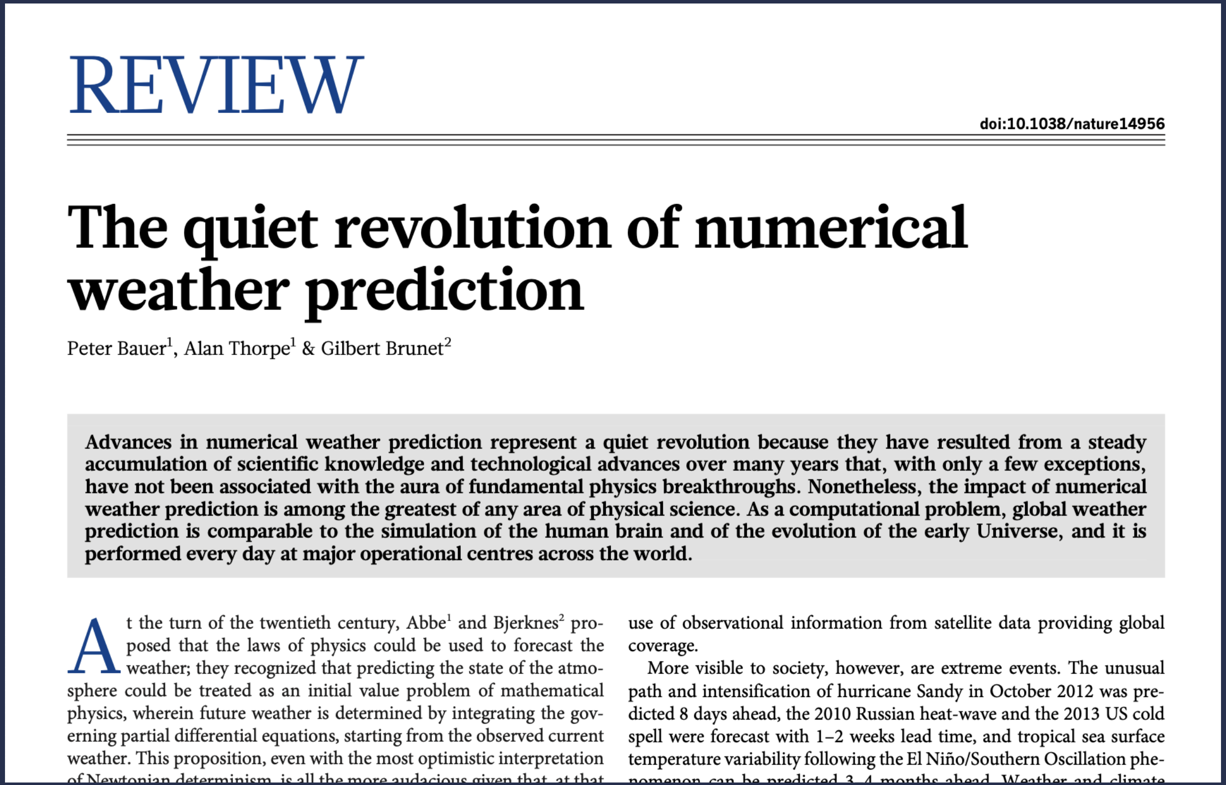
Observations: The noisy revolution

Tony McNally
Head of Earth System Assimilation Research
ECMWF

(*contributions from many ECMWF colleagues*)

What is the noisy revolution…?



REVIEW

doi:10.1038/nature14956

The quiet revolution of numerical weather prediction

Peter Bauer[1], Alan Thorpe[1] & Gilbert Brunet[2]

Advances in numerical weather prediction represent a quiet revolution because they have resulted from a steady accumulation of scientific knowledge and technological advances over many years that, with only a few exceptions, have not been associated with the aura of fundamental physics breakthroughs. Nonetheless, the impact of numerical weather prediction is among the greatest of any area of physical science. As a computational problem, global weather prediction is comparable to the simulation of the human brain and of the evolution of the early Universe, and it is performed every day at major operational centres across the world.

At the turn of the twentieth century, Abbe[1] and Bjerknes[2] proposed that the laws of physics could be used to forecast the weather; they recognized that predicting the state of the atmosphere could be treated as an initial value problem of mathematical physics, wherein future weather is determined by integrating the governing partial differential equations, starting from the observed current weather. This proposition, even with the most optimistic interpretation of Newtonian determinism, is all the more audacious given that, at that

use of observational information from satellite data providing global coverage.

More visible to society, however, are extreme events. The unusual path and intensification of hurricane Sandy in October 2012 was predicted 8 days ahead, the 2010 Russian heat-wave and the 2013 US cold spell were forecast with 1–2 weeks lead time, and tropical sea surface temperature variability following the El Niño/Southern Oscillation phenomenon can be predicted 3–4 months ahead. Weather and climate

…wait and see

But first a bit of history…

The past 50 years


ECMWF | 50
Search site...
Help
Log in
Home
About
Forecasts
Computing
Research
Learning
Publications
Anniversary
ECMWF at 50
1975–2025


Fifty years of data assimilation at ECMWF
ADVANCING WEATHER SCIENCE
THROUGH COLLABORATION
ECMWF | 50

The past 50 years…in 1slide!

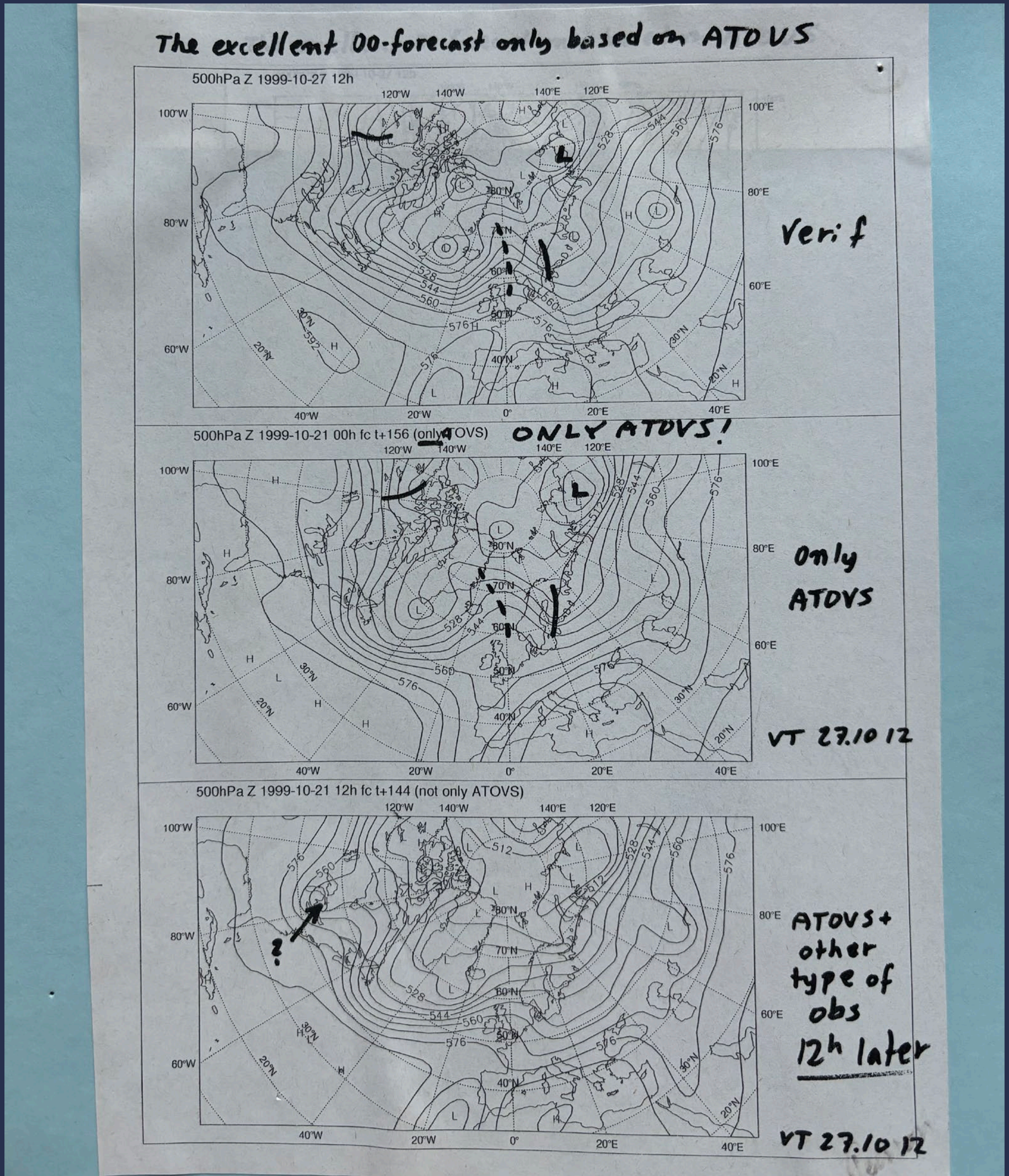
- In its early years, ECMWF recognized the **importance of global data assimilation of observations** for accurate forecasts and implemented a three-dimensional optimal interpolation (OI) scheme to provide initial conditions for its models.

- Through the 1980s increasing numbers of exciting satellite observations became available, provided by NOAA in the form level-2 retrieved products that looked like in-situ radiosonde observations. Unfortunately, when these were assimilated, they **systematically made forecasts worse**!

- This was attributed to the (ill-posed) process of converting satellite radiances to geophysical variables (e.g. temperature) and in the early 1990s triggered the development of **variational DA systems** (in the US and Europe) that could use radiances directly. After a lot of work, satellites finally showed a positive impact on forecasts!

- Over the next two decades variational methods were enhanced with dynamic background and observation error characterization, adaptive observation and model bias corrections and unified observation monitoring and QC, to be the **state-of-the-art systems** we know today

It was not always a “*quiet revolution*”

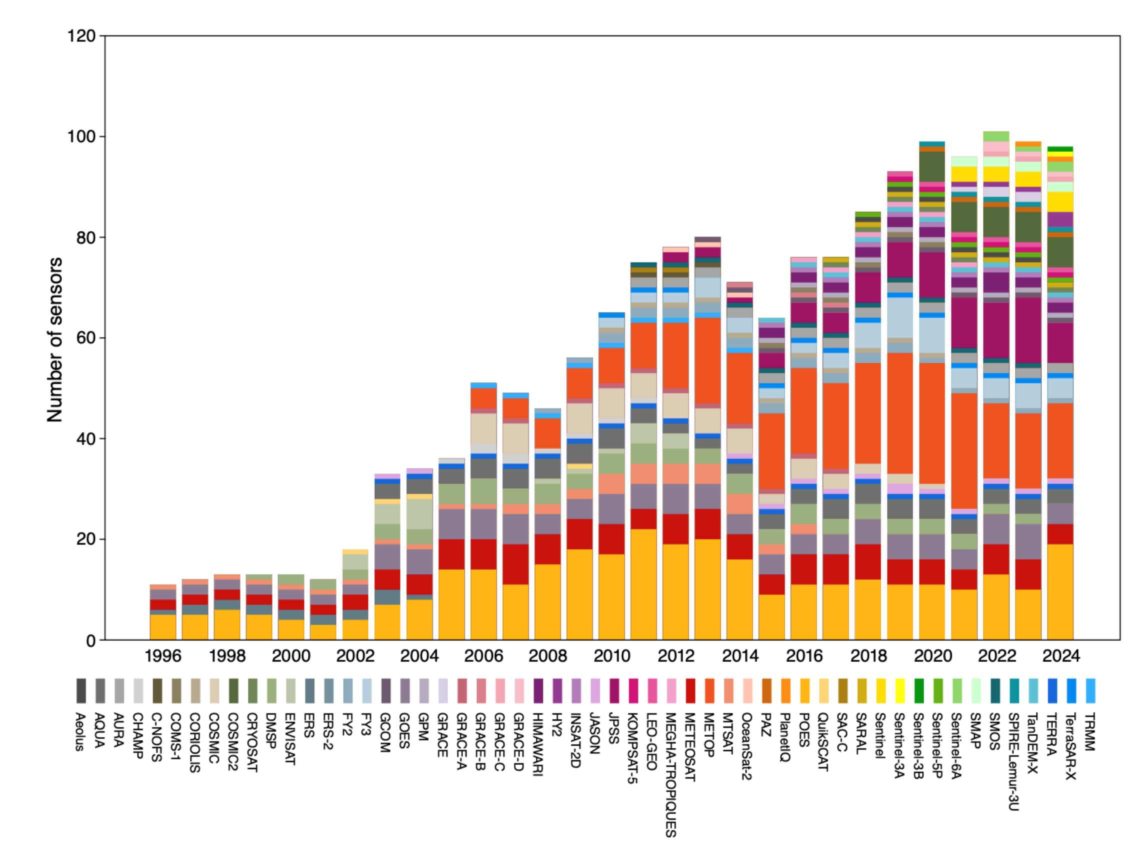


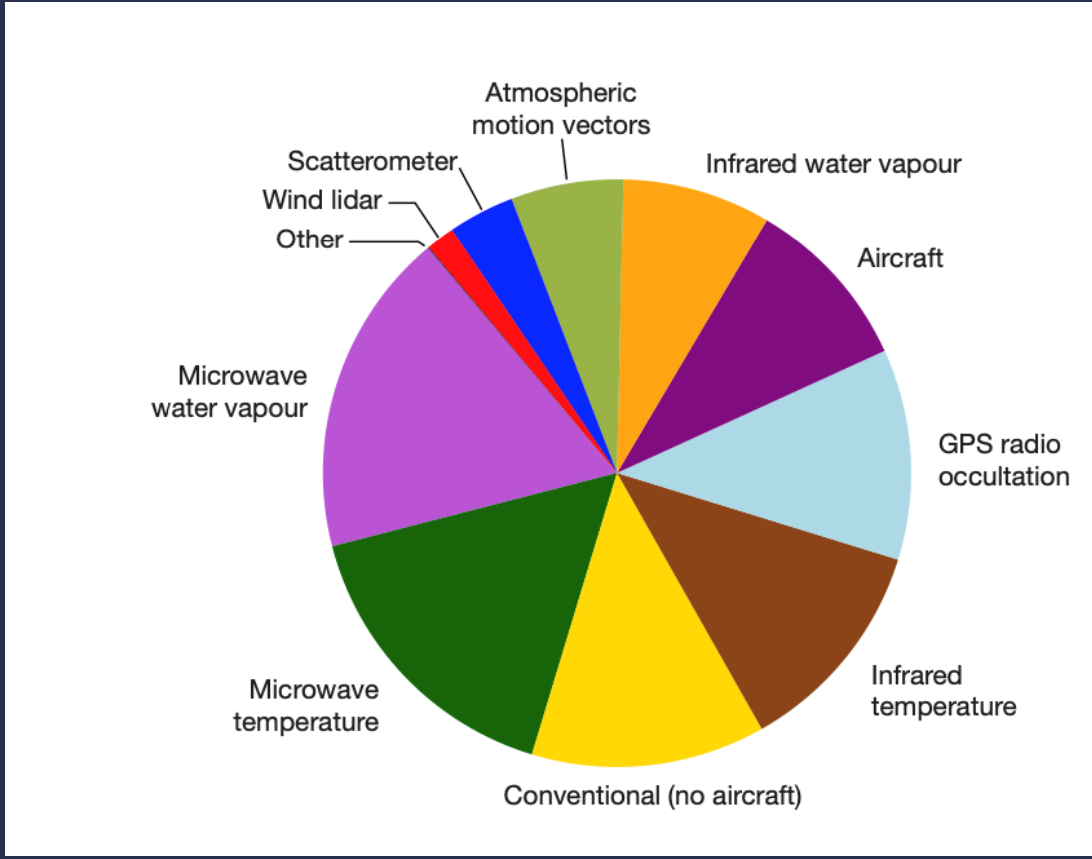
ADDITIONAL COMMENTS
A colleague from the satellite section was somewhat upset with yesterday's report which he likened to "the worst type of tabloid journalism" by spreading the illusion that the use of ATOVS has as much impact on the forecasts as a change of computer. We deeply regret the frustration we have caused and are happy to announce that the 21.10 00 UTC forecast (only based on ATOVS data) not only was almost perfect, in particular for important parts of Europe (north of Liverpool) it was by far suprior to the operational forecast 12 hours later when SYNOPs, TEMPs, ERS, AIREPS and other dubious data sources had been allowed to confuse the system.

