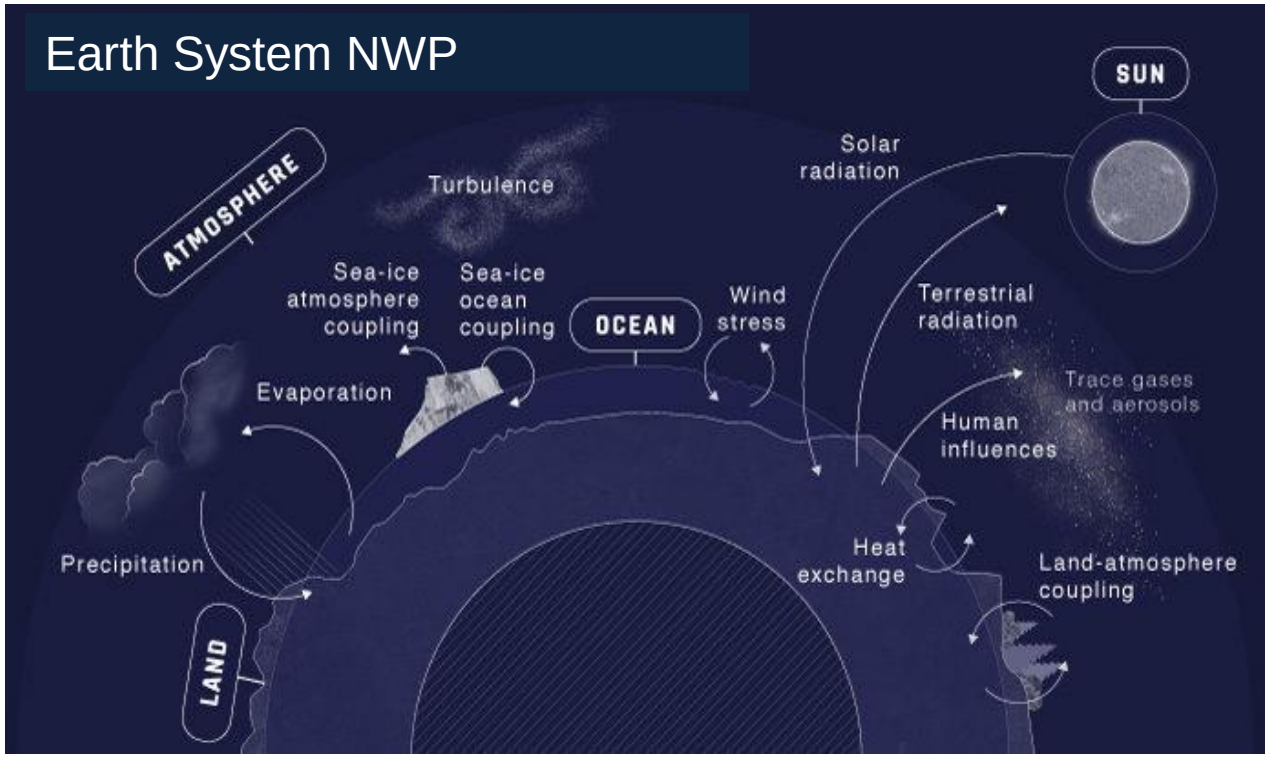
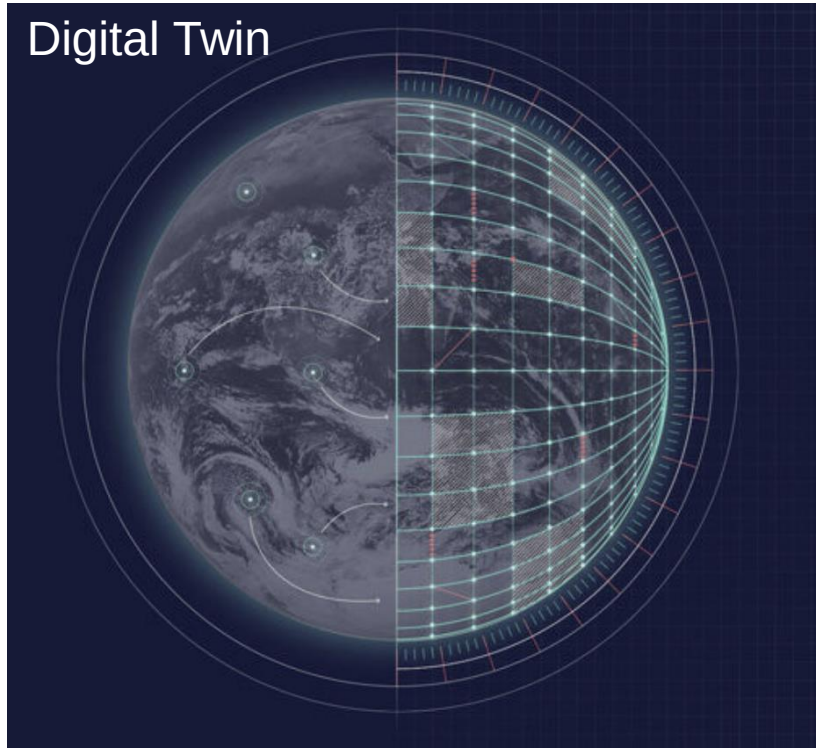
A holistic perspective of observation value in Earth System NWP and digital twins

Tony McNally (ECMWF)…and many many others!

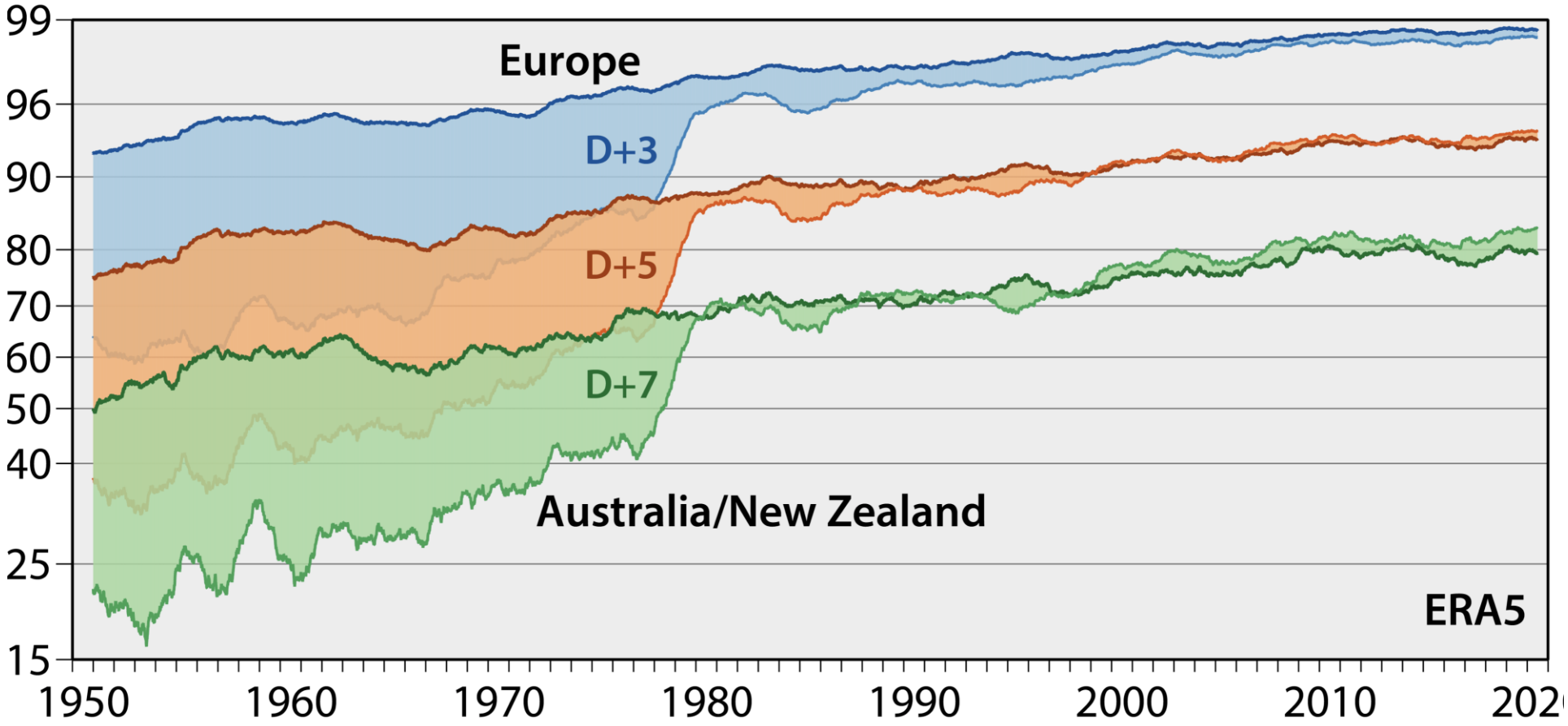




Outline

- How do we assess observation ***value*** - is it the same as ***impact*** ?
- What factors can influence ***value*** and are they captured in our diagnostics ?
- What are the different mechanisms by which an observation can add value ?
- Enhancing observation value scientifically:
- Enhancing observation value in other ways

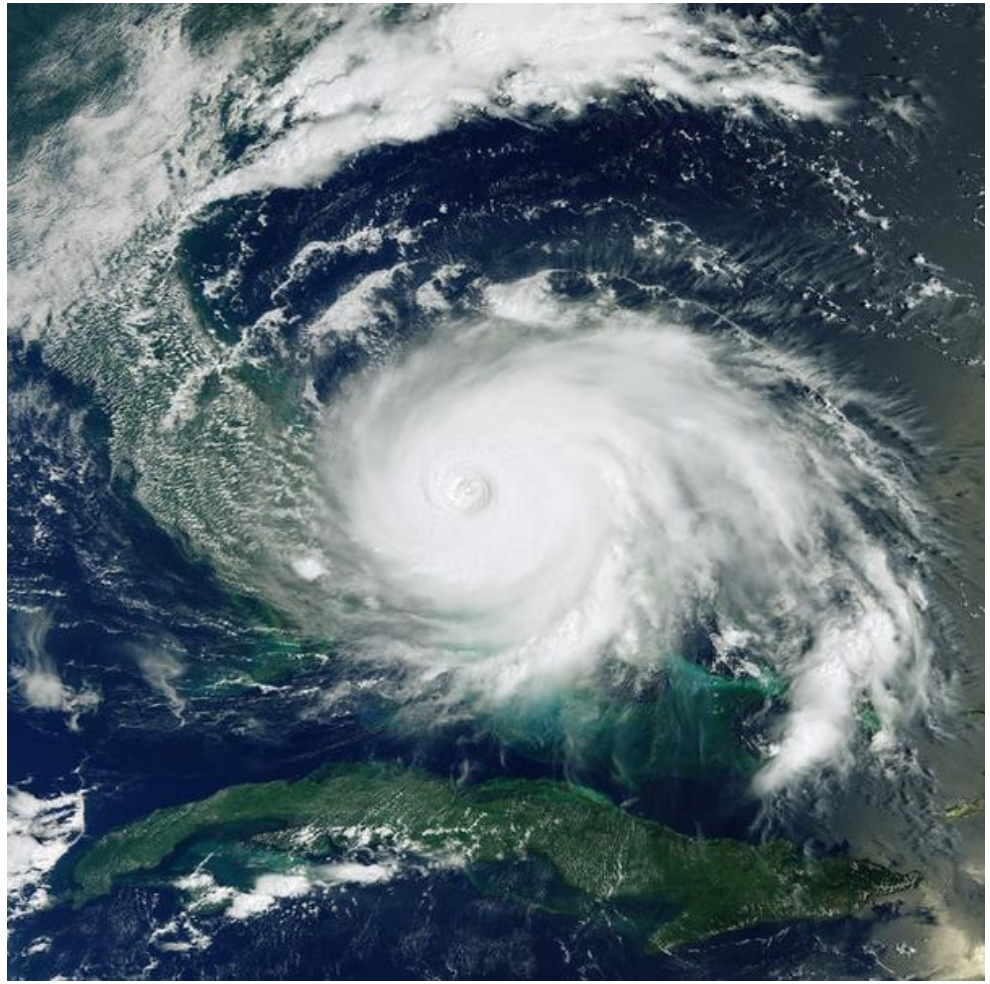
There is no doubt that collectively observations add value



Adrian Simmons

Hurricane Dorian

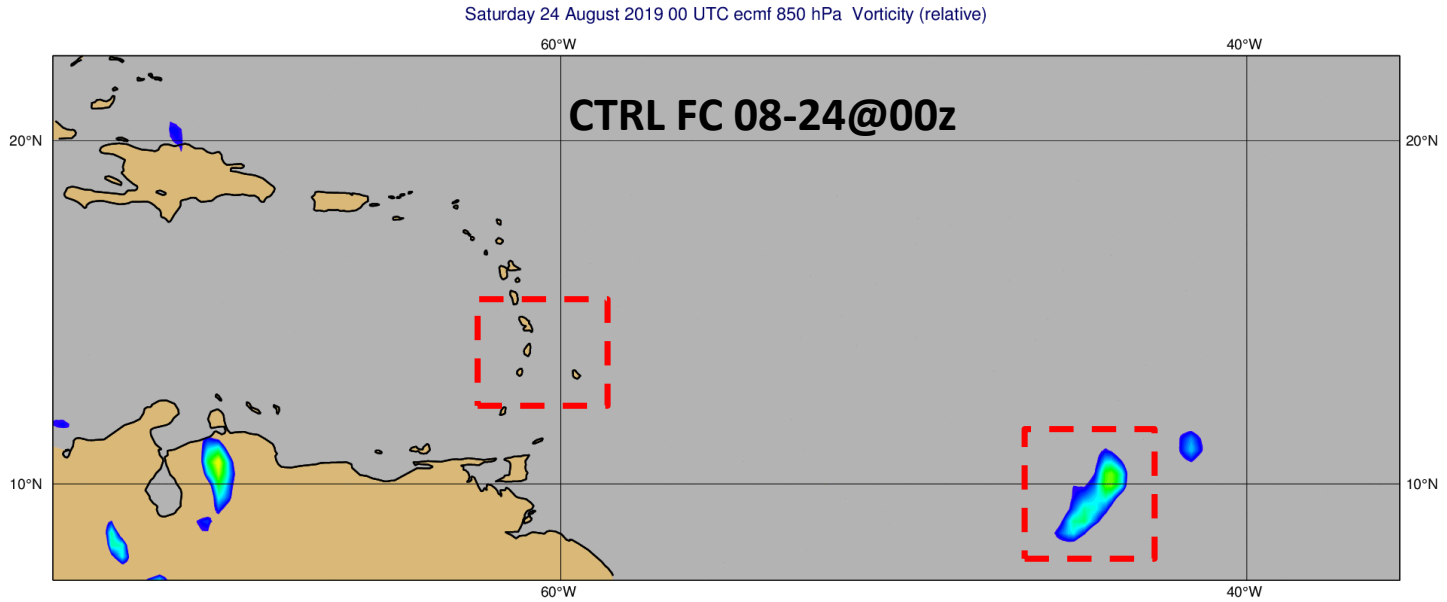
Dorian viewed from the Sentinel-3 satellite



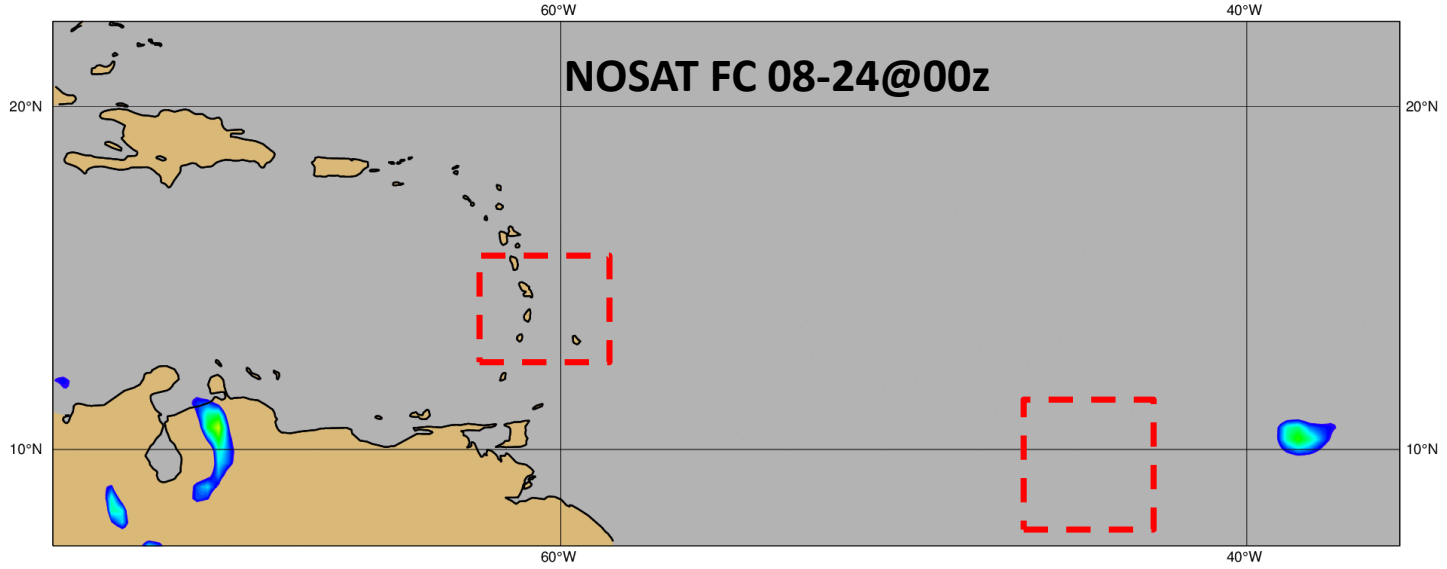
Dorian viewed from the Bahamas

Good forecasts and excellent evacuation plans <u>significantly mitigated storm human impact</u>

Dorian genesis…to first strike on Windward Islands



Control system with satellites identifies storm genesis on 24th August and provides **4 days warning** of direct strike on Windward Islands