Anders Persson 1999

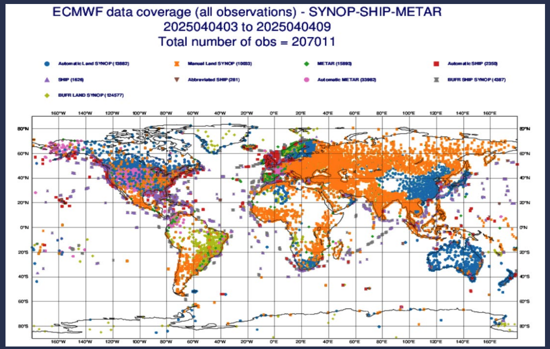
And now a look at the present day…

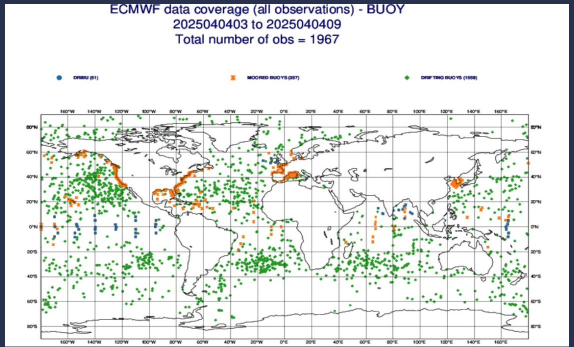
We have an excellent diverse global observing system…

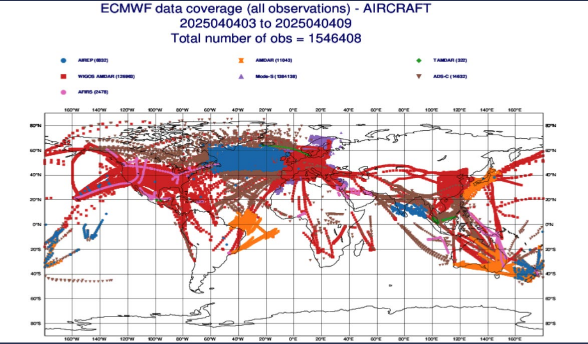


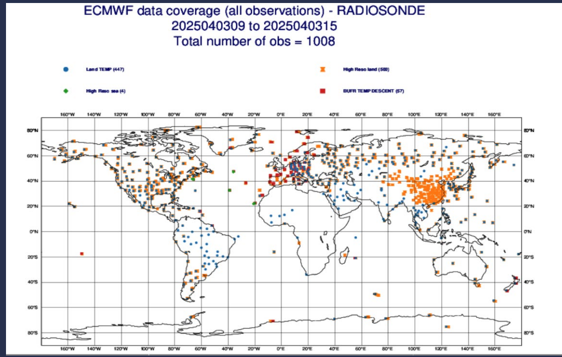


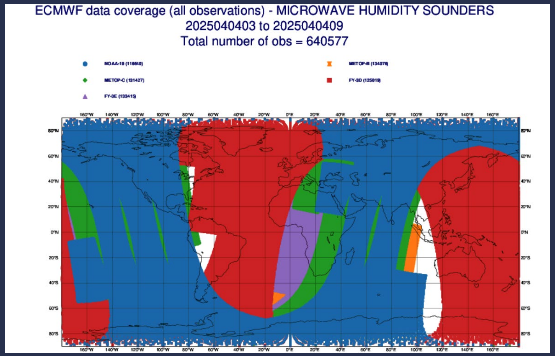
…comprising in-situ and satellite technology

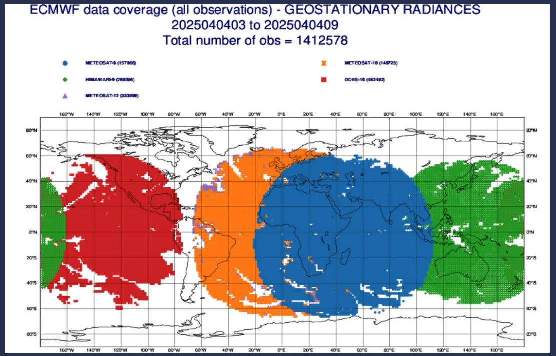


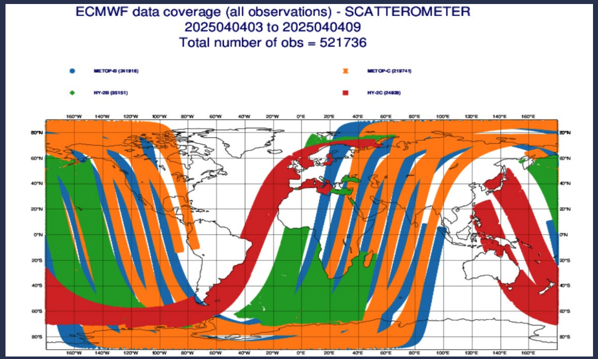


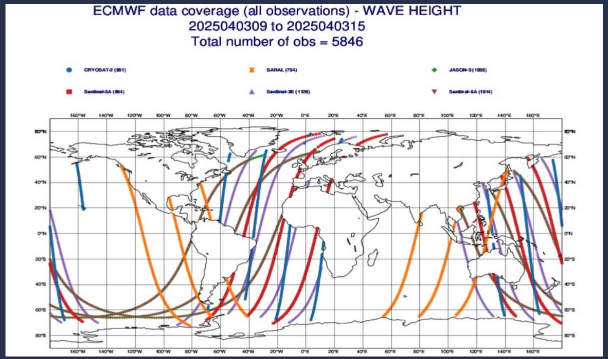




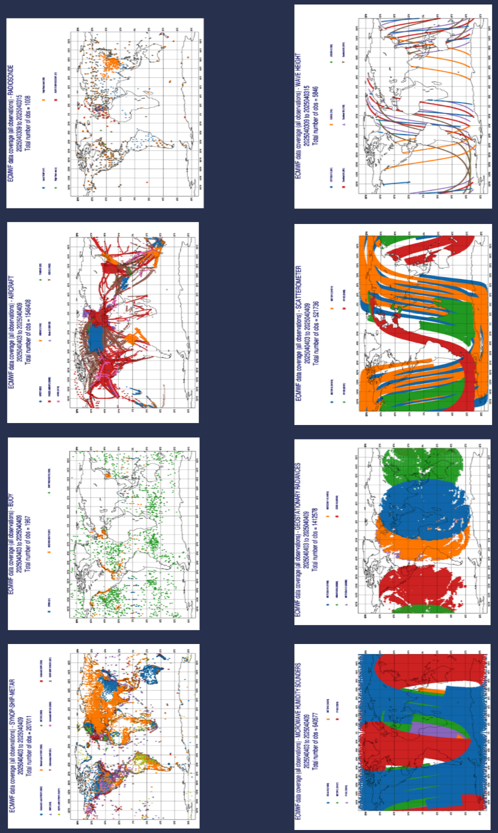


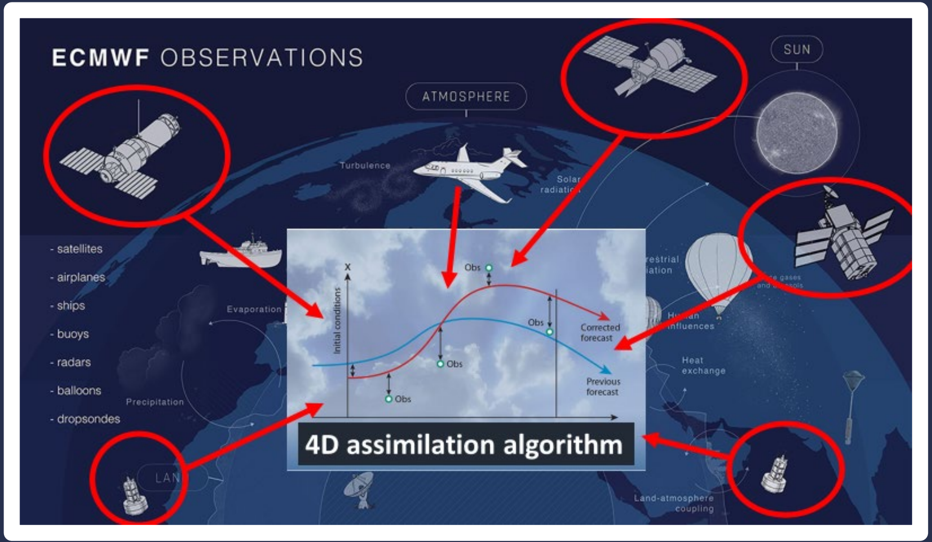


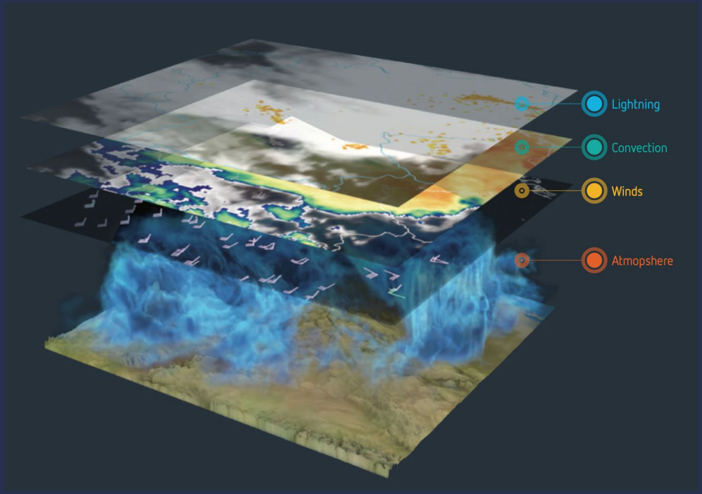




These observations are brought together by a state-of-the-art 4D-Var Data Assimilation system







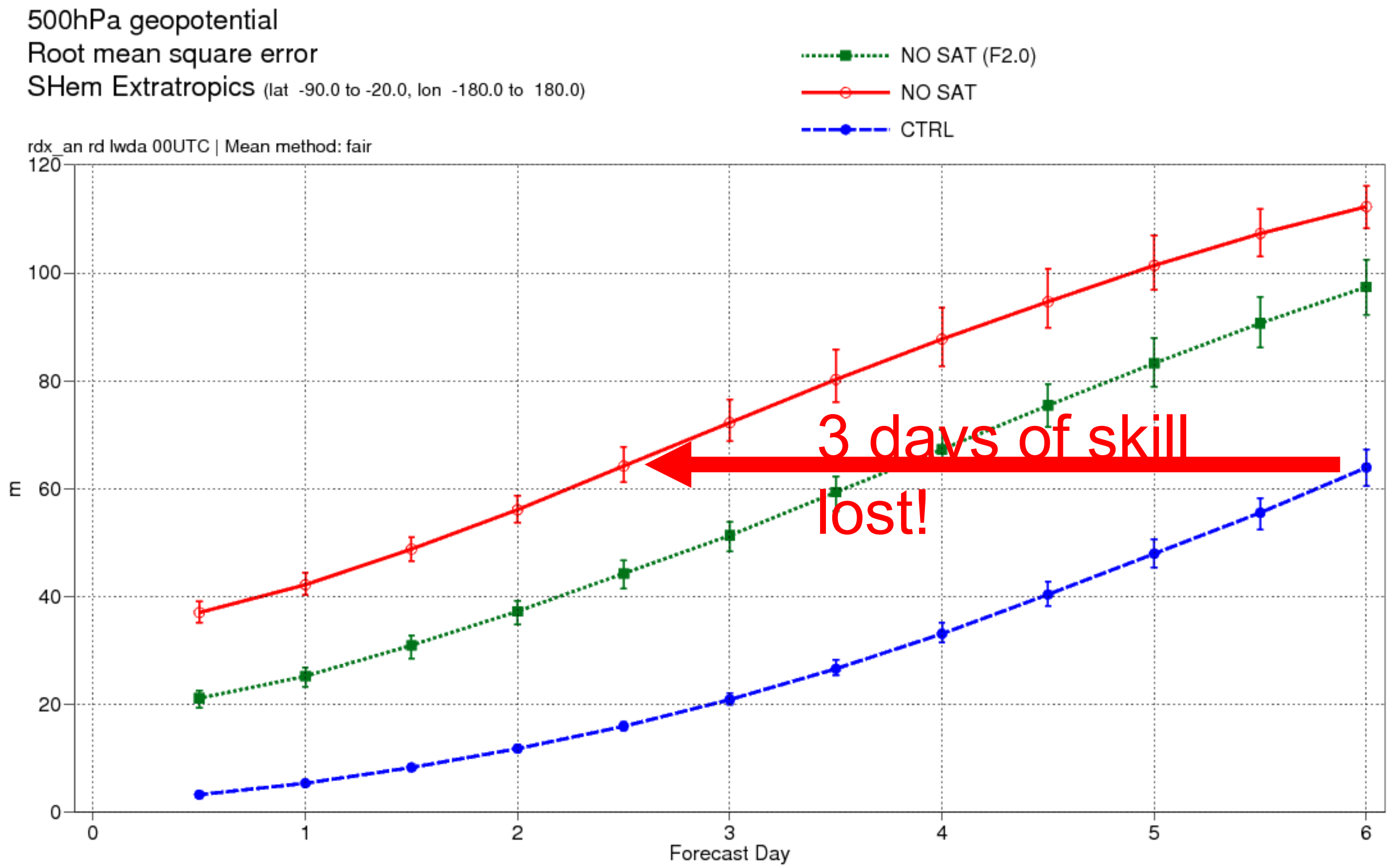
…to form a coherent initial state to launch the forecast model(s)

Can we quantify how important are observations for NWP ?

…denial experiments…

Can we quantify how important are satellites for NWP ?

Can we quantify how important are satellites are for NWP ?



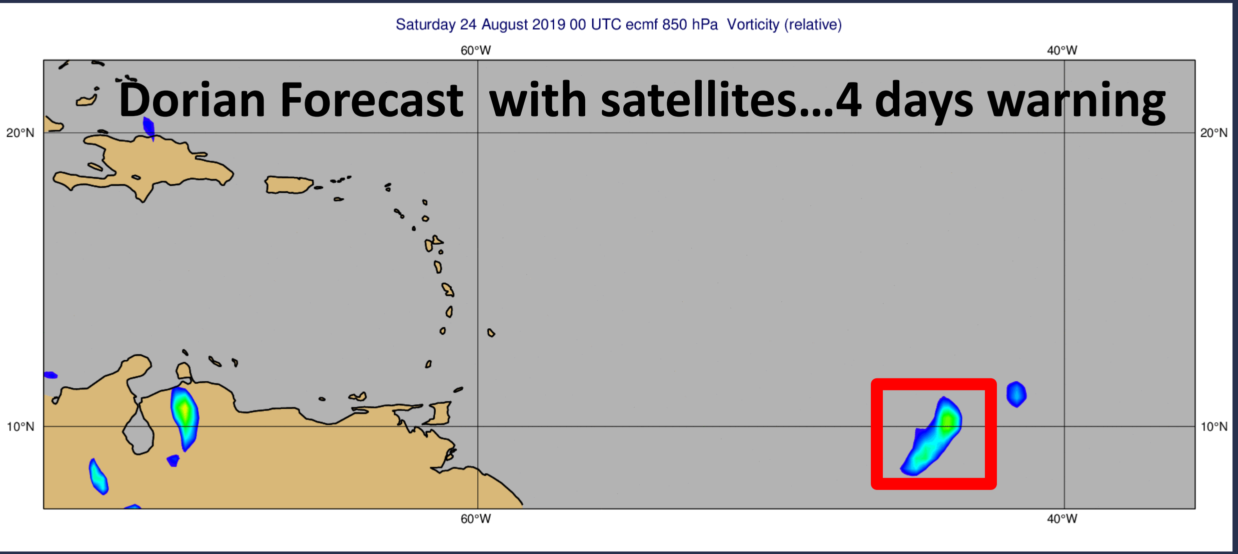
Dorian viewed from the Sentinel-3 satellite

Dorian viewed from the Sentinel-3 satellite

Dorian viewed from the Bahamas

Most deadly event in recent history is Nargis (2008) that claimed ~ 130,000 lives

Early identification of storm genesis and forecasts of trajectory saves many thousands of lives every year

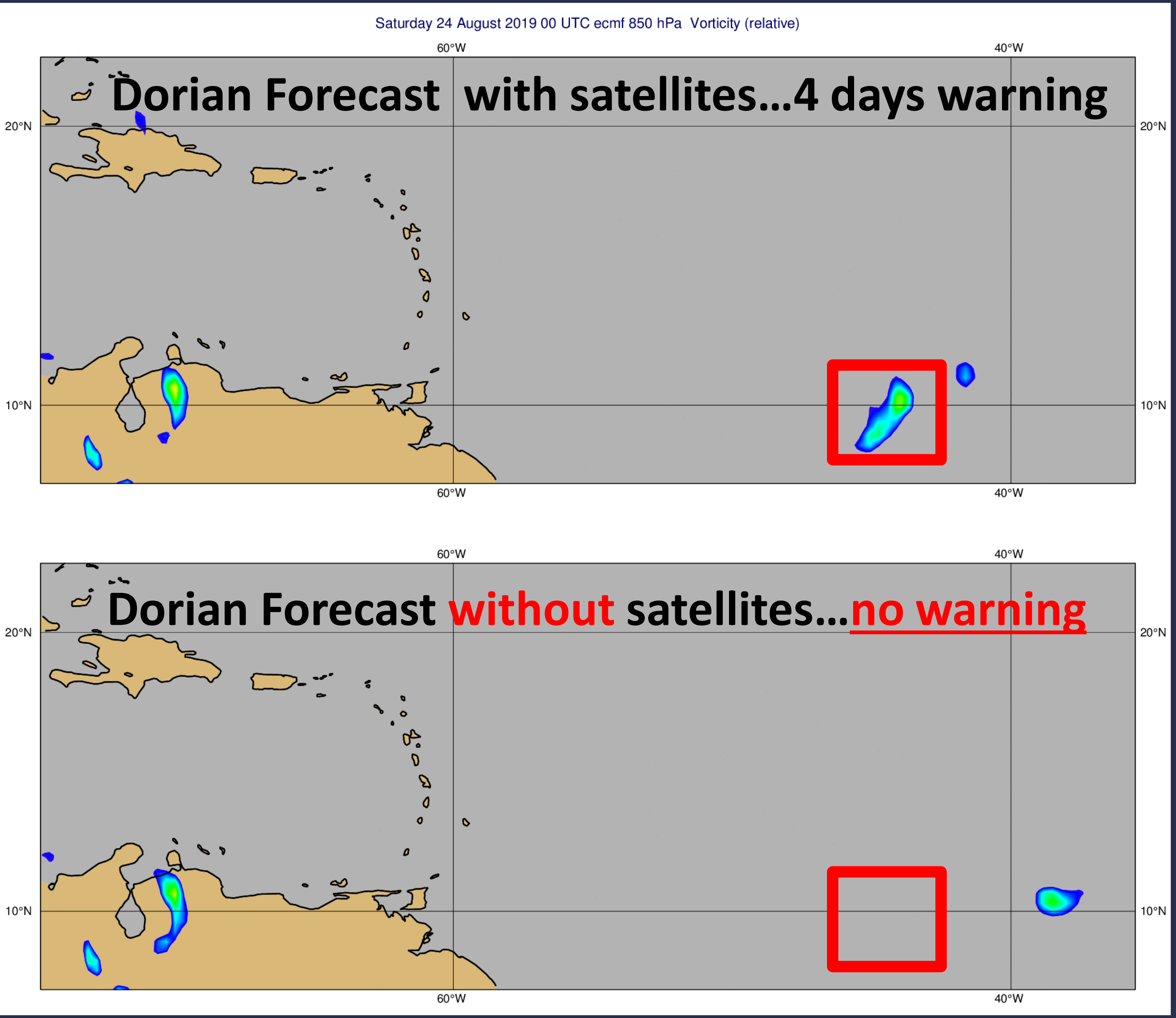


Key information

1. Ocean surface temperature
2. mid level humidity
3. wind sheer

Satellites provide this …

Without satellites we would often give no warning of severe life threateneing weather!