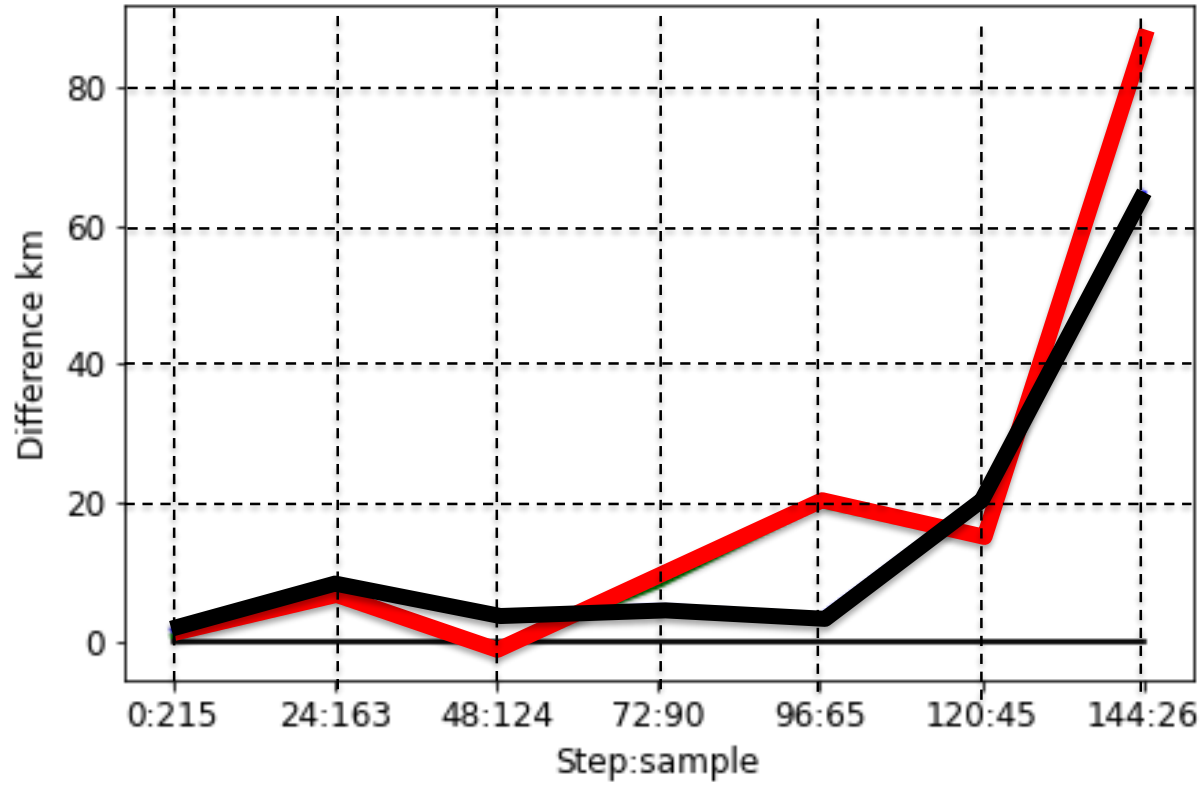
System with **satellites denied** (for **36hrs** prior to forecast) misses the storm genesis and provides **no warning of strike** on Windward Islands

Quantified impact on tropical cyclones

Very few cyclone cases in any given test period makes a robust quantitative assessment of the impact of individual satellite systems challenging

However, the **passive microwave** and **passive infrared** do have a clear positive impact upon predictions of the cyclone track and position (albeit not statistically significant)

RMS loss of accuracy in forecast cyclone position (km) for the 2020 Atlantic Cyclone season from IR/MW denial



*Individual case studies consistently show a dramatic impact from denying **all** satellites!*

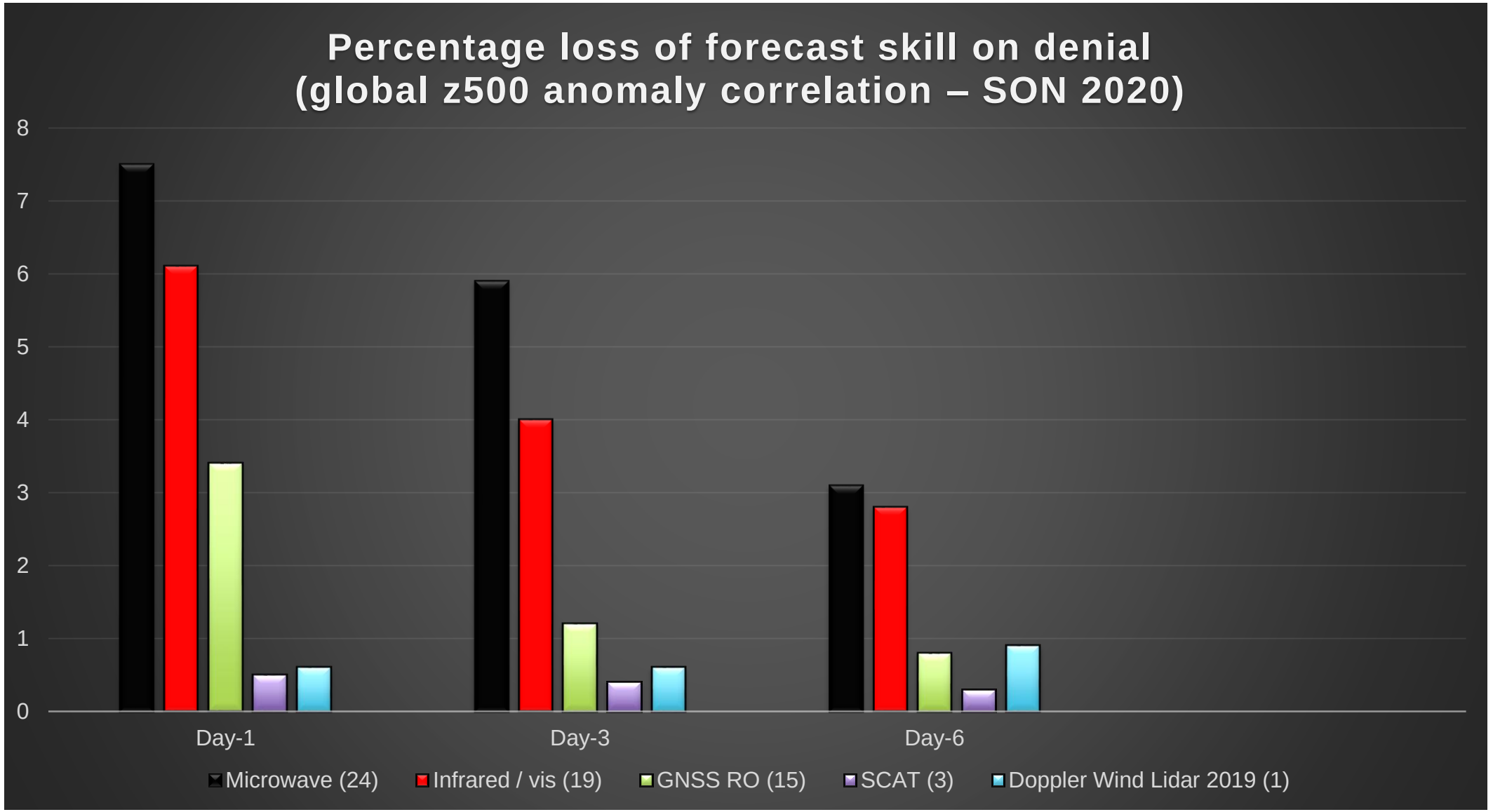
Linus Magnusson

Increasingly we are drilling down and comparing the relative impact of observing systems ?

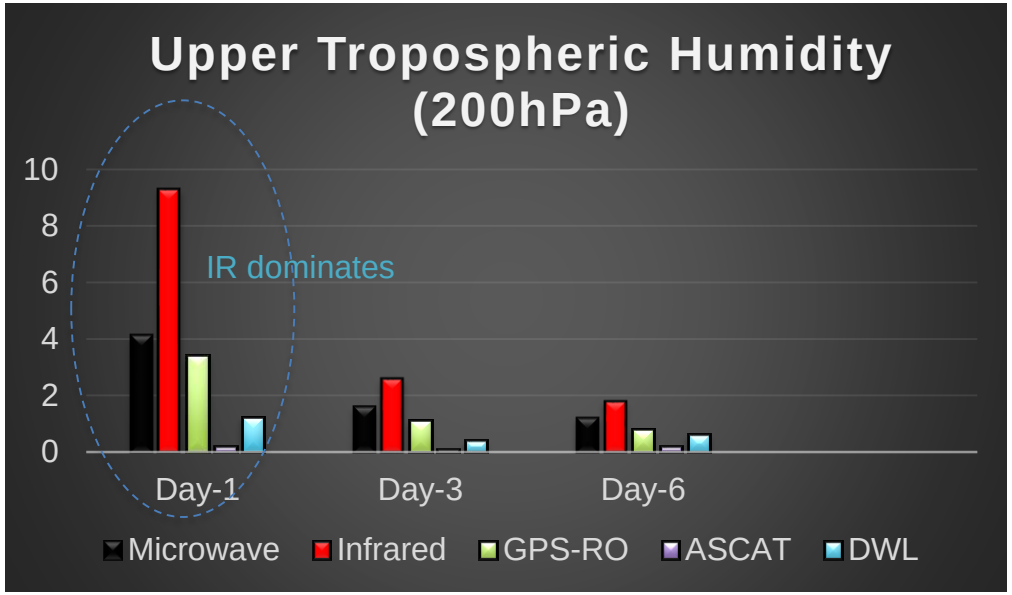
(Niels Bormann's talk)

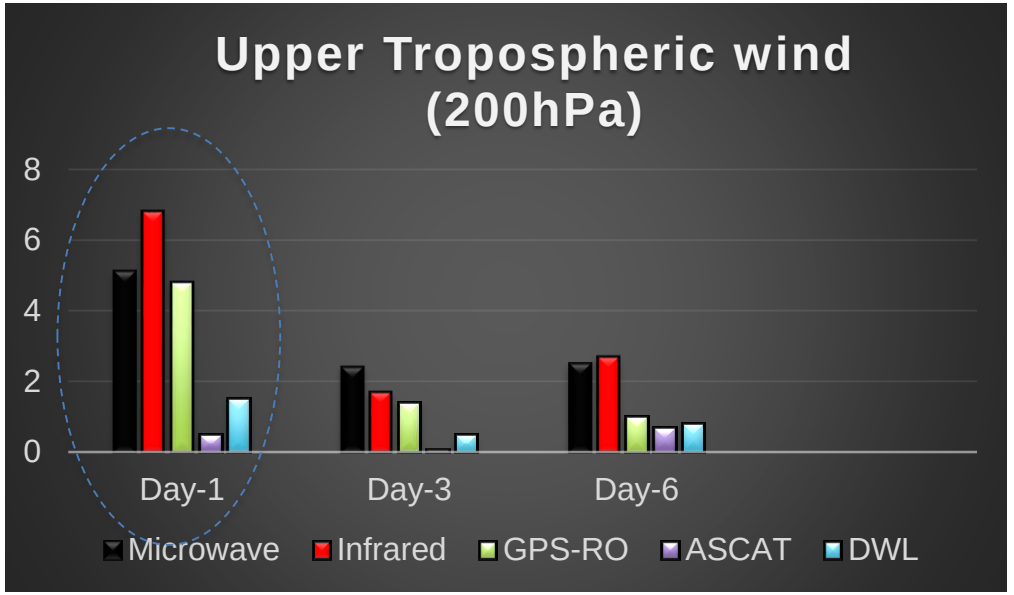
- Are we making best use of an observing system ?
- What technology should we launch in the future ?
- Which data types should we keep maintaining / disseminating ?
- How should we best deploy limited RD resources ?
- Leverage of new resources

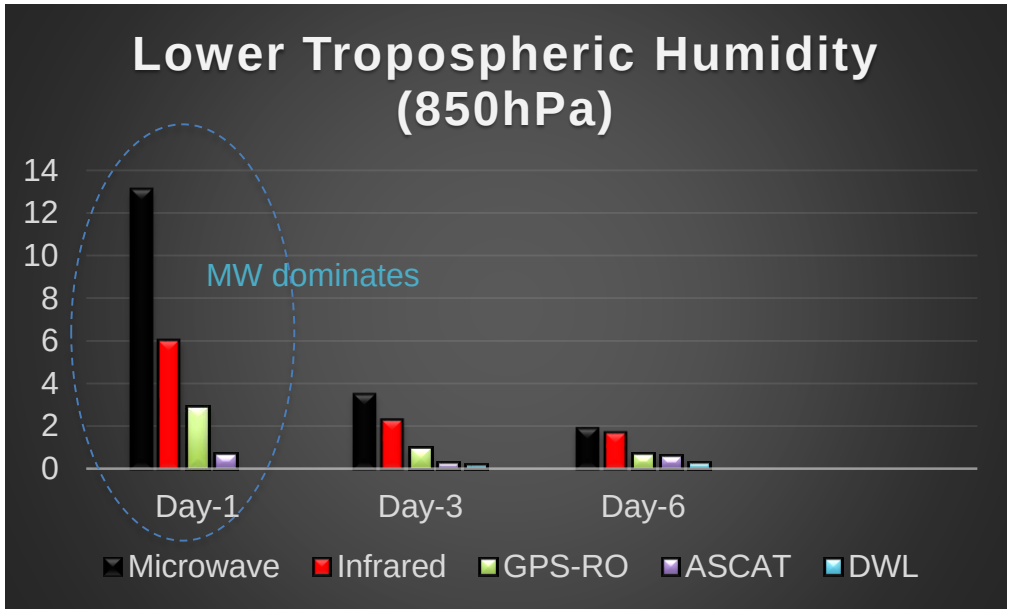
Impact of different satellite technologies…



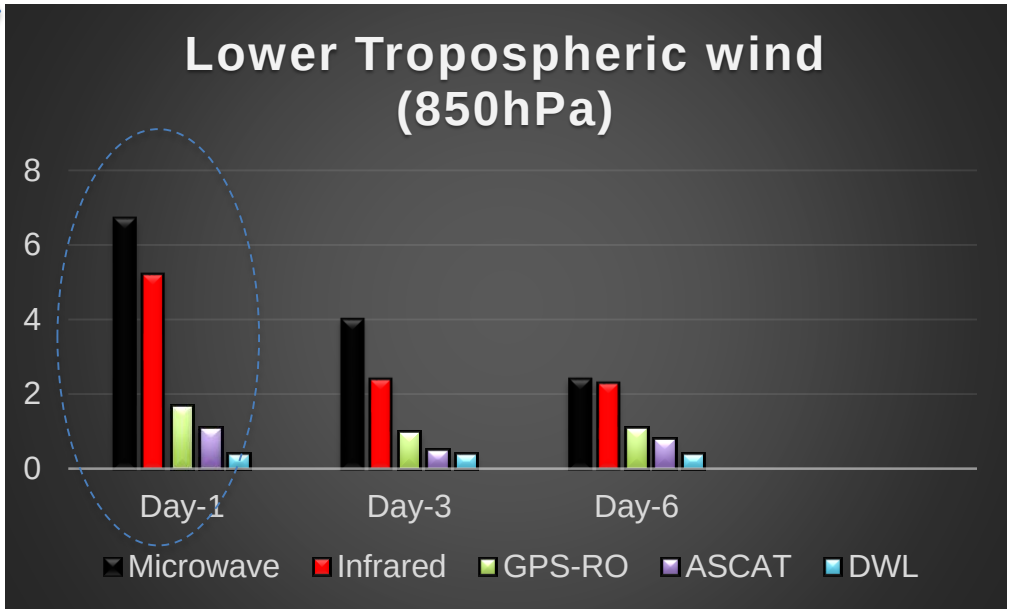
Must look at different forecast parameters!







humidity skill translates to wind skill



But behind these demonstrations of impact there are some very complex processes

What happens when we confront a modern state of the art DA system with an observation ?

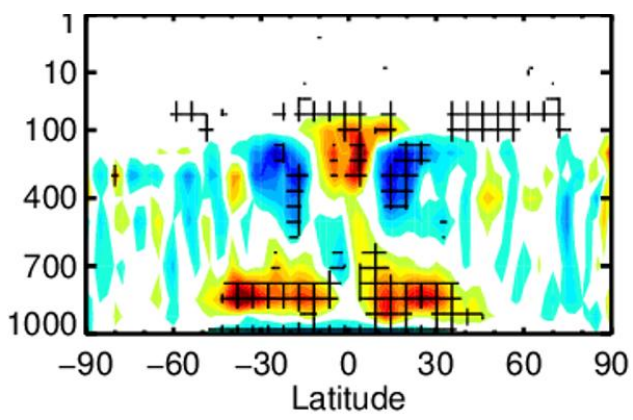
When there is a misfit between the model background and the observations (*innovation*) there are now many options for 4D-Var:

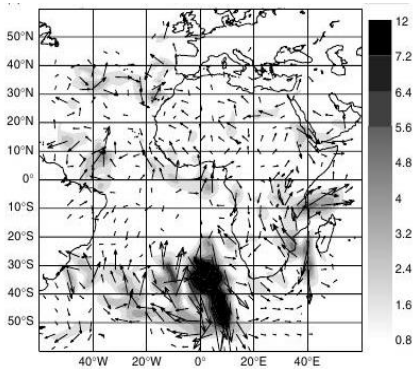
- Adjust **model state** at that time and location (4D-Var increments)
- Adjust **model state** remotely at another time (4D-Var advection tracing)
- Adjust **model bias correction** (adaptive Weak constraint 4D-Var)
- Adjust **observation bias correction** (its own or that of other data in adaptive VAR-BC)
- Adjust **background errors** via an adaptive cycling EDA

Note **all** of the above take place automatically, adaptively and simultaneously…modern DA systems have been “machine learning” for many years…but with a **physical model** at the core.