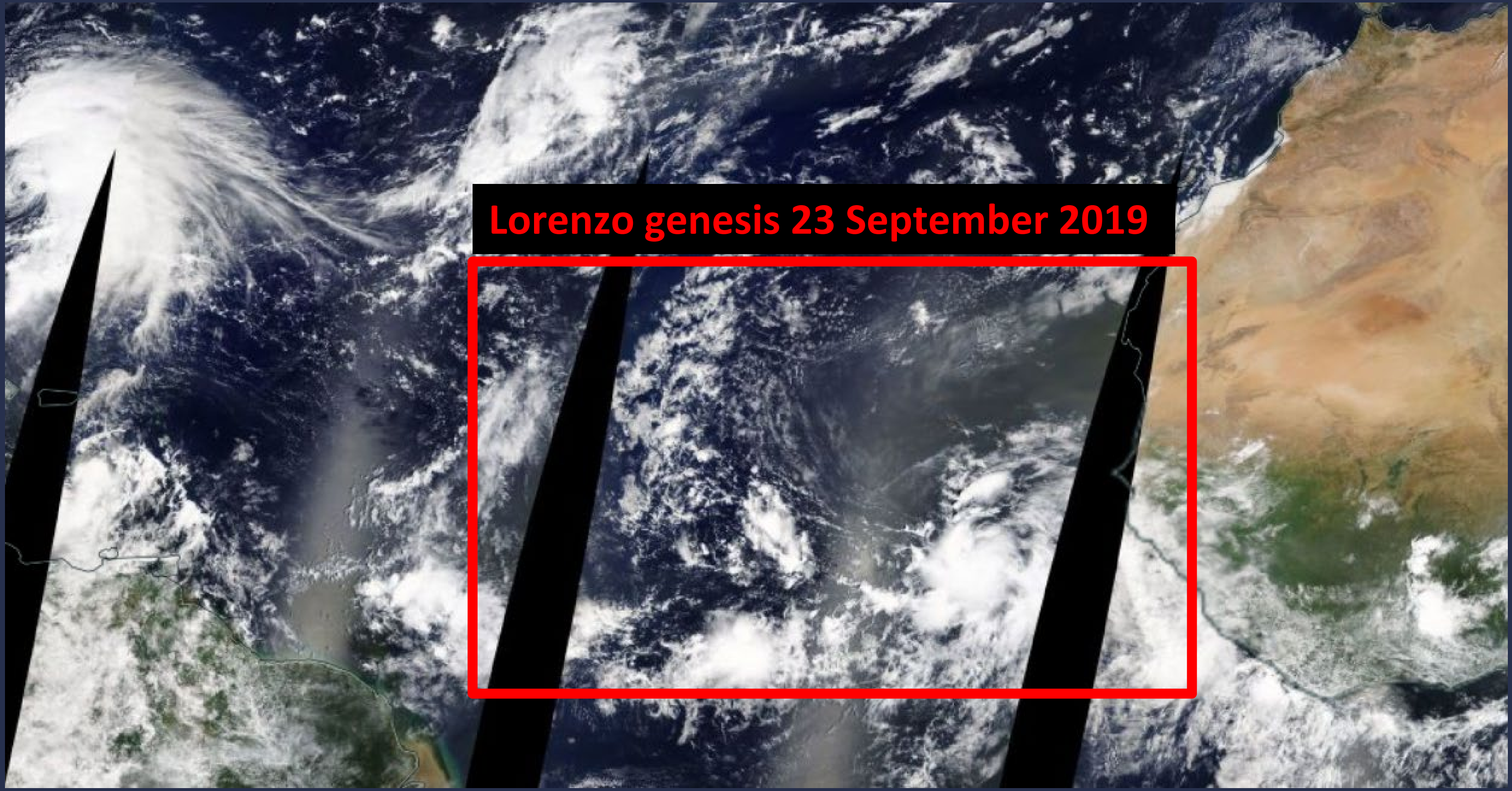
~~Key observations~~

1. ~~Ocean surface temperature~~
2. ~~mid level humidity~~
3. ~~wind sheer~~

Early identification of storm genesis...Lorenzo

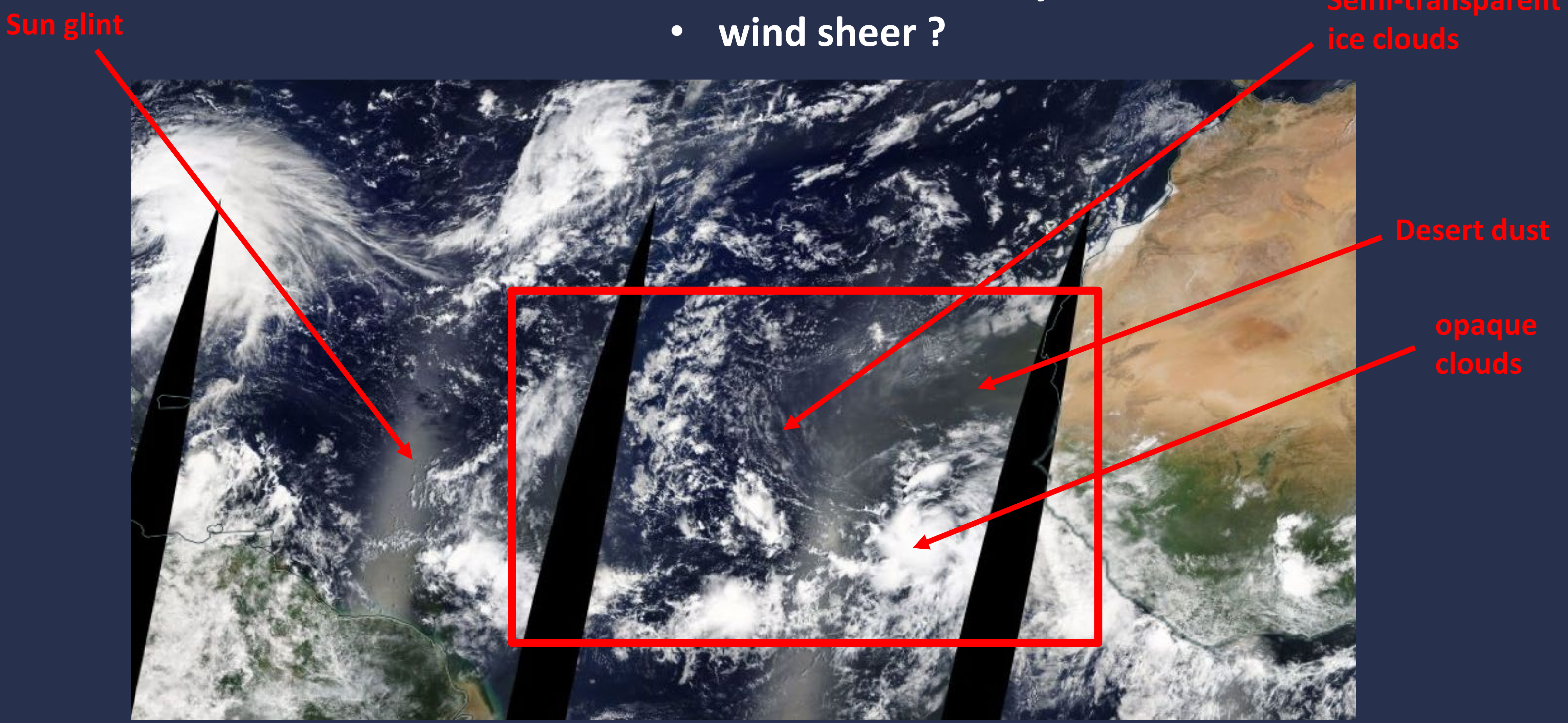
Key observations

- Ocean surface temperature ?
- mid level humidity ?
- wind sheer ?



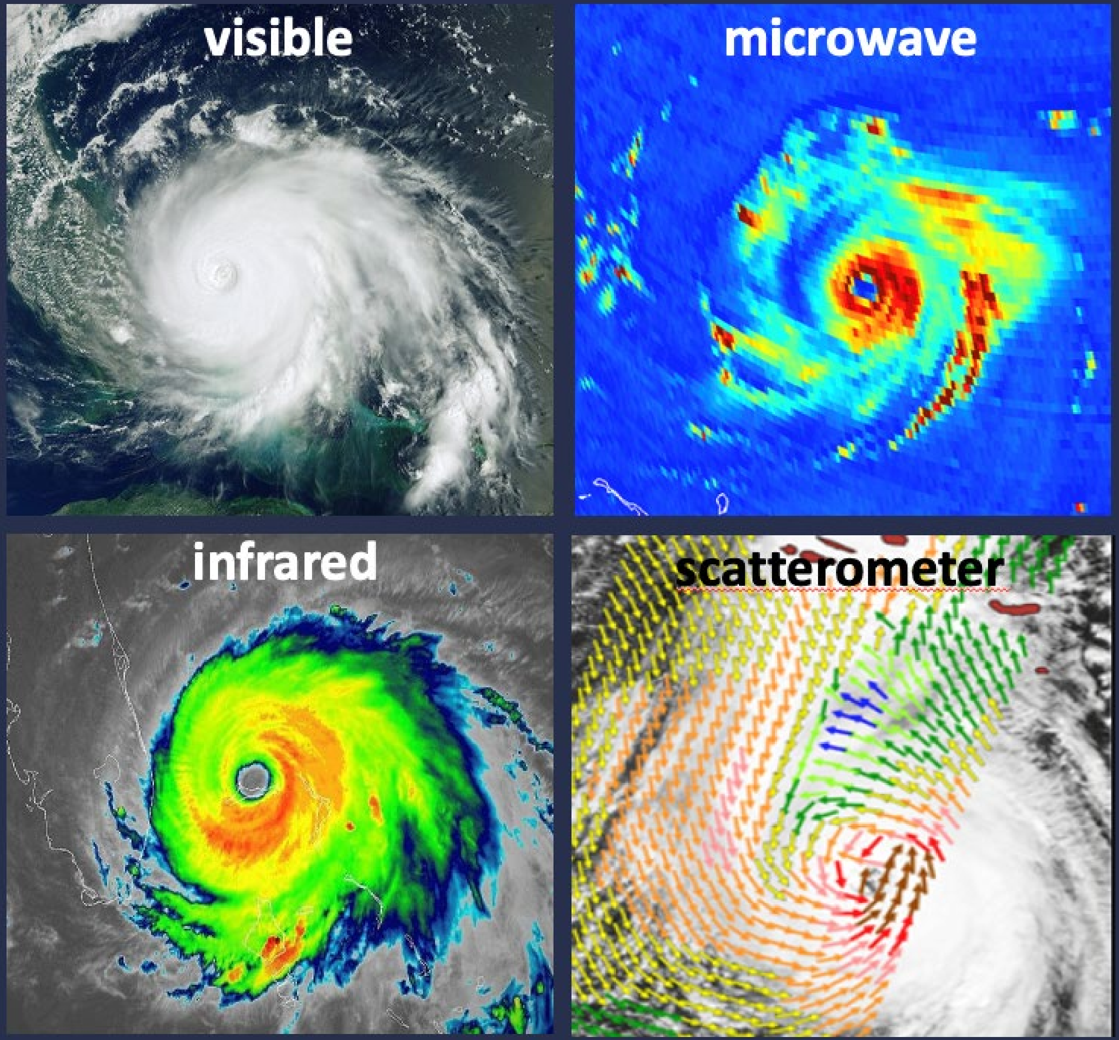
Early identification of storm genesis…in a challenging environment

- Ocean surface temperature ?
- mid level humidity ?
- wind sheer ?



Satellite sensors operating at <u>different</u> <u>frequencies</u> are used to understand the full atmospheric state…

Cloud phase and motion (wind)

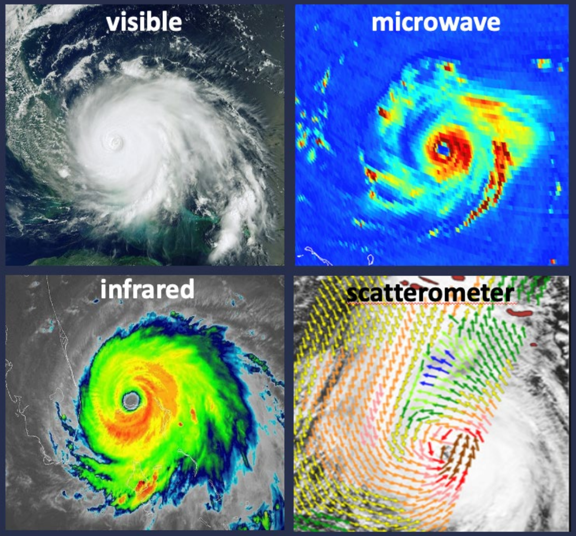


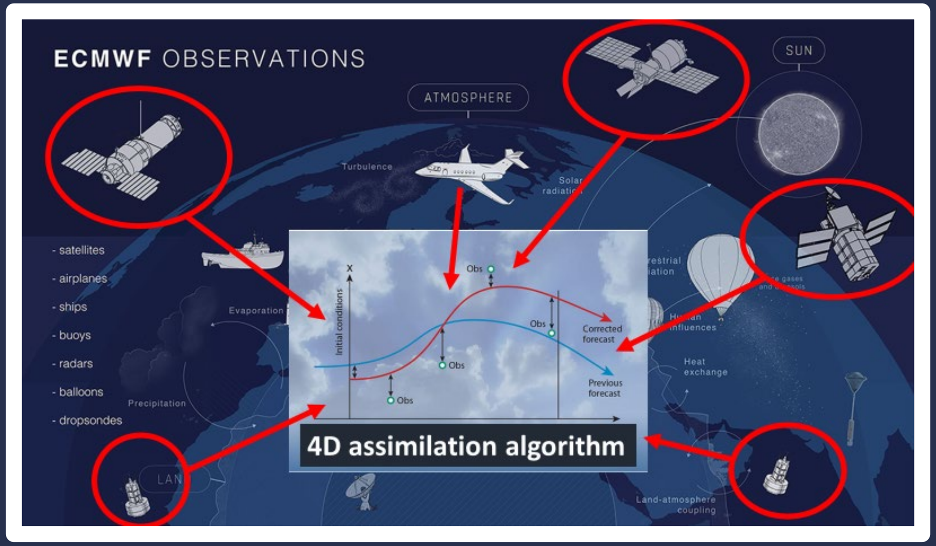
Water and rain content within clouds

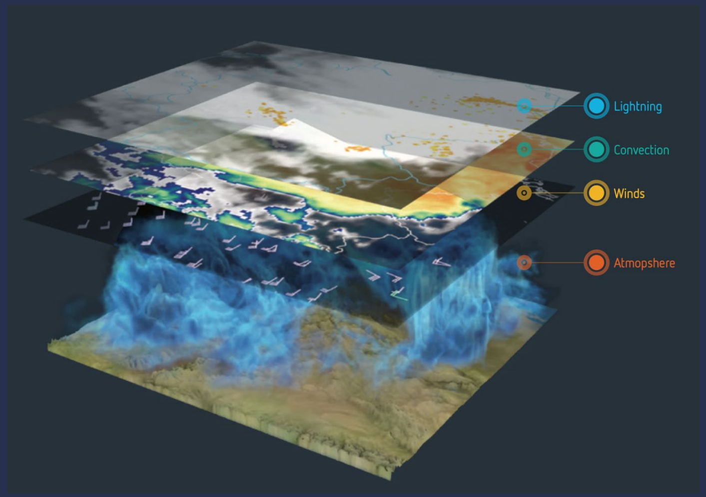
Temperature and height of clouds, humidity in clear sky

Penetrating the clouds to look at ocean roughness and land state

…But require highly sophisticated Data Assimilation Systems to combine these into a coherent 3D picture







Some notable recent achievements …

Some notable recent achievements …

1) Coupled DA across the different Earth systems

2) Feeding into intelligent WIGOS design and future OBS deployment (in collaboration with space agencies / WMO)

3) Onboarding ML across the entire OBS / DA workflow…not just emulate, but improve physics

Some examples of where we are today with observations and data assimilation

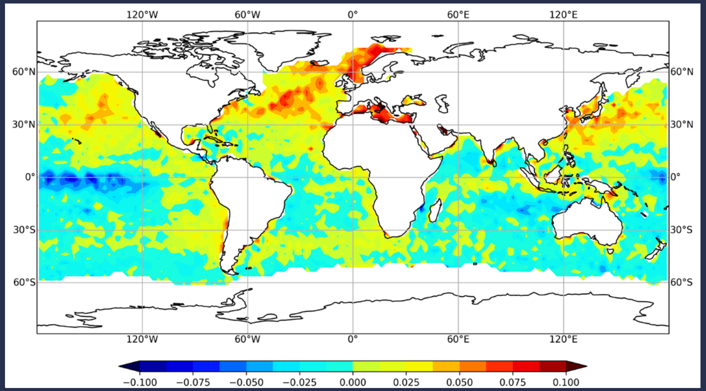
1) Coupled DA across the different Earth systems