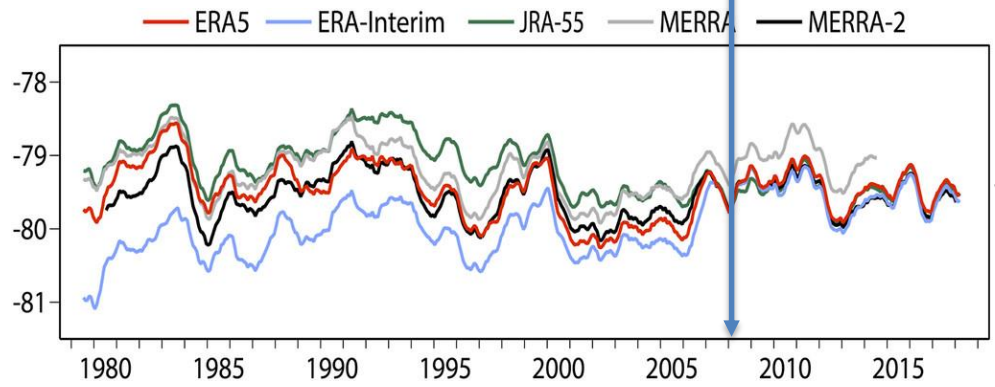
Confronting DA systems with an observation

4D multivariate increments of the model state vector



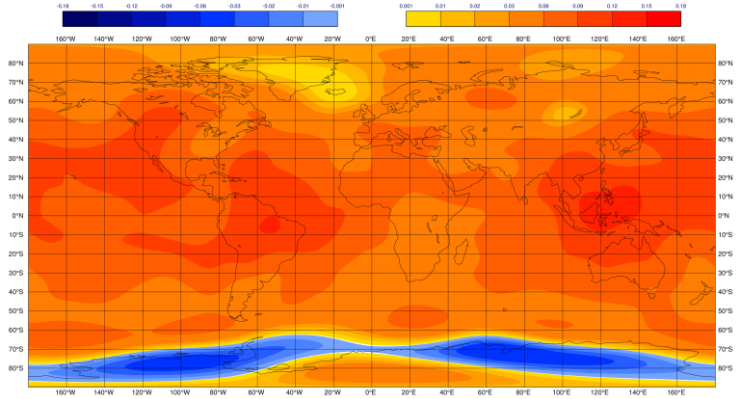


VARBC Bias anchoring with GPS-RO



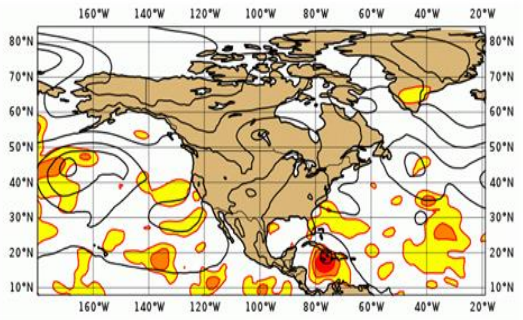
S. Healy

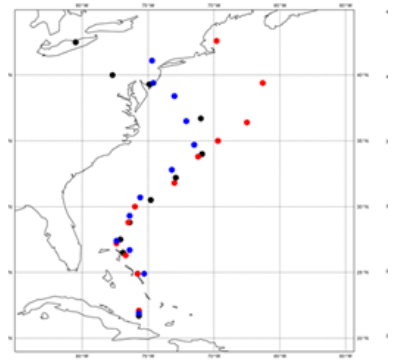
Correcting model bias via weak-constraint 4D-Var



P. Laloyaux

Re-calibrating background errors via EDA





All of these processes are **simultaneously active** when we perform an OSE or FSOI analysis, some metrics inevitably rewarding different actions more than others

What factors influence an observation's value and are they captured in existing impact diagnostics ?

Intrinsic to the observation in OSE/FSOI

- Quality and quantity
- NRT availability
- coverage
- resolution
- time sampling
- uniqueness (including orbit)

Non-intrinsic factors in OSE/FSOI

- Position in assimilation window
- Skill of DA tuning (Obs error)
- Reaction with model biases (spinup/down)
- Scope of the DA (e.g. clouds)

Value factors not captured by OSE / FSOI

- Longevity for RD investment and climate
- Useful in different applications
- Campaign data (model development)
- Calibration standard observations
- Prototype data (e.g. GIIRS)
- Technology demonstrations ?

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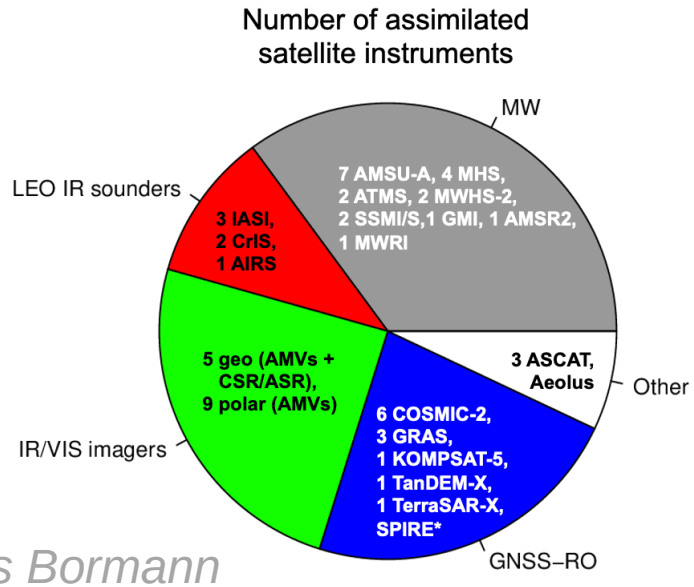
Quality and quantity…which FSOI should we use ?



Niels Bormann

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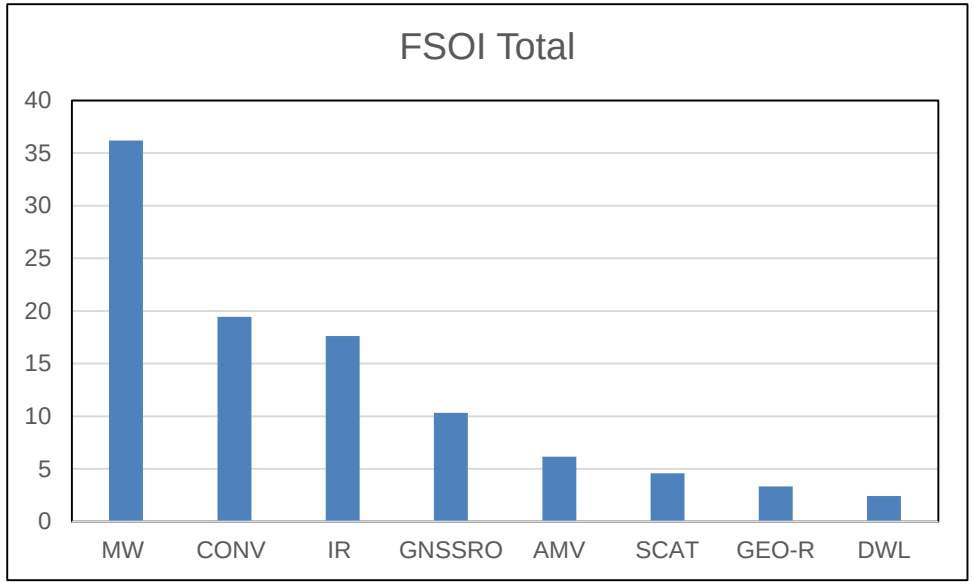
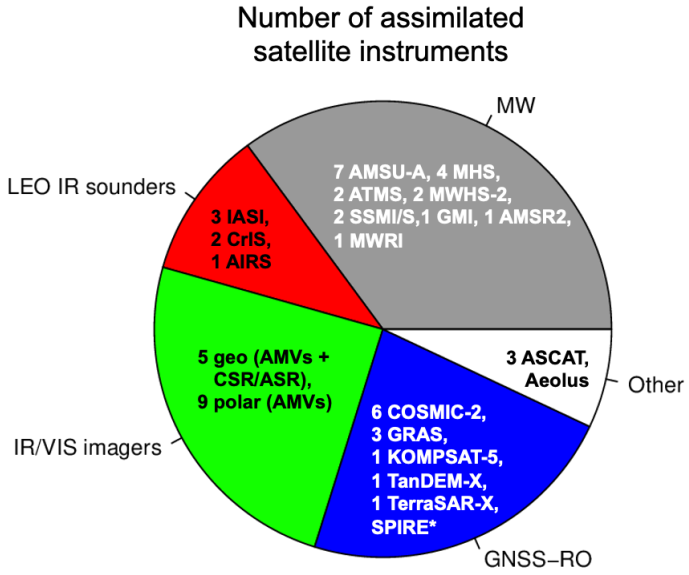


Impact scales rather closely to number of satellites

Mohamed Dahoui



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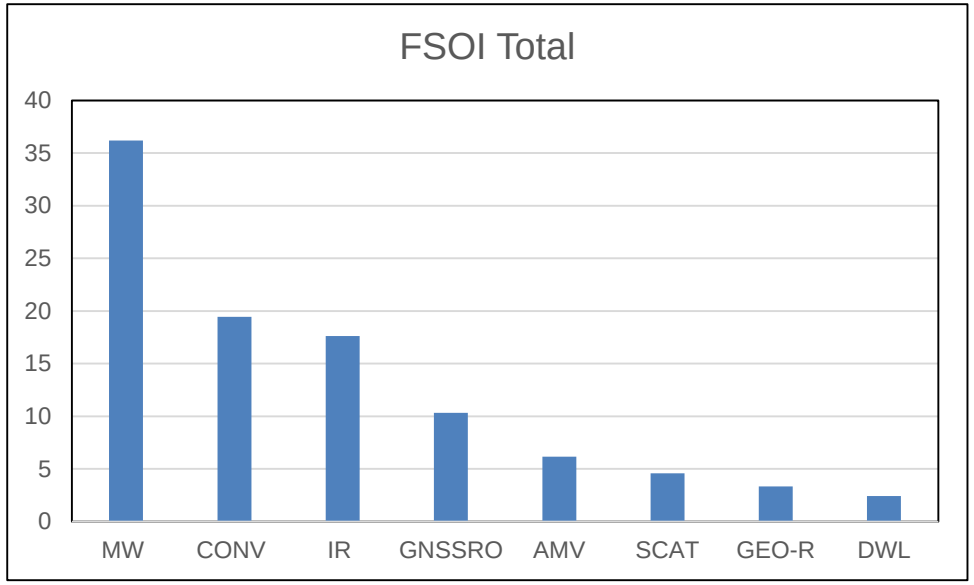