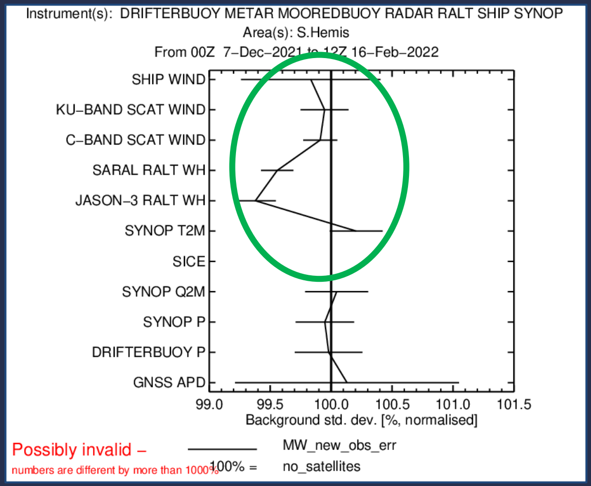
2) Feeding into intelligent WIGOS design and future OBS deployment

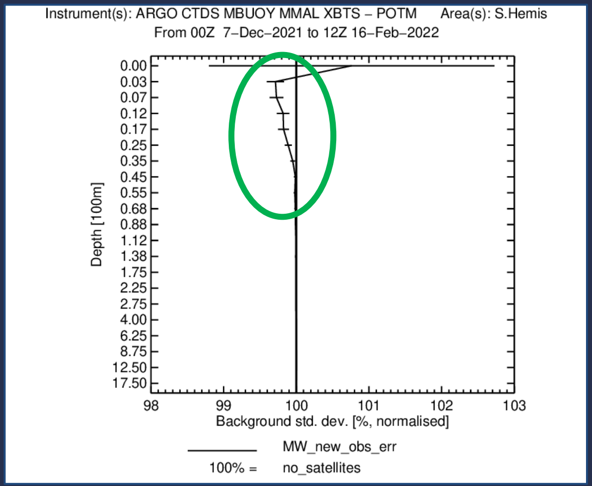
3) Onboarding ML across the entire OBS / DA workflow…not just emulate, but improve physics

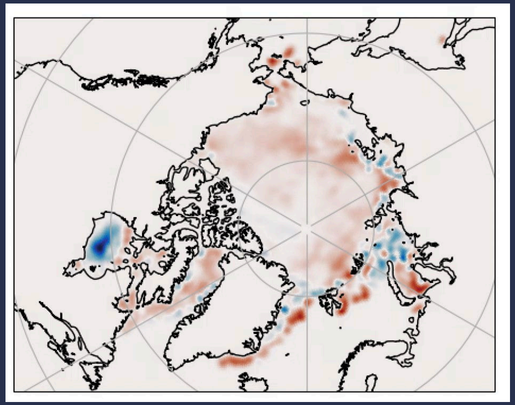
Satellites radiances constraining the ocean and sea-ice in coupled DA

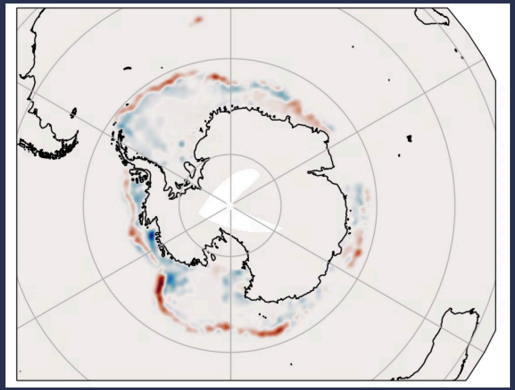
Low frequency MW radiances improving SST **and** the sub-surface…and improving sea-ice concentration











Some examples of where we are today with observations and data assimilation

1) Coupled DA across the different Earth systems

2) Feeding into intelligent WIGOS design and future OBS deployment (in collaboration with space agencies / WMO)

3) Onboarding ML across the entire OBS / DA workflow…not just emulate, but improve physics

Planning the Observing System of tomorrow…WMO SOFF

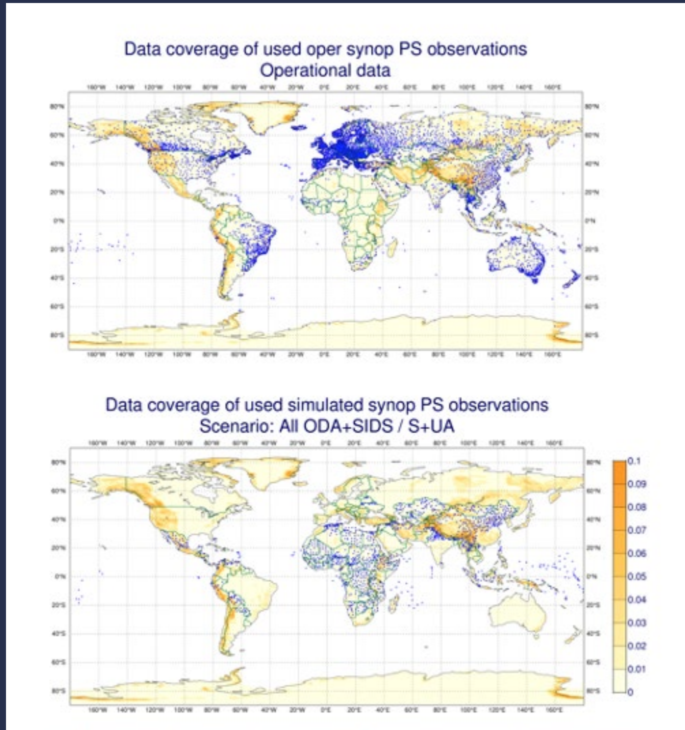
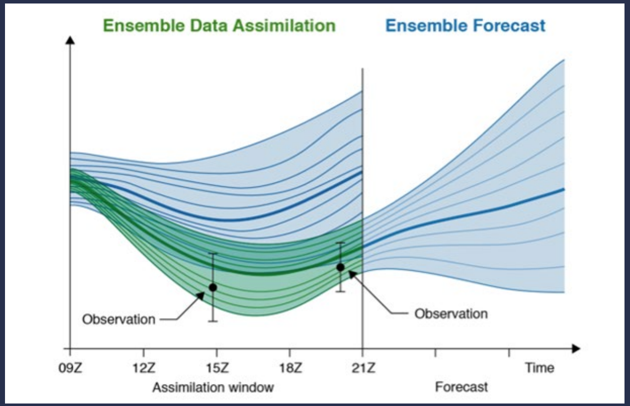
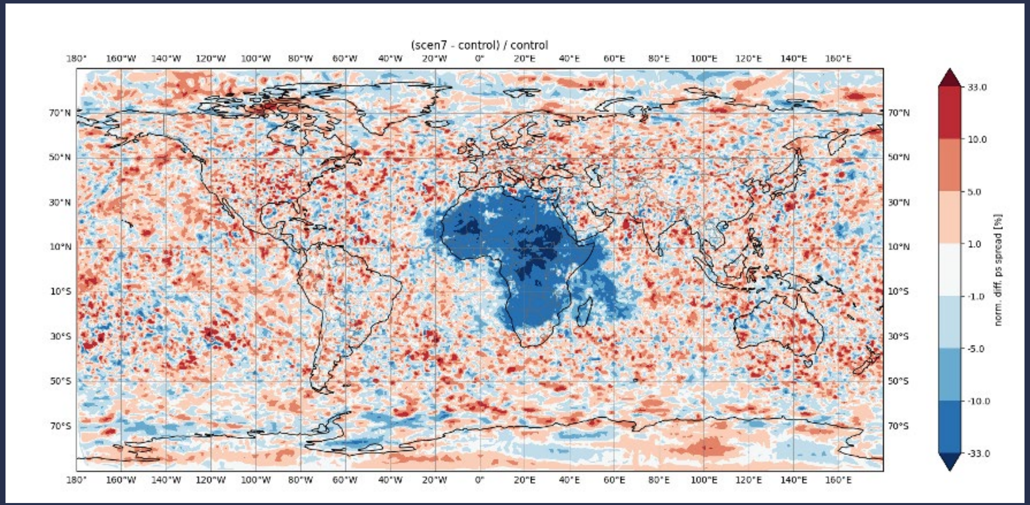
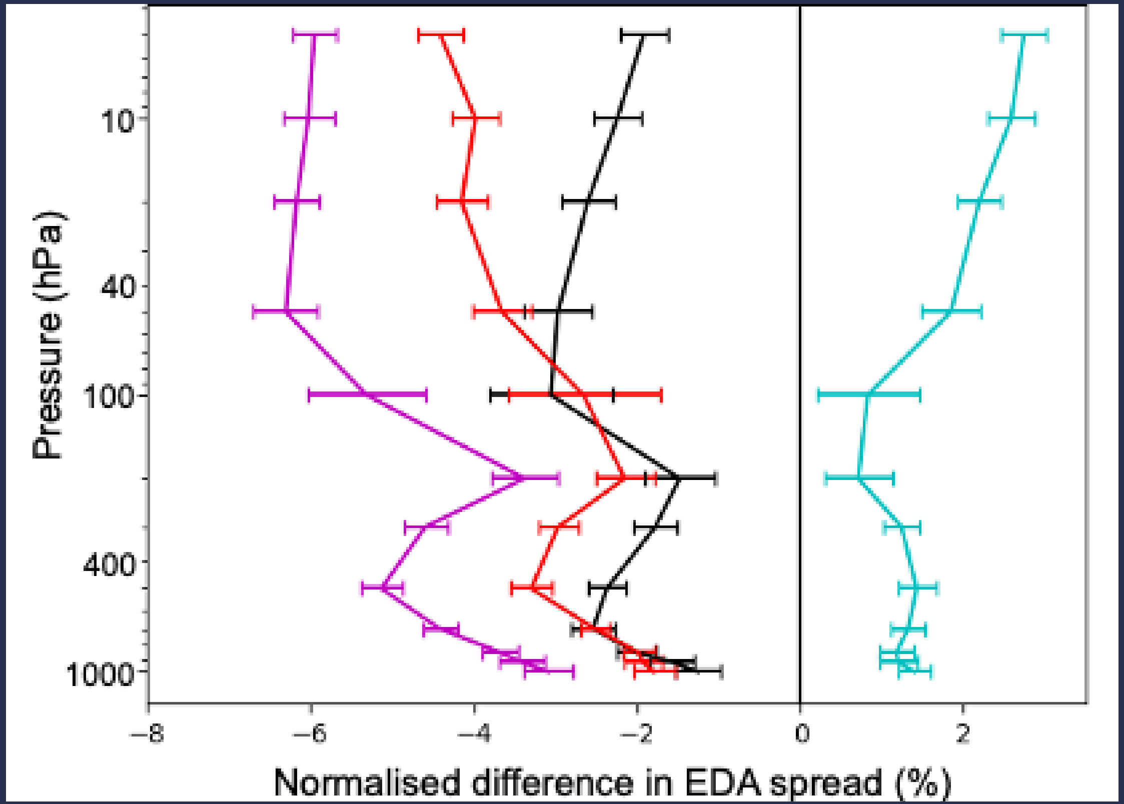


Figure 1: The blue dots show the coverage of real synop/Metar (upper panel) measurements and simulated surface measurements from scenario 3 (lower panel) The shading is the slope of the orography.

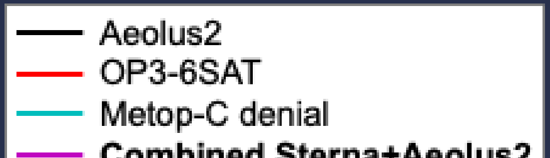




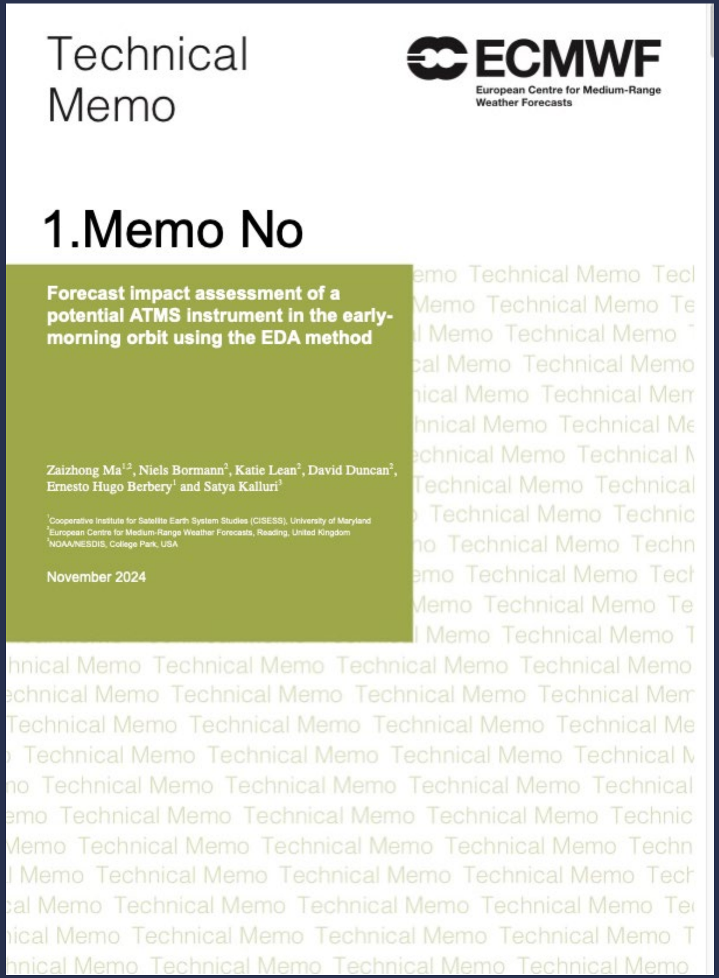
Planning the Observing System of tomorrow…EPS Sterna / Aeolus



Wind (NH)



Planning the Observing System of tomorrow…NOAA orbit deployment



Technical Memo

ECMWF
European Centre for Medium-Range Weather Forecasts

1.Memo No

Forecast impact assessment of a potential ATMS instrument in the early-morning orbit using the EDA method

Zaizhong Ma[1,2], Niels Bormann[2], Katie Lean[2], David Duncan[2], Ernesto Hugo Berbery[1] and Satya Kalluri[3]

[1]Cooperative Institute for Satellite Earth System Studies (CISESS), University of Maryland
[2]European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom
[3]NOAA/NESDIS, College Park, USA

November 2024

Some examples of where we are today with observations and data assimilation

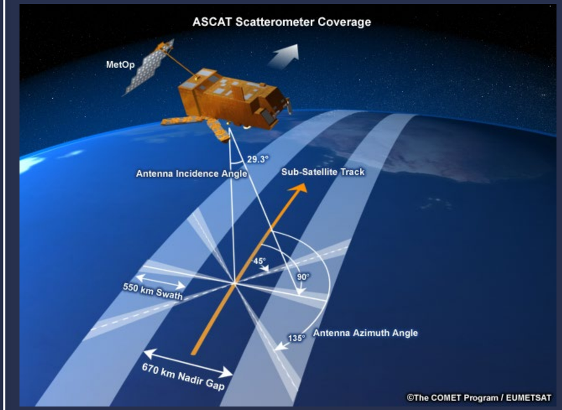
1) Coupled DA across the different Earth systems

2) Feeding into intelligent WIGOS design and future OBS deployment (in collaboration with space agencies / WMO)

3) Onboarding ML across the entire OBS / DA workflow…not just emulate, but improve physics

Direct assimilation of ASCAT sigma0 with a machine learned model function

Current approach



$\sigma^0_{fore}, \sigma^0_{mid}, \sigma^0_{aft}$

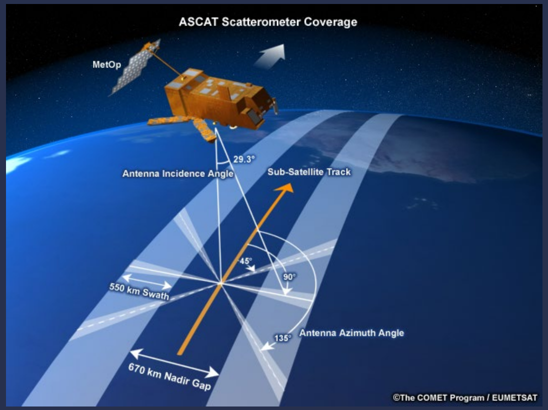
$\theta_{fore}, \theta_{mid}, \theta_{aft}, \phi$

Intermediate wind ambiguous wind retrieval

$\cancel{U_{10N}, V_{10N}}$

4DVar

New approach



$\sigma^0_{fore}, \sigma^0_{mid}, \sigma^0_{aft}$

$\theta_{fore}, \theta_{mid}, \theta_{aft}, \phi$

- sea-state,
- ocean currents,
- precipitation
- …

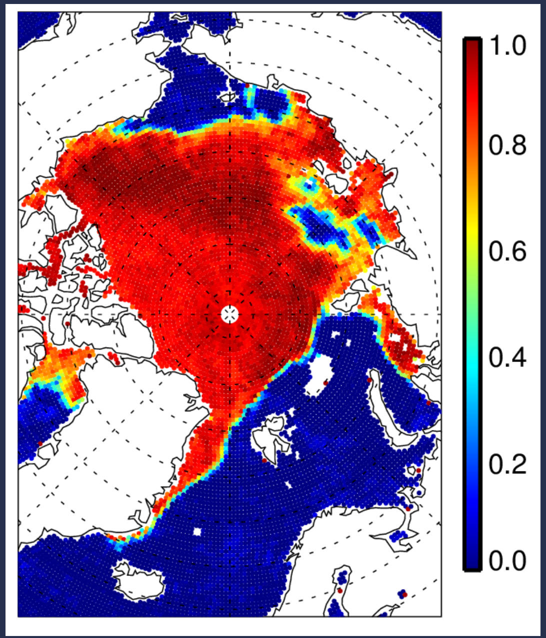
Machine learned (TL/AD)

including sea state

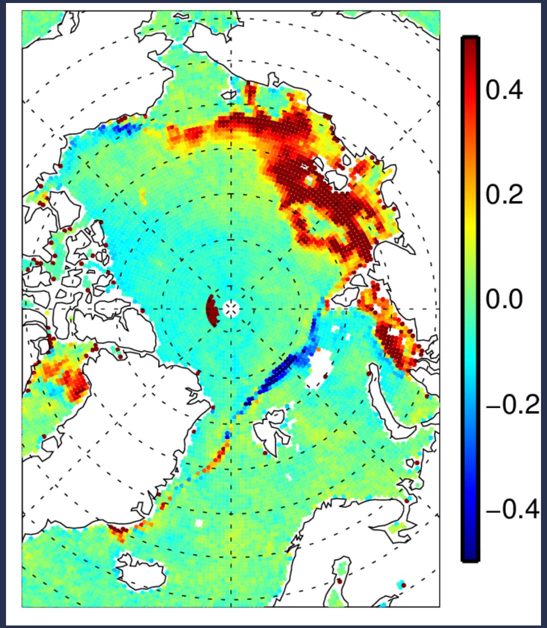
4DVar

Machine learned sea ice emissivity + concentration assisting microwave radiance assimilation (10GHz / TensorFlow)

ML sea ice from AMSR2/10GHz

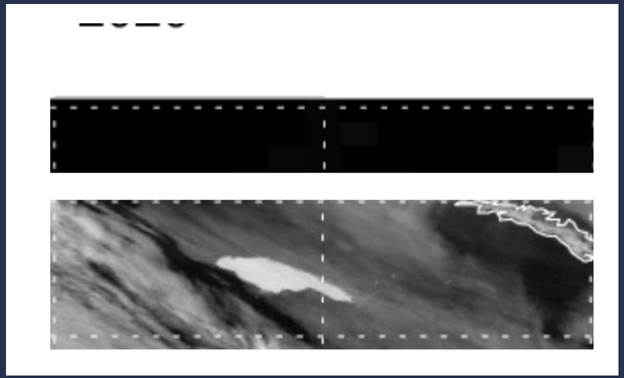


OSTIA difference



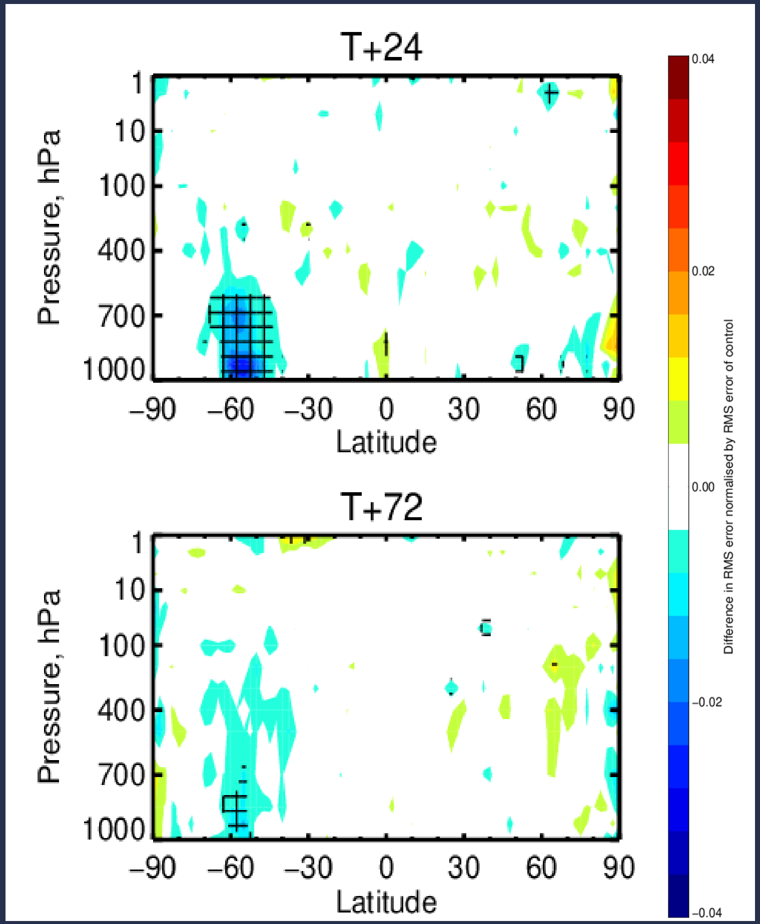
ML-ice

OLCI



Iceberg A68A
4th Dec 2020

The 10GHz sea ice allows the assimilation of <u>other imager channels</u> over frozen oceans

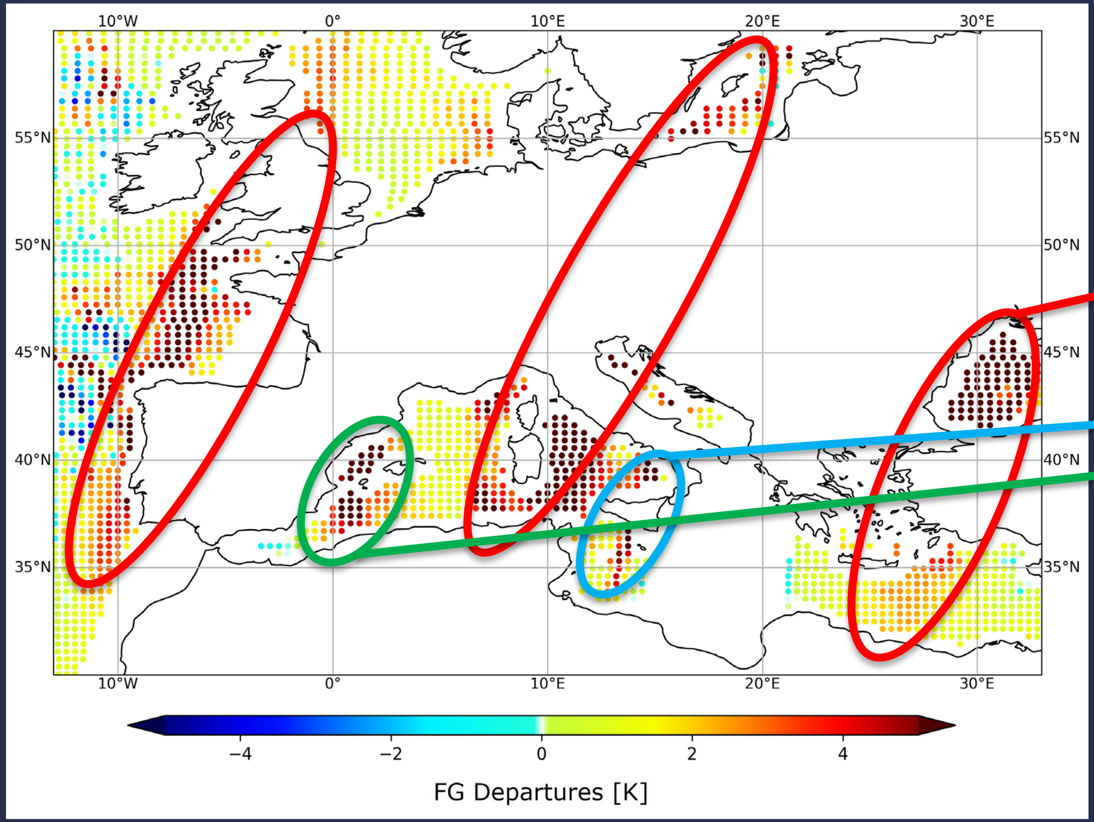


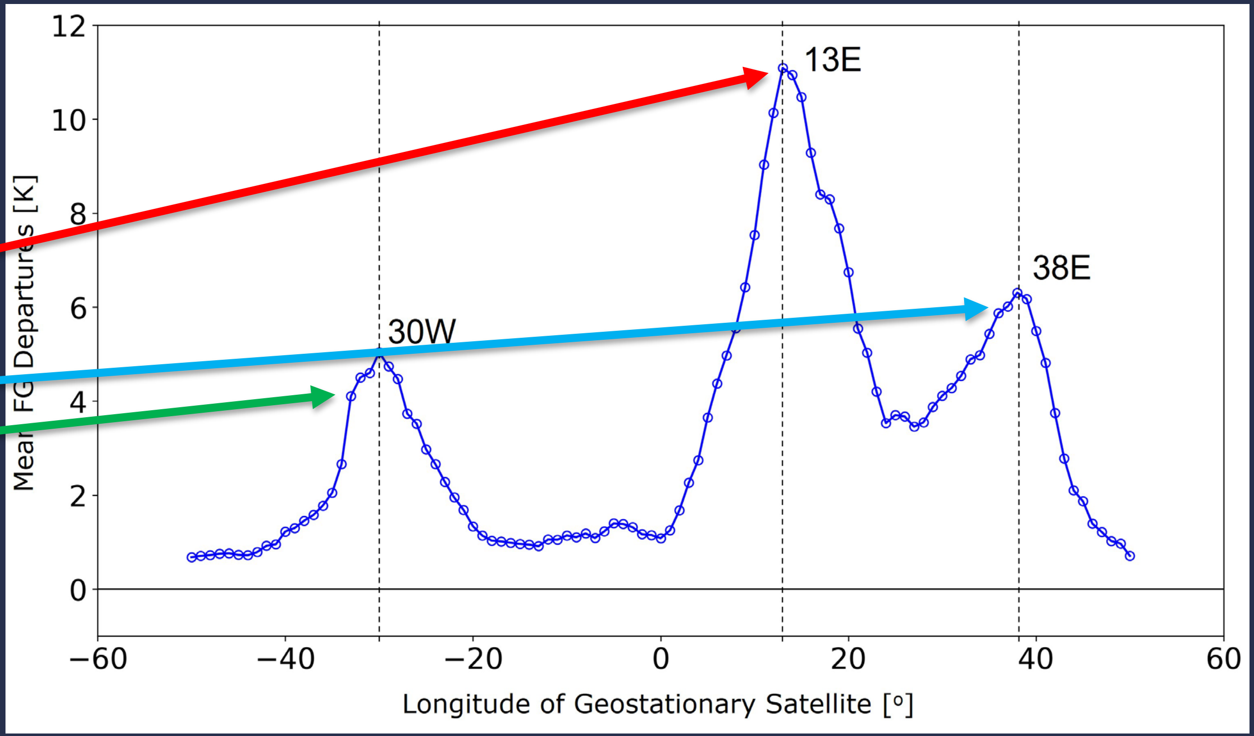
A. Geer

But also some battles being fought …

Protecting our observations

- RFI caused by reflections of signals from direct broadcast satellites in geostationary orbit – clearly visible in background departures at 10 GHz.
- We can identify where the relevant satellites are by calculating the glint for a given satellite position and analysing the background departures.

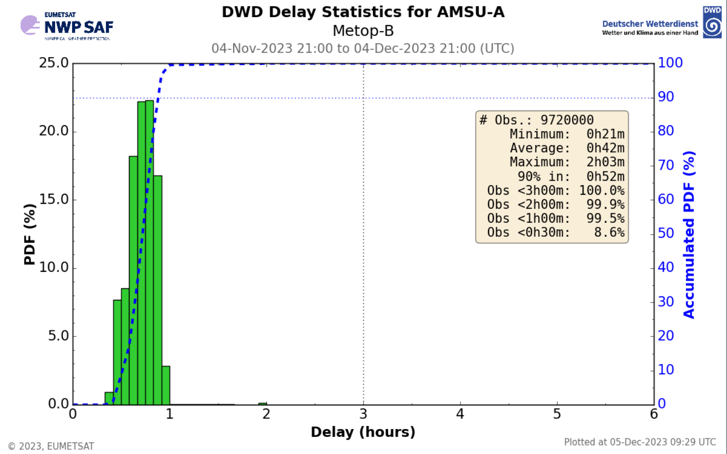


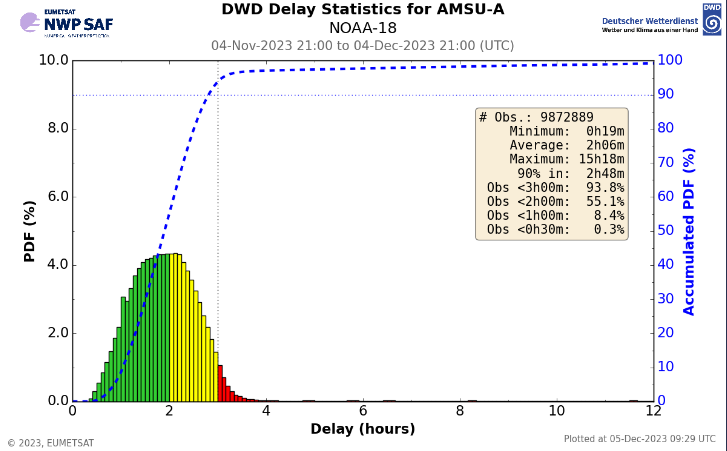


(Tracy Scanlon, Alan Geer)

Forecast impact of data timeliness

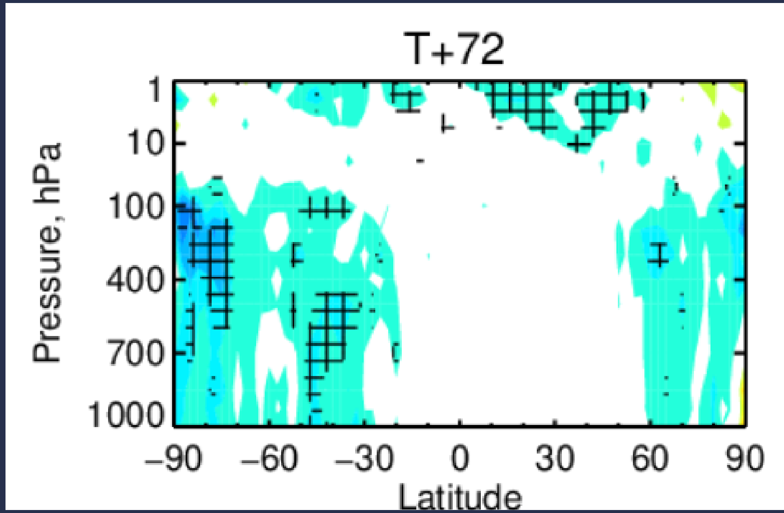
- End of window observations are the most recent and informative of the current state of the Earth System
- Since the introduction of Continuous DA, ECMWF is able to exploit observations made <u>very</u> close to the assimilation window end…as long as they arrive in time!!



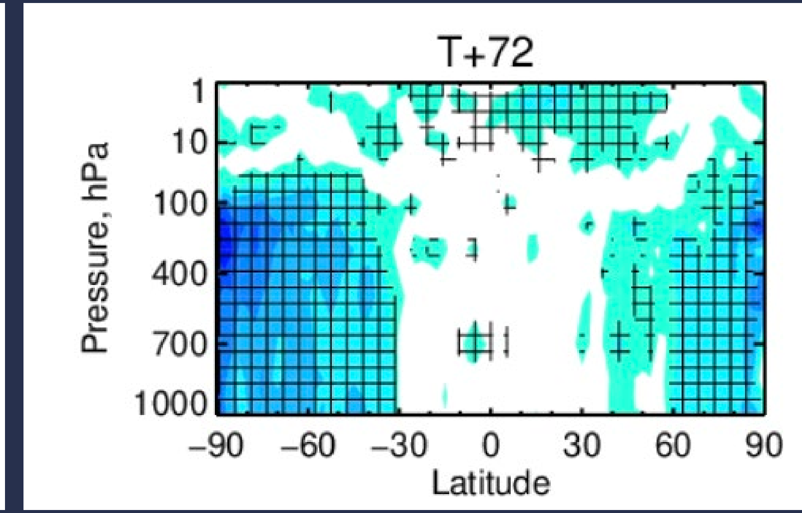


The impact of observation timeliness on forecast skill can be of the same order as adding a new satellite!

50 min vs 100 min
(1 vs 2 polar down links)



20 min vs 100 min
(1 polar down link vs DbNet)



Purchasing private sector observations

spire

Overview | News & Events | Stock Data | Financial Information | SEC Filings | Governance | Contacts | Spire.com

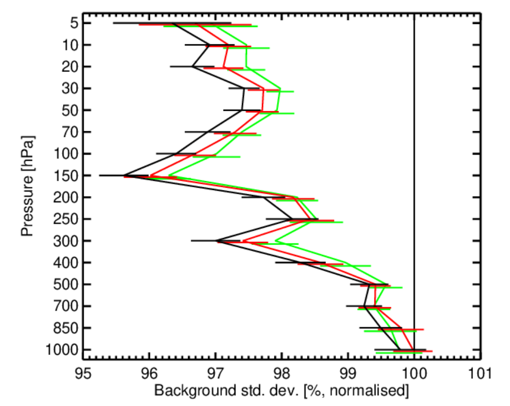
Spire Global Awarded $9.4 Million Contract by NOAA for Satellite Weather Data

January 08, 2024 6:45am EST

Download as PDF

Radio occultation data collected by the Company's satellite constellation improves the accuracy of global weather forecasts

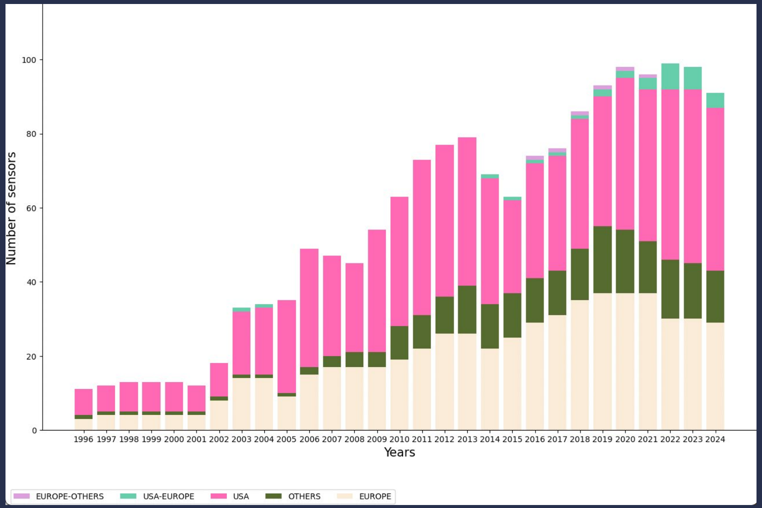
VIENNA, Va.--(BUSINESS WIRE)-- Spire Global, Inc. (NYSE: SPIR) ("Spire" or "the Company"), a global provider of space-based data, analytics and space services, has been awarded $9.4 million by the National Oceanographic and Oceanic Administration (NOAA) to provide radio occultation (RO) data for an 8-month period. The award is part of an Indefinite Delivery Indefinite Quantity (IDIQ) contract for NOAA's Commercial Weather Data Program's Radio Occultation Data Buy II.