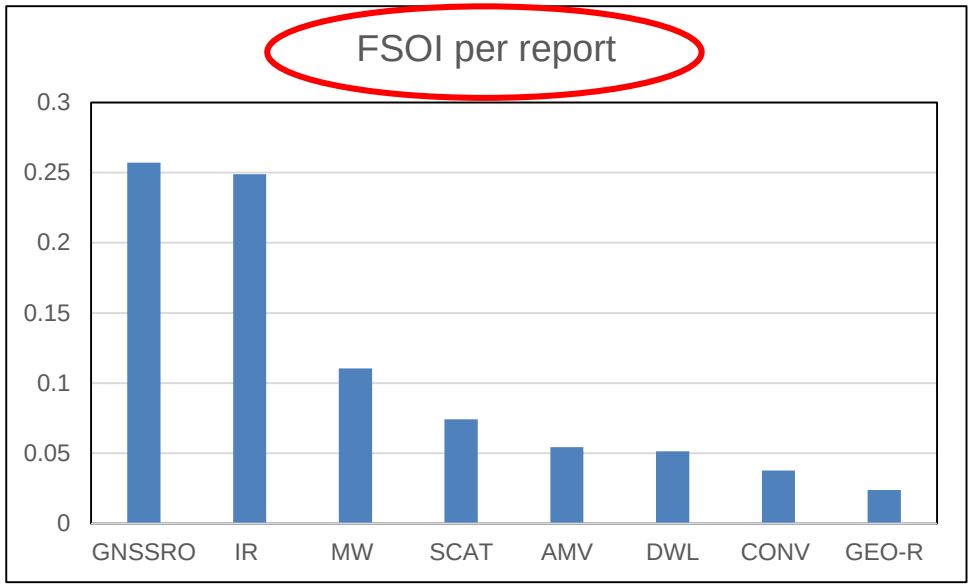

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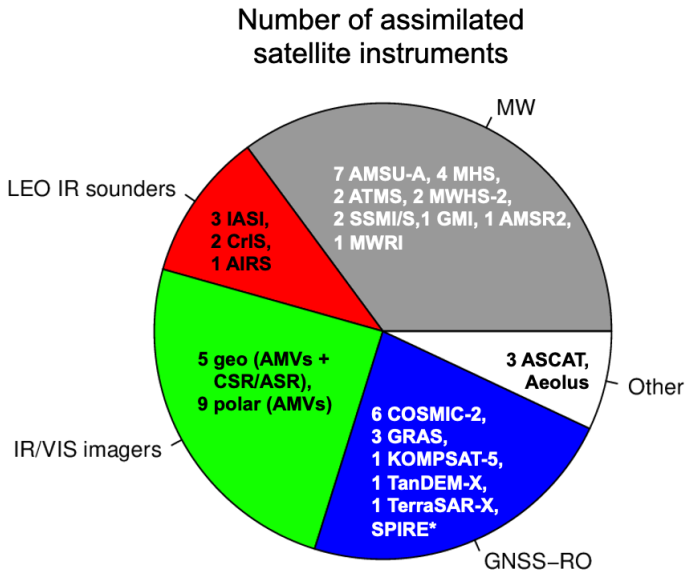

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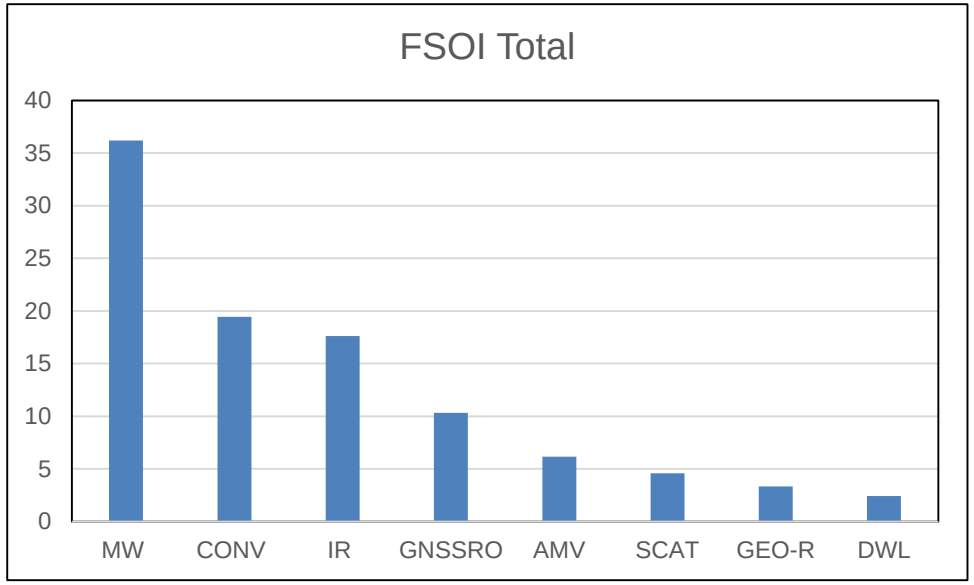

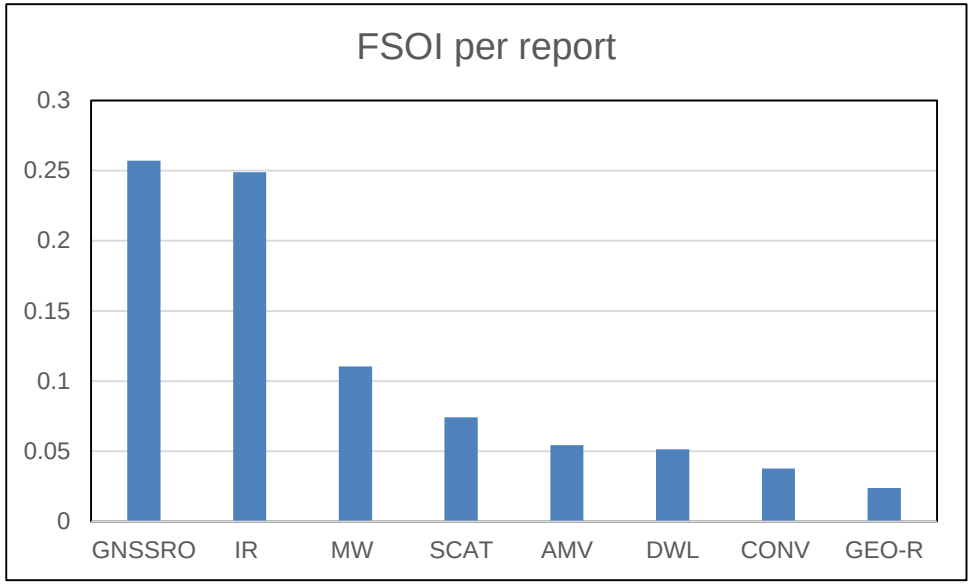

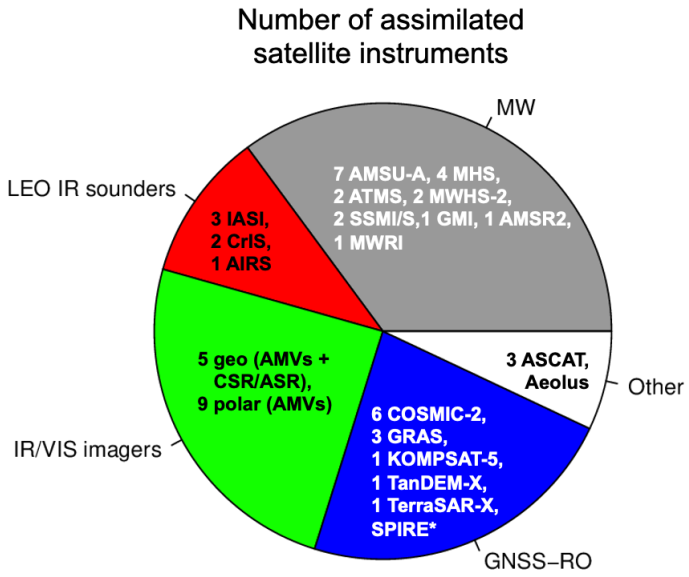

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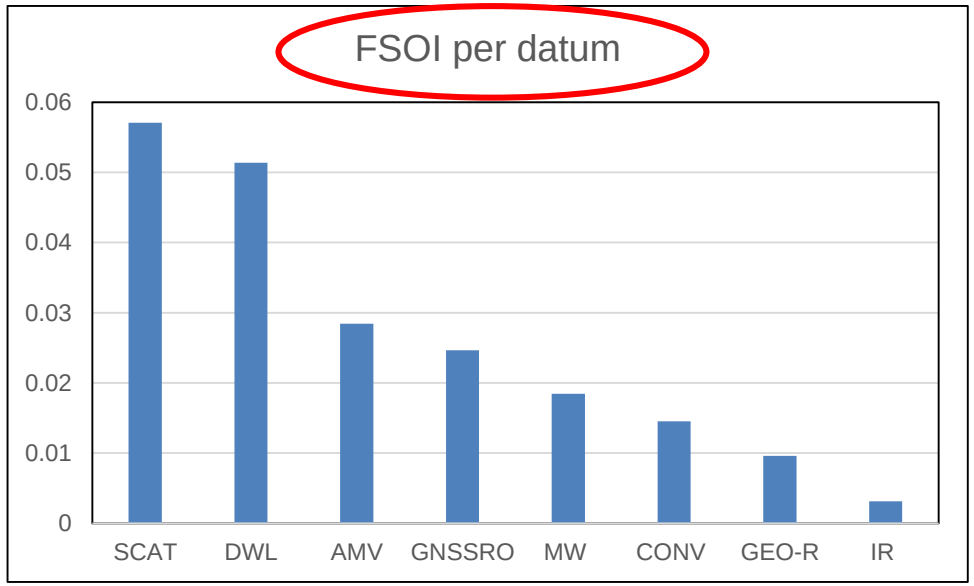