All none SPIRE
All none SPIRE + EUMETSAT SPIRE
All none SPIRE + EUMETSAT SPIRE + NOAA SPIRE

ROMEX Data Volume (estimated)		
Mission	RO/day	Control
GRAS	1,200	y
COSMIC-2	6,000	y
US DO Order	5,500	n
EU Spire	1,400	n
GNOS	2,000	n
PlanetiQ	3,300	n
Yunyao	7,000	n
Binhu	100	n
KOMPSAT-5	300	y
PAZ	200	y
TerraSAR-X	100	y
TanDEM-X	100	y
Sentinel-6	800	y
Sum control	**8700**	**y**
ROMEX supplemental	**19300**	**n**
Sum ROMEX	**28000**	**n**

Continuing exchange of observations



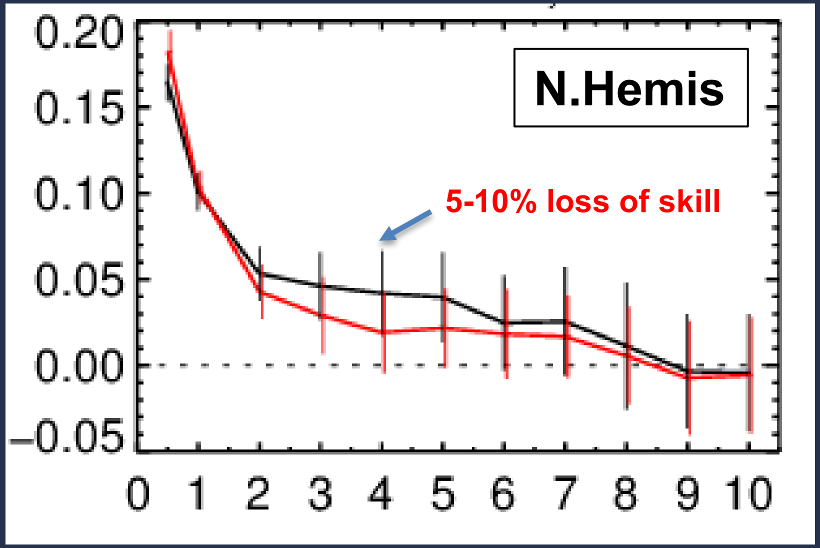
USA
AQUA
AURA
C-NOFS
CORIOLIS
COSMIC2
COSMIC
DMSP
GOES
JPSS
PlanetIQ
POES
QuikSCAT
SAC-C
SMAP
TERRA

EUROPE
Aeolus
CHAMP
CRYOSAT
ENVISAT
ERS
JASON
METEOSAT
METOP
Sentinel
SMOS
TanDEM-X
TerraSAR-X

USA-EUROPE
GRACE
JASON
Sentinel-6A
SPIRE-Lemur-3U
SPIRE

OTHERS
COMS-1
FY2
FY3
GCOM
GPM
HIMAWARI
HY2
INSAT-3D
KOMPSAT-5
MTSAT
OceanSat-2
SARAL
TRMM

EUROPE-OTHERS
MEGHA-TROPIQUES

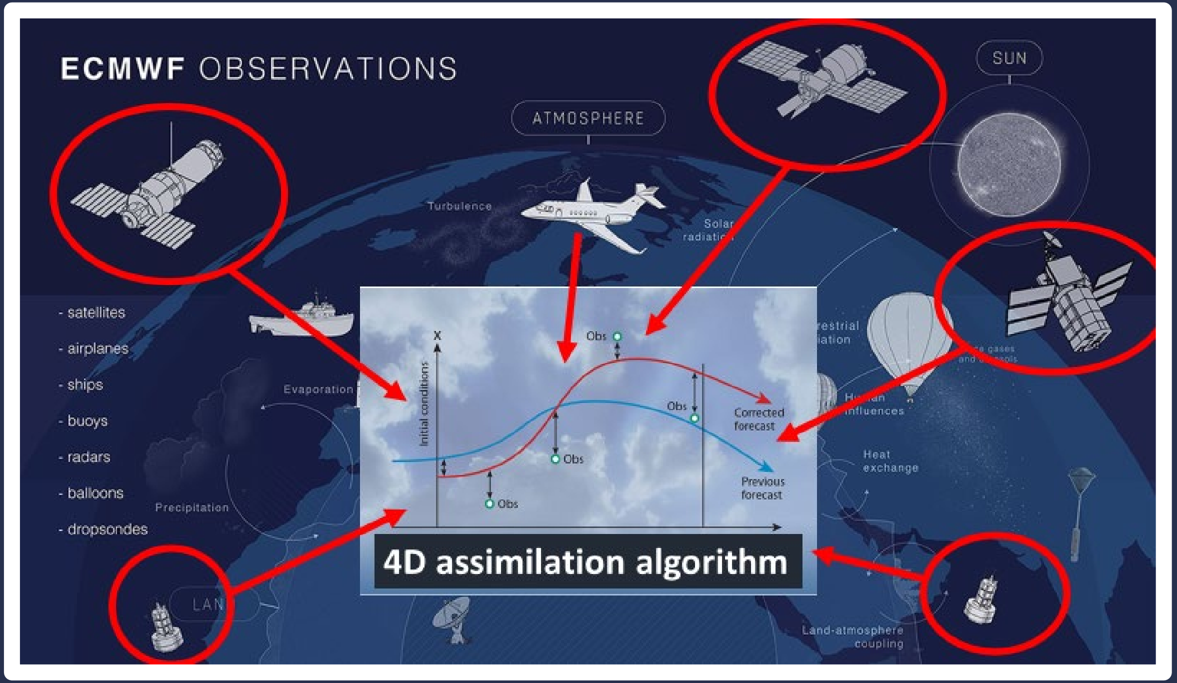


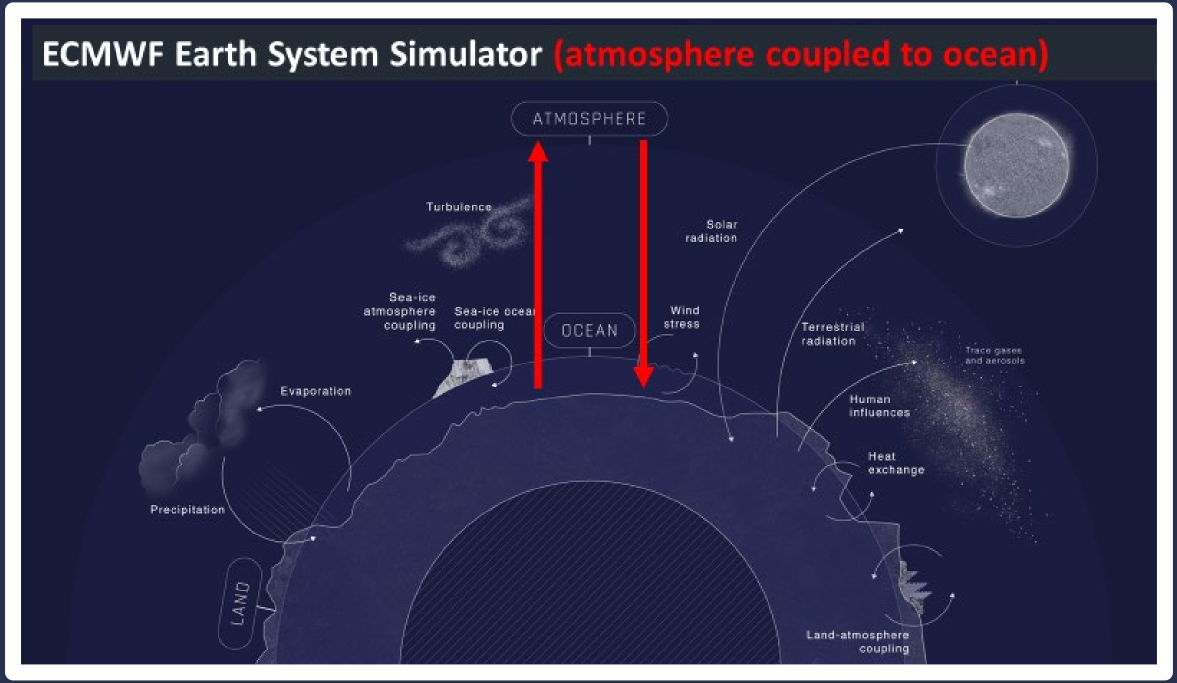
Using **only** US or **only** EU satellite data gives forecasts **significantly inferior to the control** ….successful inter-agency data exchange continues to be vital

Finally a quick look at the future …

…the real "Noisy revolution"

The Satellites and other observations provide **<u>initial conditions</u>** (what the atmosphere doing now) from which forecasts are launched





Can observations contribute **more directly** to improved weather forecasts ?

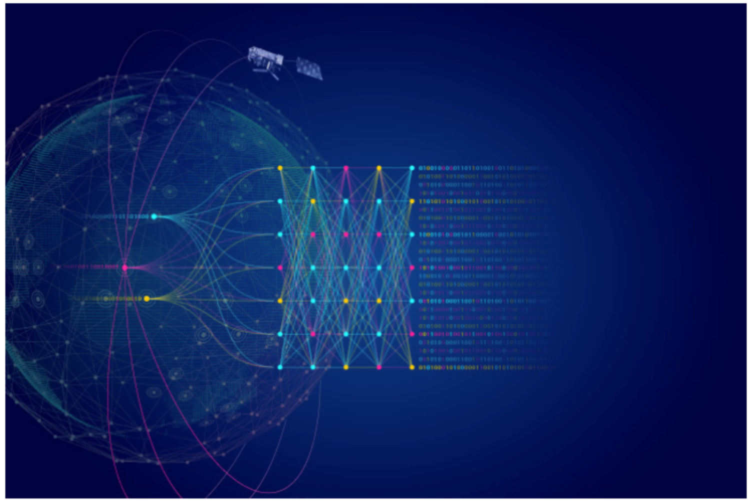
…go beyond initial conditions

Workshop on data assimilation: initial conditions and beyond

Overview
Programme
Confirmed speakers
Location
Hotel suggestions
Phishing warning
Code of conduct
Accessibility
Contact

Bonn, Germany | 9-10 April 2025

Part of ECMWF's 50th anniversary celebrations



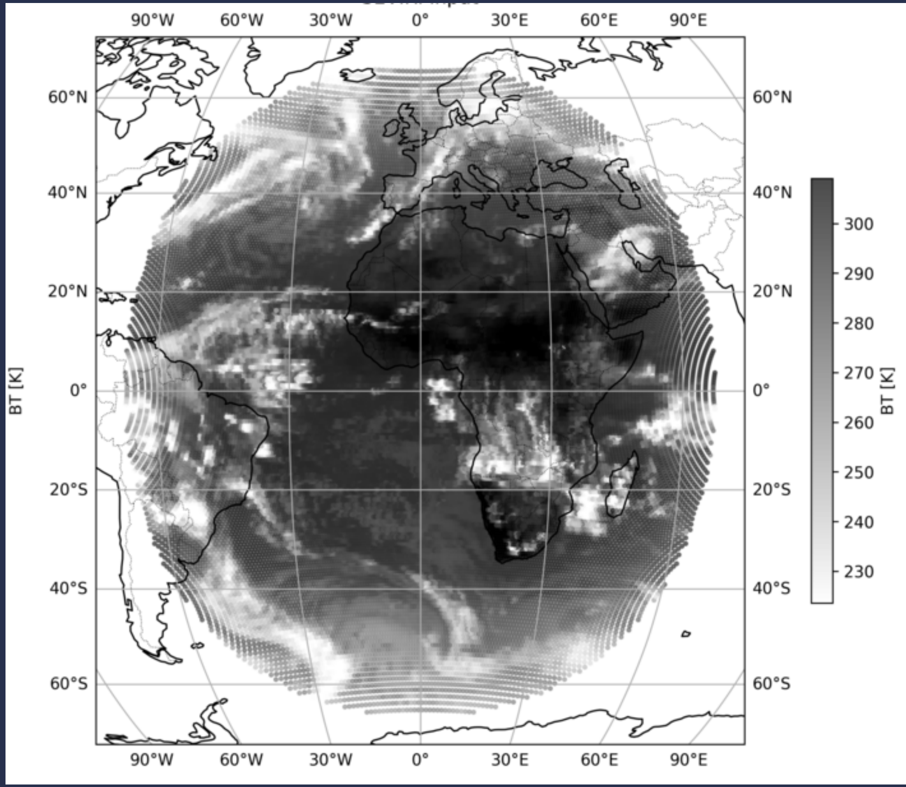
ECMWF | 50

Public livestream

Background

Data assimilation is traditionally about optimally blending observations and model information to provide the best estimate of the current state of the Earth system for both monitoring and prediction purposes. However,

If we build a forecast model in observation space…

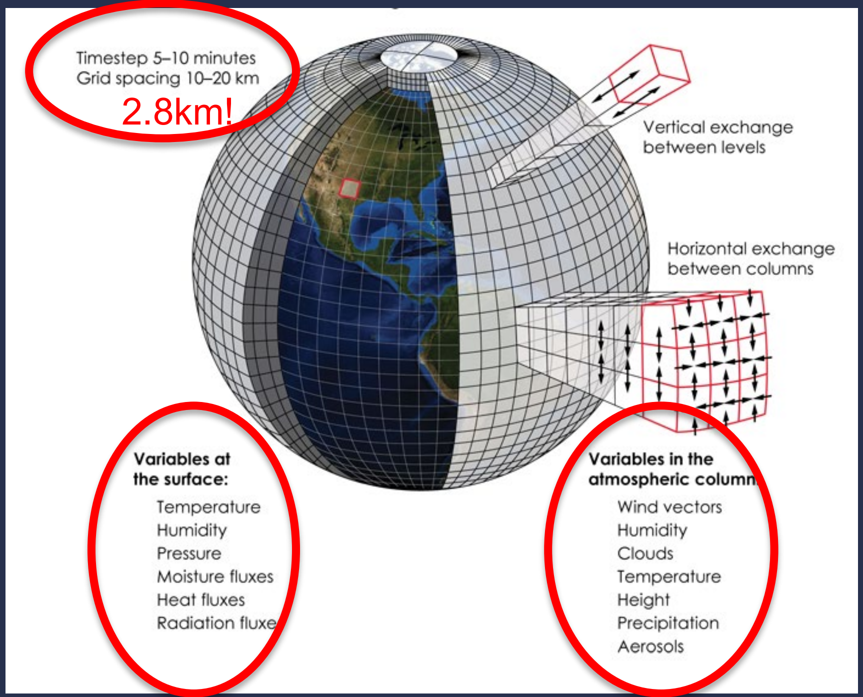


- use historical observations to train a Neural Network to predict future observations (don't need analyses)
- include observations of the full Earth system (atmosphere, ocean, land) simultaneously
- Use all observations, without demanding a detailed physical model of the measurement
- Once trained, we could initialize the model directly with the latest daily observations themselves

High-resolution and highly complex physics-based models present extreme challenges for DA

Observations are simply **insufficient** and generally of the **wrong variables** to provide initial conditions for NWP models of this resolution and complexity!

…so we are forced to blend observations with a background using DA….

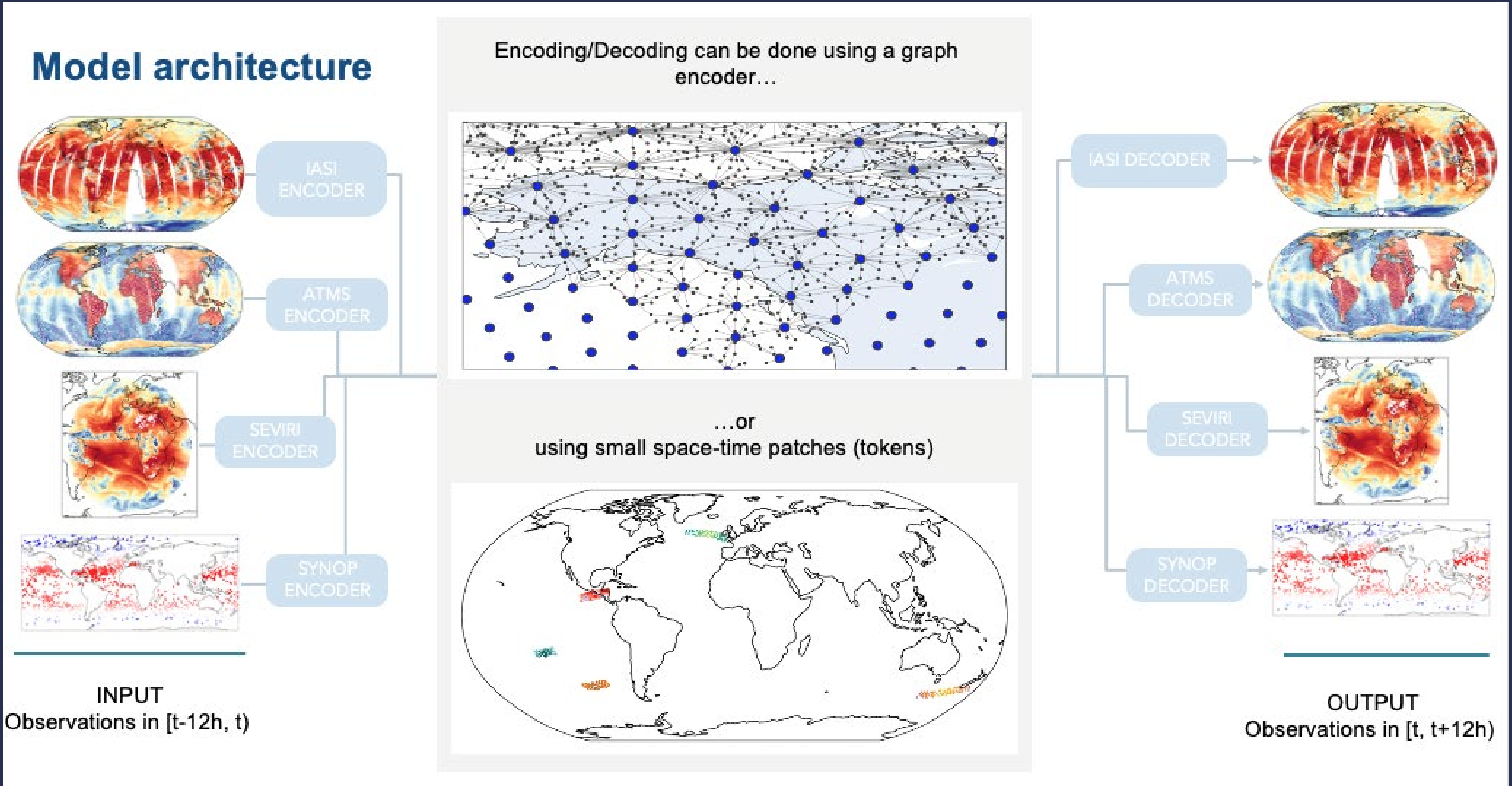


…requiring an exacting specification of poorly known error covariances (all huge multivariate tensors)

$$J(\mathbf{x}) \;=\; \frac{1}{2}(\mathbf{x}-\mathbf{x}_b)^T\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_b)+\frac{1}{2}[\mathcal{H}(\mathbf{x})-\mathbf{y}]^T\mathbf{R}^{-1}[\mathcal{H}(\mathbf{x})-\mathbf{y}]$$

Accurate observation operators potentially limiting limiting the observations we can exploit…

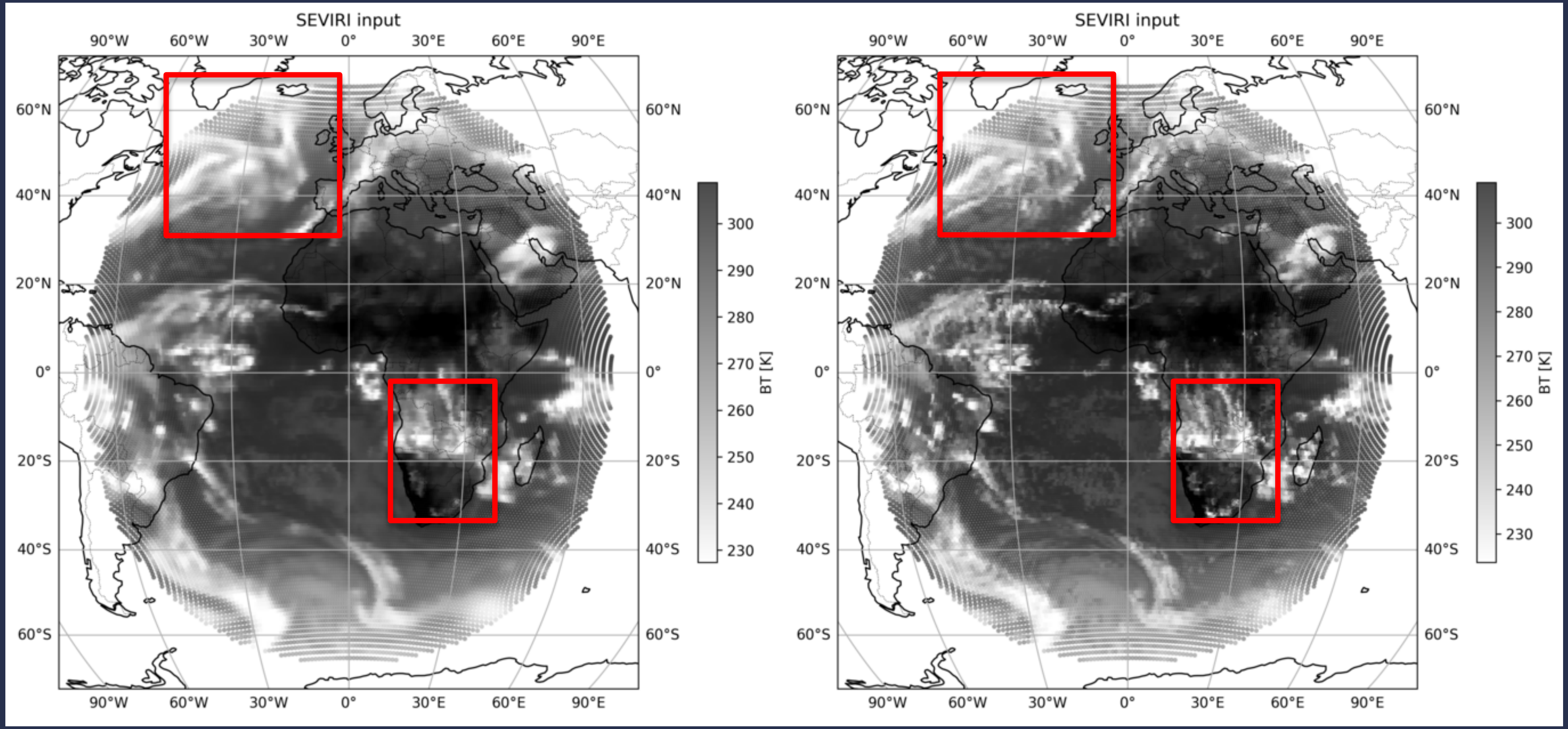
AI-DOP – prototype design



First medium-range forecasts directly from observations:

AI-DOP model

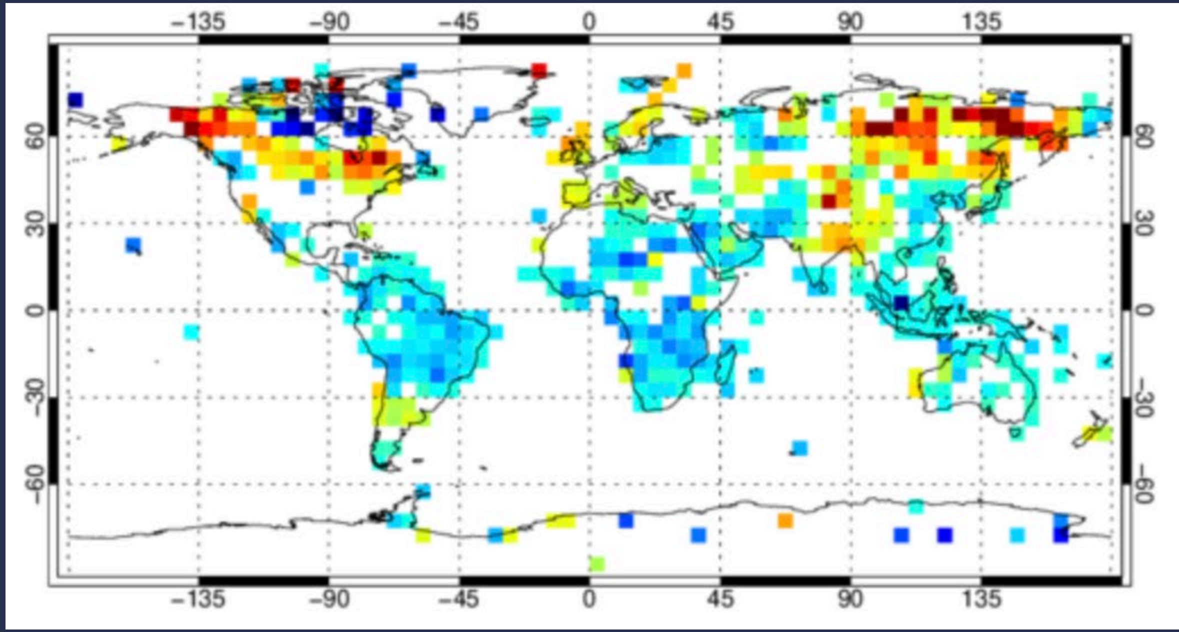
Target real observations



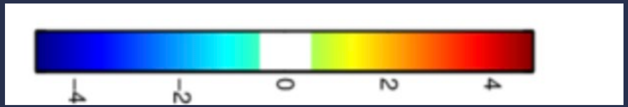
- No physics-based model
- No ERA5
- No background errors
- No observation errors
- No bias corrections
- No OBS operators

AI-DOP verification of weather parameter forecasts

T2m RMSE forecast error at t+120h for IFS and AI-DOP



AI-DOP better

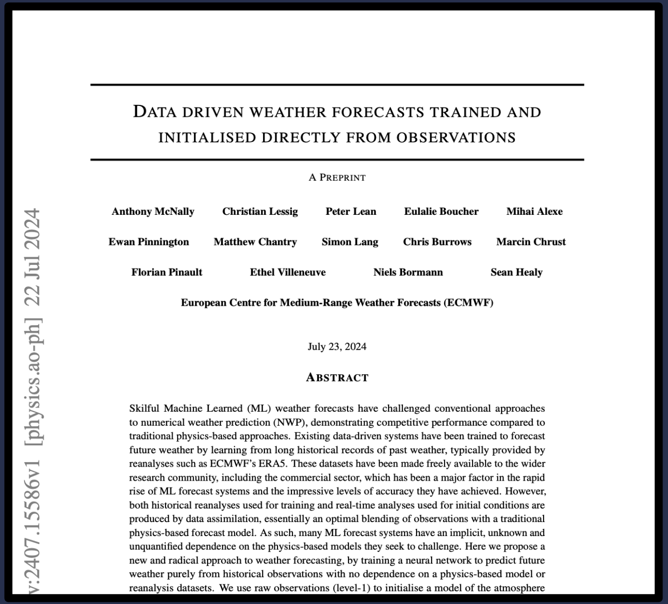


IFS 9km better

- Globally, slightly better than IFS at 24h, slightly worse at 120h
- Better than IFS over the tropics out to 120h (and beyond)
- Winter high latitude (snow) surfaces clearly a problem

Very early days, but if we can make this work…

- Obviate the most challenging aspects of conventional DA (which are only likely to get worse at km scale!)
- Full Earth system forecasting **without coupling**, by learning simultaneously from atmosphere, ocean and land / cryosphere observations and exploitation of **ALL** observations, even those with complex errors and difficult physics…even IOT!
- The value of observations goes **beyond just providing initial conditions** for physics-based NWP models – they become the model!
- Sustainable R2O process…with the only dependency on observations!



v:2407.15586v1 [physics.ao-ph] 22 Jul 2024

DATA DRIVEN WEATHER FORECASTS TRAINED AND INITIALISED DIRECTLY FROM OBSERVATIONS

A PREPRINT

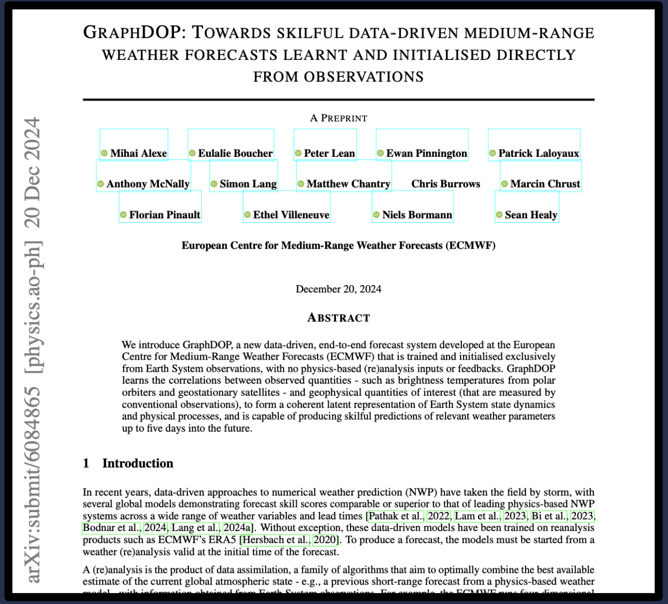
Anthony McNally, Christian Lessig, Peter Lean, Eulalie Boucher, Mihai Alexe, Ewan Pinnington, Matthew Chantry, Simon Lang, Chris Burrows, Marcin Chrust, Florian Pinault, Ethel Villeneuve, Niels Bormann, Sean Healy

European Centre for Medium-Range Weather Forecasts (ECMWF)

July 23, 2024

ABSTRACT

Skilful Machine Learned (ML) weather forecasts have challenged conventional approaches to numerical weather prediction (NWP), demonstrating competitive performance compared to traditional physics-based approaches. Existing data-driven systems have been trained to forecast future weather by learning from long historical records of past weather, typically provided by reanalyses such as ECMWF's ERA5. These datasets have been made freely available to the wider research community, including the commercial sector, which has been a major factor in the rapid rise of ML forecast systems and the impressive levels of accuracy they have achieved. However, both historical reanalyses used for training and real-time analyses used for initial conditions are produced by data assimilation, essentially an optimal blending of observations with a traditional physics-based forecast model. As such, many ML forecast systems have an implicit, unknown and unquantified dependence on the physics-based models they seek to challenge. Here we propose a new and radical approach to weather forecasting, by training a neural network to predict future weather purely from historical observations with no dependence on a physics-based model or reanalysis datasets. We use raw observations (level-1) to initialise a model of the atmosphere



arXiv:submit/6084865 [physics.ao-ph] 20 Dec 2024

GRAPHDOP: TOWARDS SKILFUL DATA-DRIVEN MEDIUM-RANGE WEATHER FORECASTS LEARNT AND INITIALISED DIRECTLY FROM OBSERVATIONS

A PREPRINT

Mihai Alexe, Eulalie Boucher, Peter Lean, Ewan Pinnington, Patrick Laloyaux, Anthony McNally, Simon Lang, Matthew Chantry, Chris Burrows, Marcin Chrust, Florian Pinault, Ethel Villeneuve, Niels Bormann, Sean Healy

European Centre for Medium-Range Weather Forecasts (ECMWF)

December 20, 2024

ABSTRACT

We introduce GraphDOP, a new data-driven, end-to-end forecast system developed at the European Centre for Medium-Range Weather Forecasts (ECMWF) that is trained and initialised exclusively from Earth System observations, with no physics-based (re)analysis inputs or feedbacks. GraphDOP learns the correlations between observed quantities - such as brightness temperatures from polar orbiters and geostationary satellites - and geophysical quantities of interest (that are measured by conventional observations), to form a coherent latent representation of Earth System state dynamics and physical processes, and is capable of producing skilful predictions of relevant weather parameters up to five days into the future.

1 Introduction

In recent years, data-driven approaches to numerical weather prediction (NWP) have taken the field by storm, with several global models demonstrating forecast skill scores comparable or superior to that of leading physics-based NWP systems across a wide range of weather variables and lead times [Pathak et al., 2022, Lam et al., 2023, Bi et al., 2023, Bodnar et al., 2024, Lang et al., 2024a]. Without exception, these data-driven models have been trained on reanalysis products such as ECMWF's ERA5 [Hersbach et al., 2020]. To produce a forecast, the models must be started from a weather (re)analysis valid at the initial time of the forecast.

A (re)analysis is the product of data assimilation, a family of algorithms that aim to optimally combine the best available estimate of the current global atmospheric state - e.g., a previous short-range forecast from a physics-based weather

Some concluding remarks

- Observations are the **only fundamental** in our business but have zero value until somebody does something useful with them. So, data providers and data users need to continue to collaborate!