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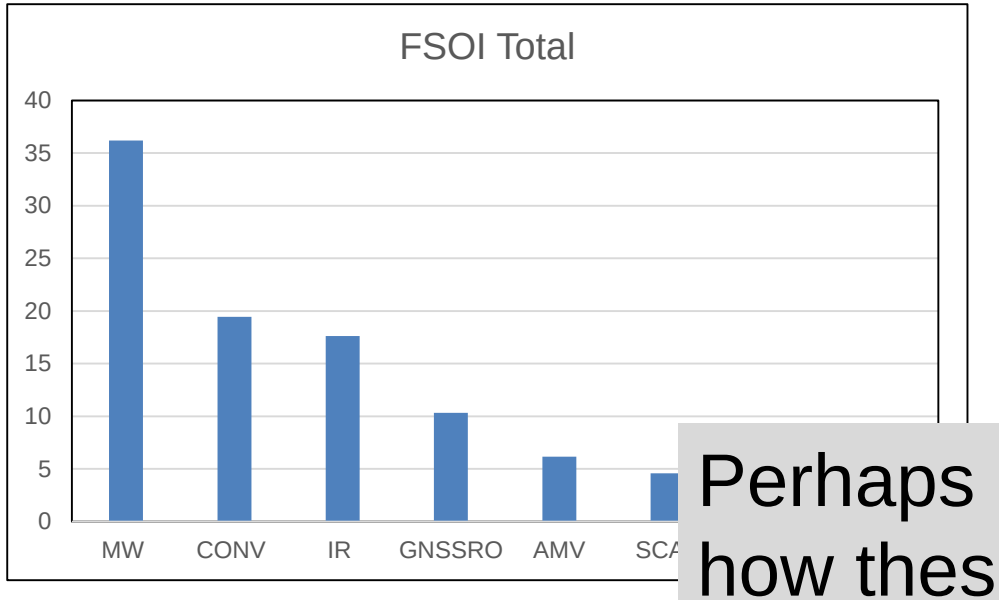
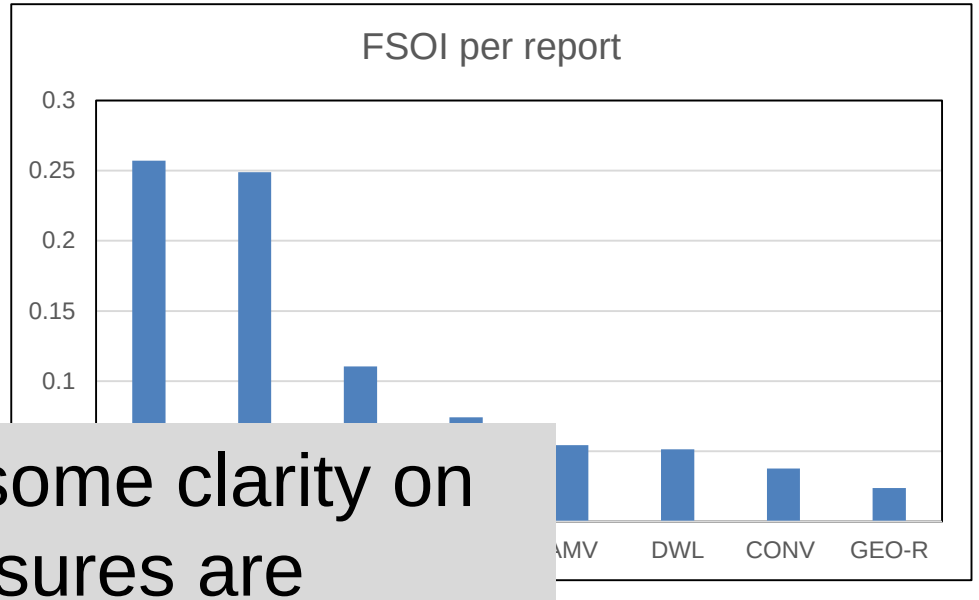
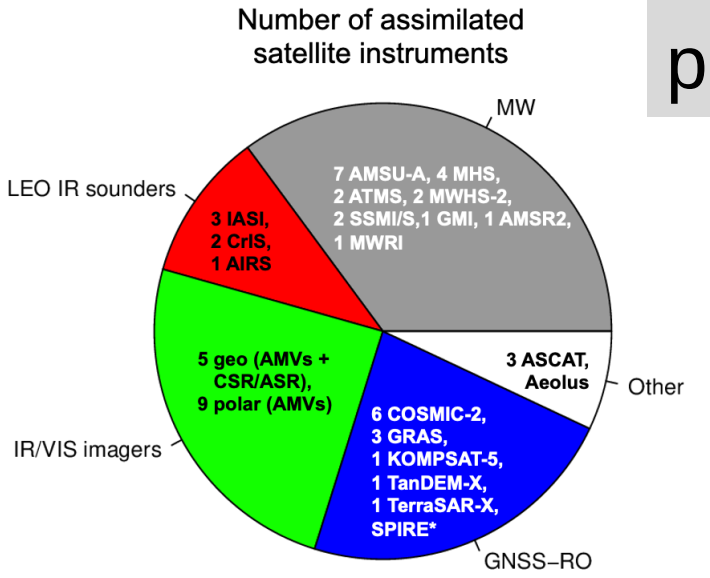
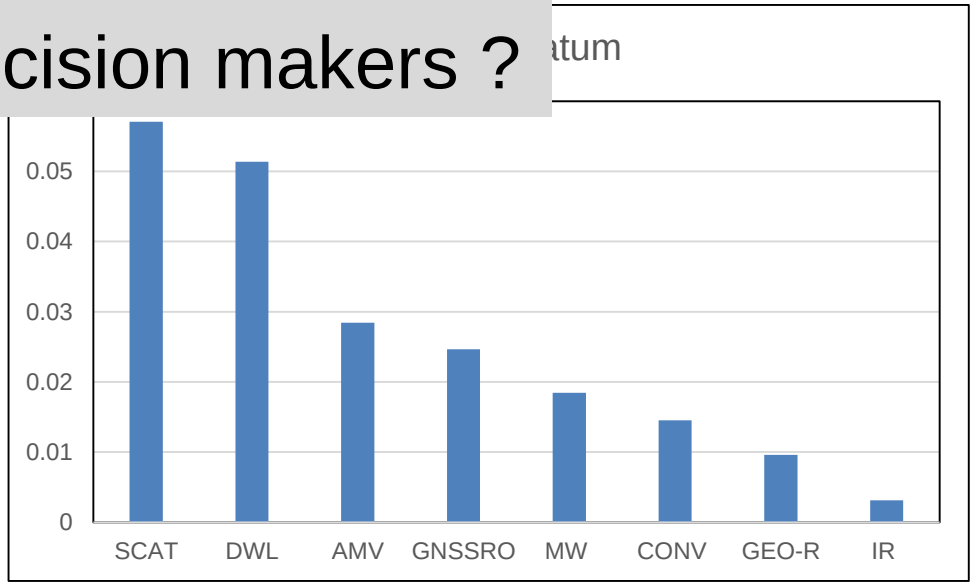




Perhaps need some clarity on how these measures are presented to decision makers ?