- We have an amazing global observing system, but we need to protect this and continue to invest in new observations **and** the services that deliver value from these to citizens (NWP, COP)

- We are on the edge of a **noisy revolution** where observations will play a new and exciting role in the deliver of accurate weather predictions

Spare slides

AI-DOP – curation of observation training data

Microwave sounders
- ATMS
- AMSU-A
- SSMIS
- AMSR-2

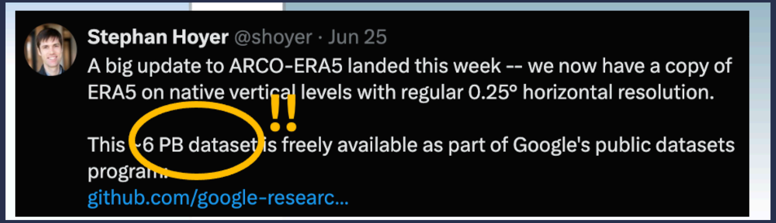
Infrared sounders
- IASI + AVHRR vis
- CrIS
- SEVIRI

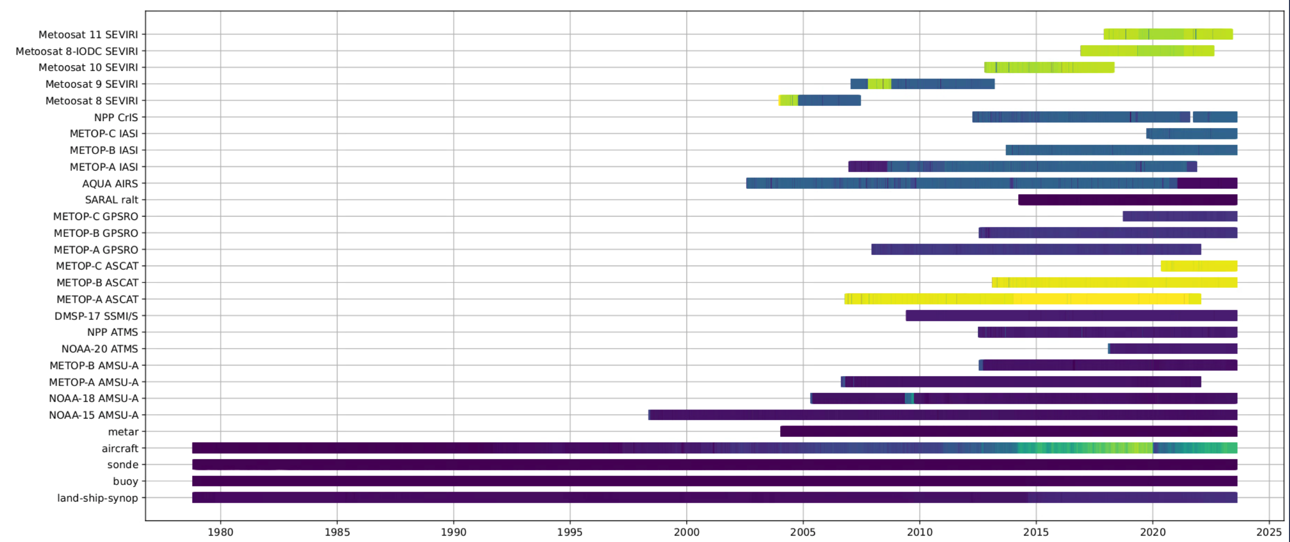
Scatterometer
- ASCAT

Radio occultation
- GPSRO

Radar altimeter
- RALT

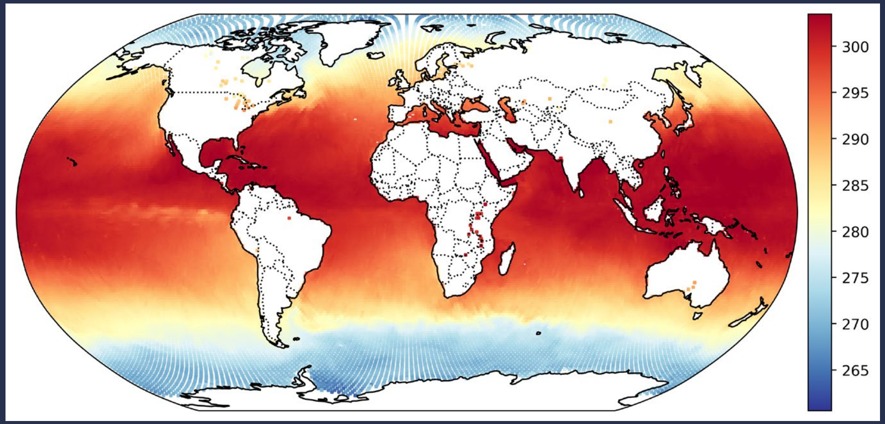
Conventional
- Surface stations (including buoys)
- Radiosondes
- Aircraft
- *Snow depth*
- *NEXRAD Precipitation*



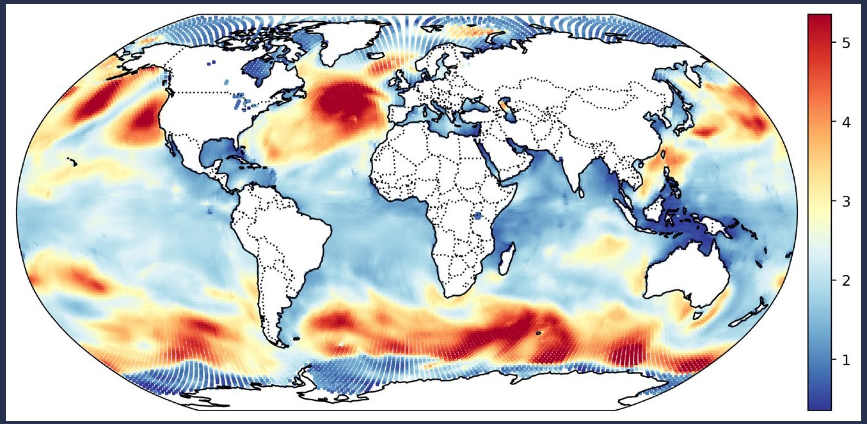


AI-DOP 10-day forecasts

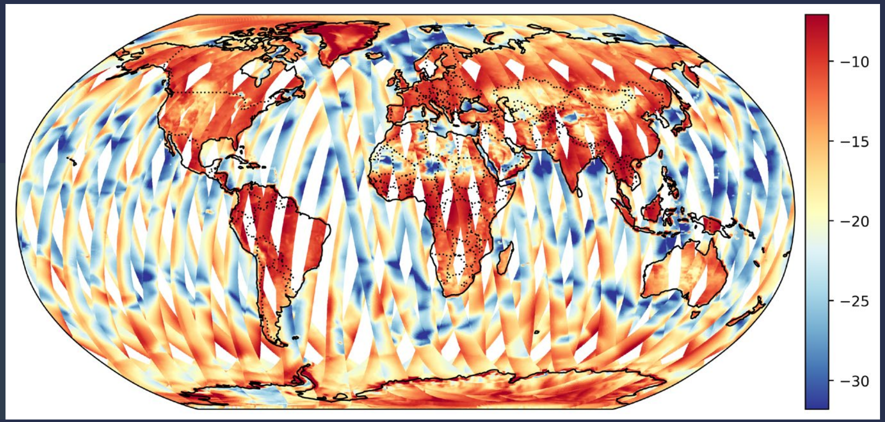
SST drifters

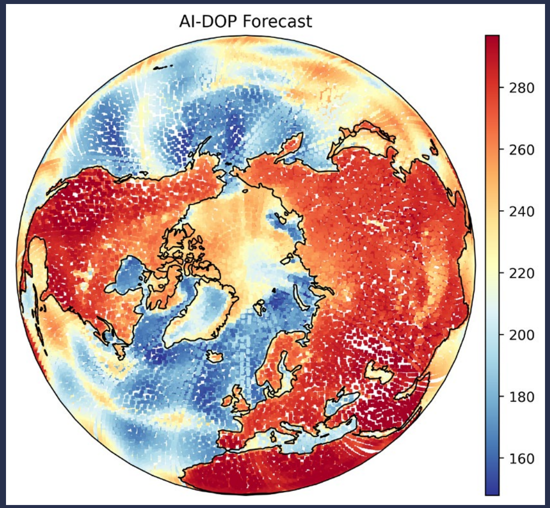


Altimeter wave height



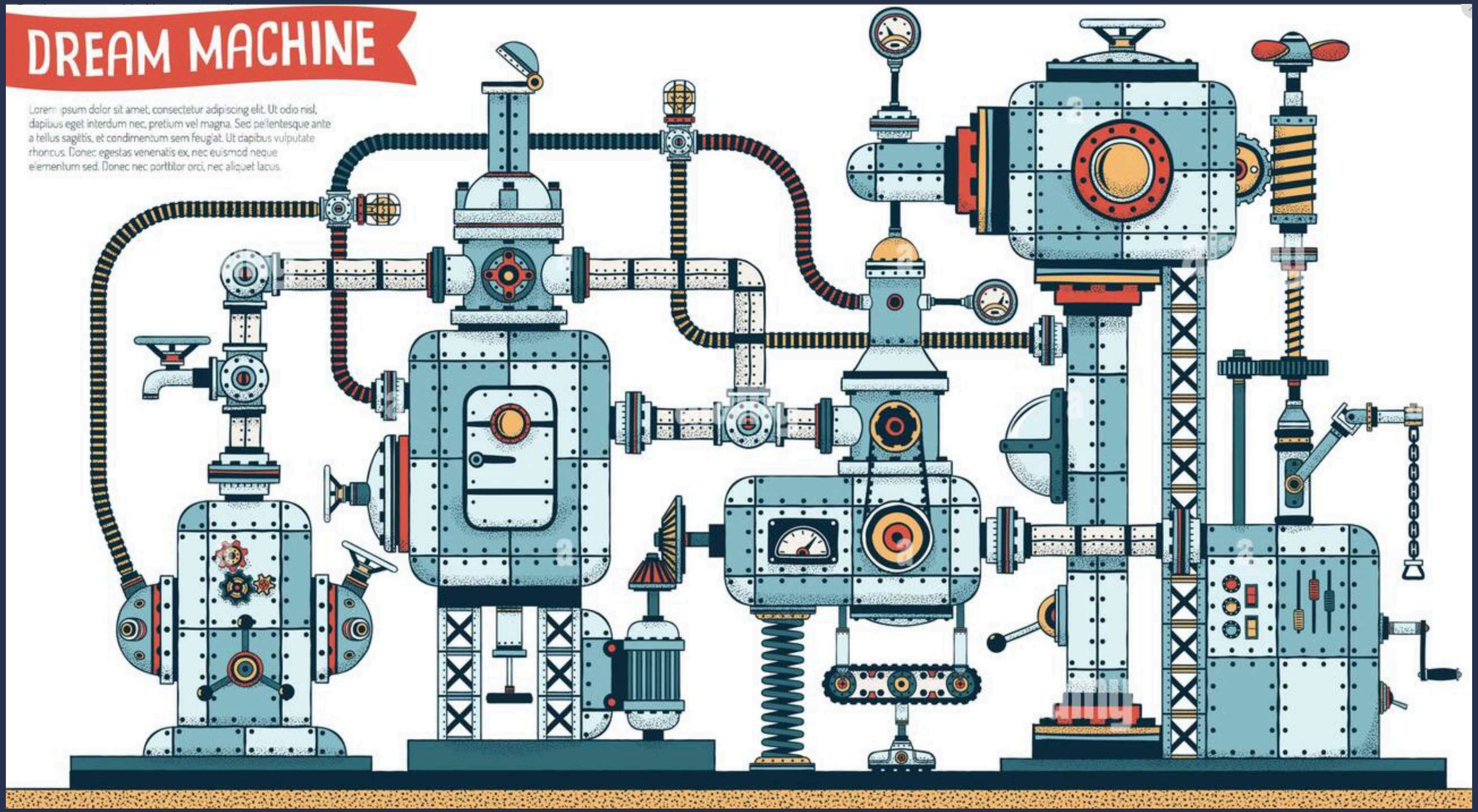
SCAT winds

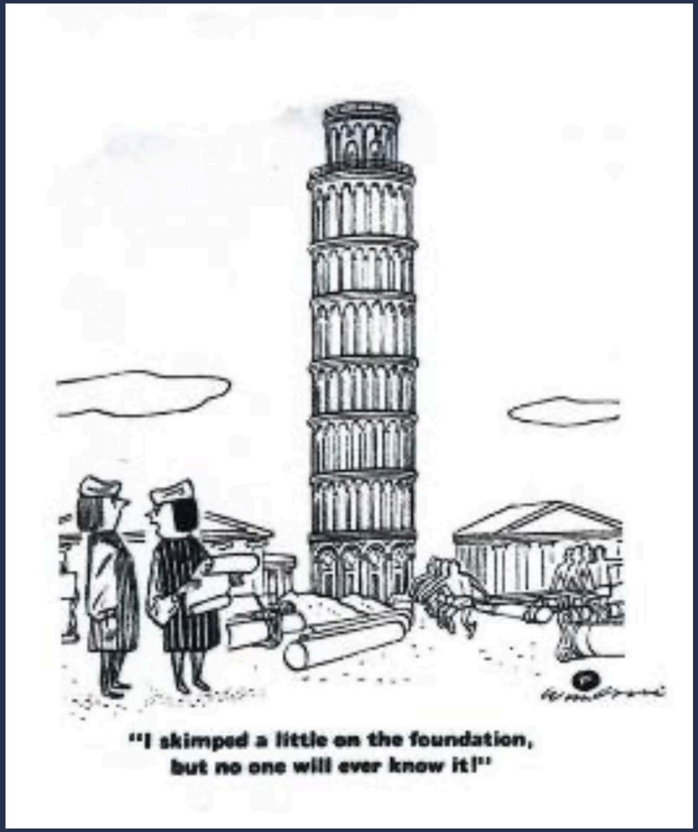




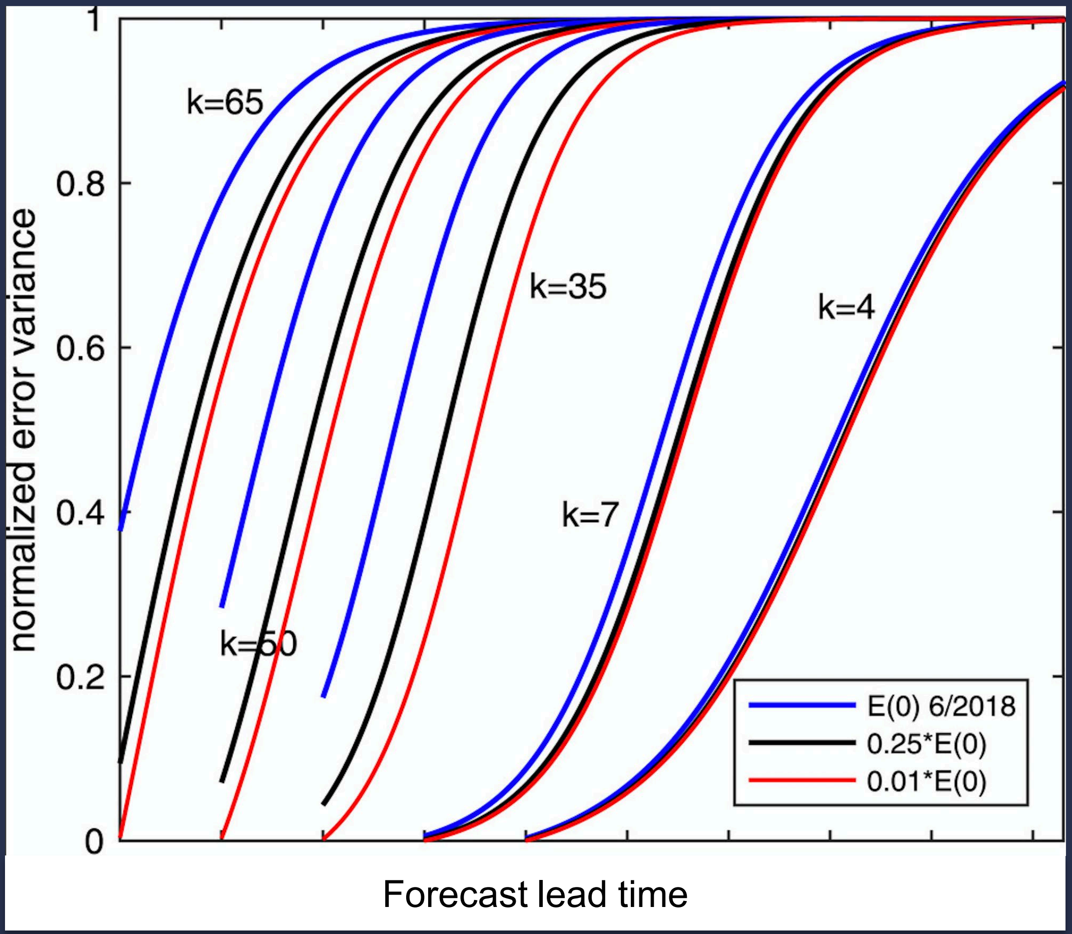
AMSR-2 MW sea ice cover and snow

Managing ML hybridization with physics-based systems (and people!)





Using DA for model parameter estimation and model error correction



From Žagar and Szunyogh (2020)
https://doi.org/10.1175/JAS-D-19-0166.1

- At some spatial scales, model error growth is so rapid that significant forecast improvements are difficult to obtain from improving initial conditions alone
- For these scales, larger gains could come from using DA to estimate model parameters which improve the forecasts
- Or similarly using DA to explicitly estimate and correct model error
- Slowing model error growth (using the above) then opens up new possibilities for gains from improving initial conditions!!

- Changing political climate
  - Instability threatening global sharing of observations
  - We must prove the commercial value of sharing the burden of Earth observation
  - Empowering developing nations to play a role
- Changing commercial climate
  - Move to private sector OBS provision
  - Will need to prove the value of an observation
  - Will need to close the loop and audit value of investment back to investors
- Changing science climate
  - Need to retain the skill sets of the scientists / engineers we will need
  - Need to accept that some skill sets will be more available than others and adapt our systems to these
- Changing technological climate
- Need to accept fast pace of OBS and HPS technology advances
- Ensure that our longer-time scale vision does not mean we are blind to the immediate
- Develop systems and methods to exploit this exciting rapid advances

Main development threads of the ECMWF DA system

- Maximizing observation exploitation with “traditional” DA
- DA augmented by ML emulation of individual components
- DA incorporating ML model error correction (Hybrid forecasting)
- DA to support Data Driven ML FC trained / initialized from analyses
- Data Driven ML FC trained / initialized from observations

Drivers:

- Performance (accuracy / delivery to users)
- Resource landscape (HPC, skills, partnerships)
- Long-term operational sustainability of approach
- Maintaining support of member state activity