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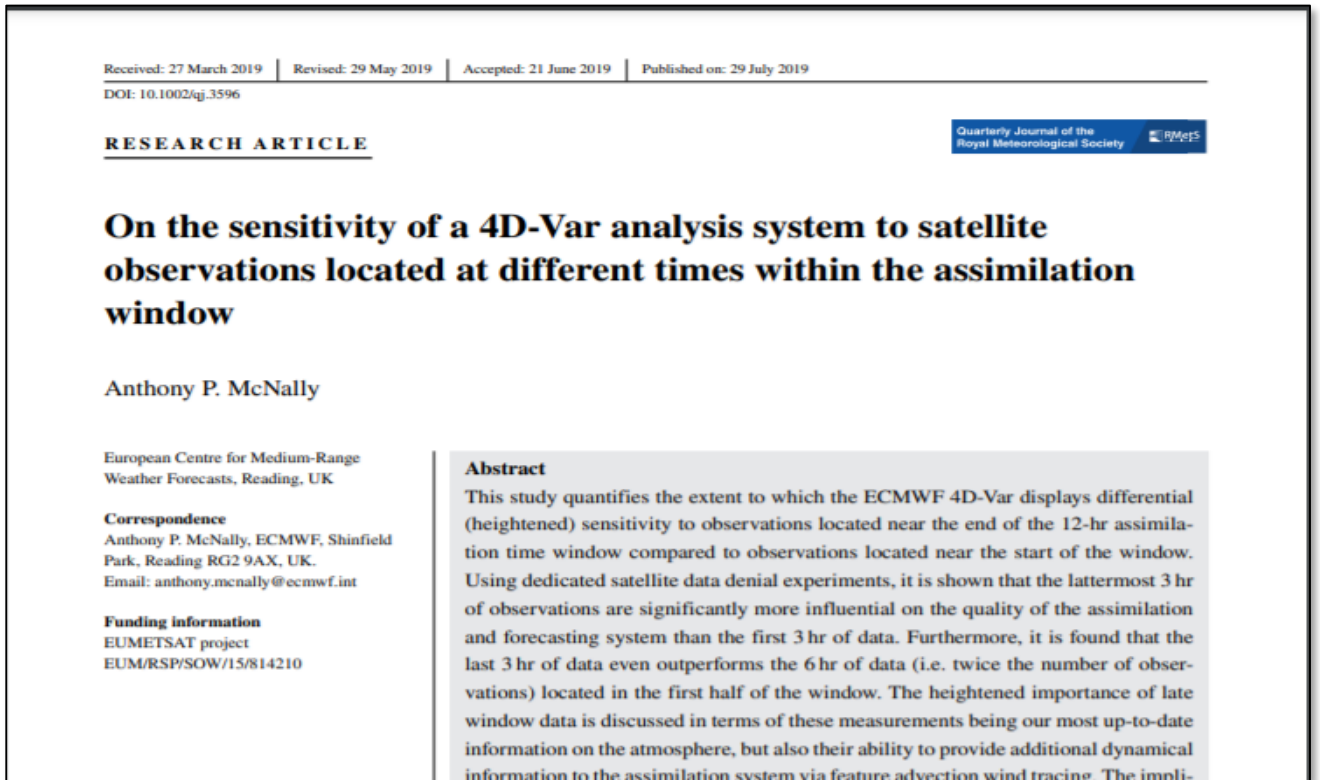
Being in the right place at the right time...

…or being in the wrong place at the wrong time!



Received: 27 March 2019 | Revised: 29 May 2019 | Accepted: 21 June 2019 | Published on: 29 July 2019
DOI: 10.1002/qj.3596

RESEARCH ARTICLE

Quarterly Journal of the Royal Meteorological Society RMetS

On the sensitivity of a 4D-Var analysis system to satellite observations located at different times within the assimilation window

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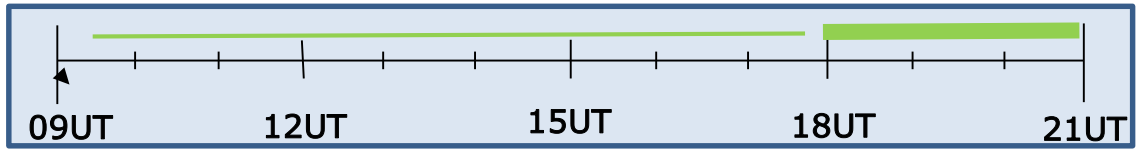
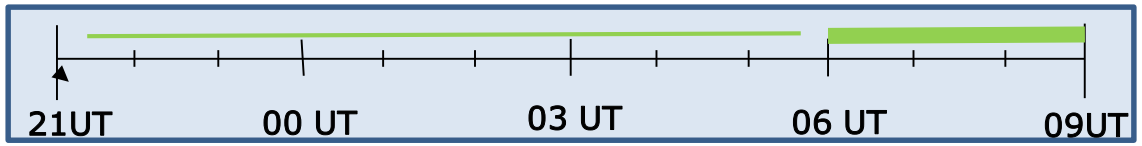
Funding information
EUMETSAT project
EUM/RSP/SOW/15/814210

Abstract
This study quantifies the extent to which the ECMWF 4D-Var displays differential (heightened) sensitivity to observations located near the end of the 12-hr assimilation time window compared to observations located near the start of the window. Using dedicated satellite data denial experiments, it is shown that the lattermost 3 hr of observations are significantly more influential on the quality of the assimilation and forecasting system than the first 3 hr of data. Furthermore, it is found that the last 3 hr of data even outperforms the 6 hr of data (i.e. twice the number of observations) located in the first half of the window. The heightened importance of late window data is discussed in terms of these measurements being our most up-to-date information on the atmosphere, but also their ability to provide additional dynamical information to the assimilation system via feature advection wind tracing. The impli-

Influential observations in the 4D-Var window

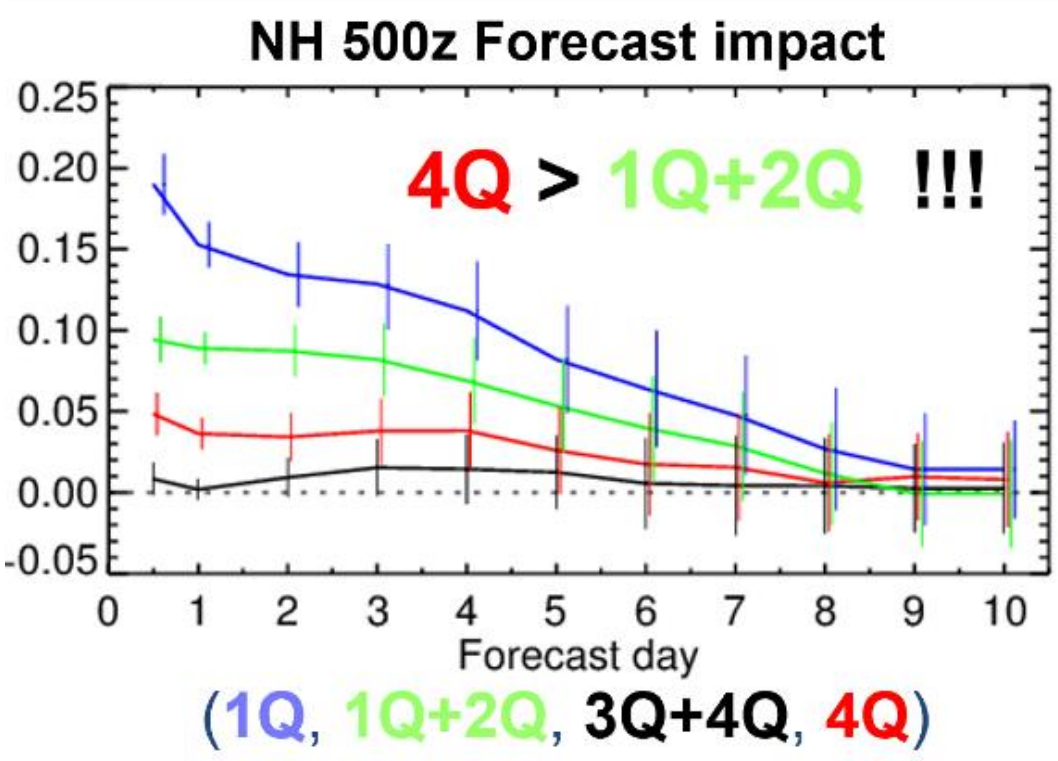




Observations located near the **end of the 12 hour window are significantly more influential** than observations located at the start of the window for two reasons:

- Firstly, end of window observations provide the **most up to date** information on the atmospheric state and are our *last look* at the atmosphere before we make a forecast.

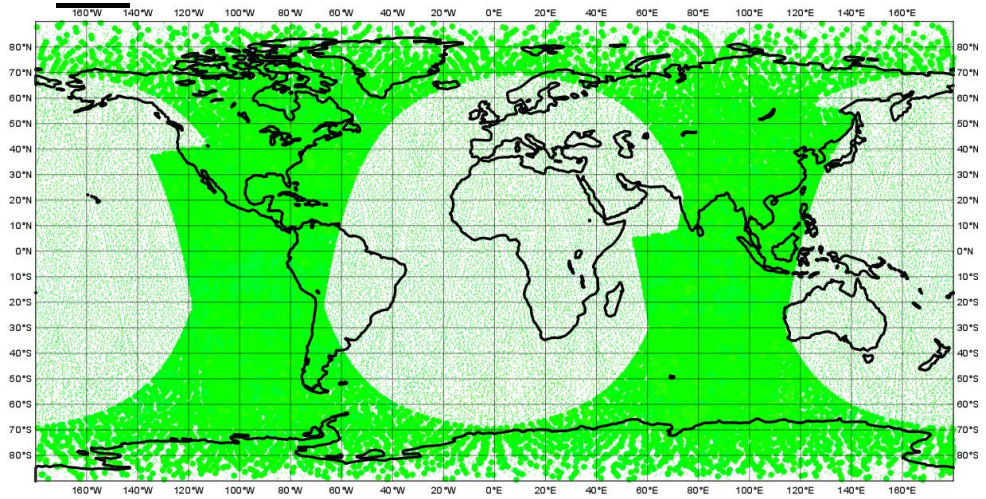
- Secondly, end of window satellite observations can be fitted by time evolving multivariate analysis increments and thus **provide wind information** via 4D advection tracing



For satellites this gives rise to the idea of *influential orbits*

Where are the influential orbits of METOP and NPP ?

NPP last 3 hours for 00z and 12z 4DVAR window



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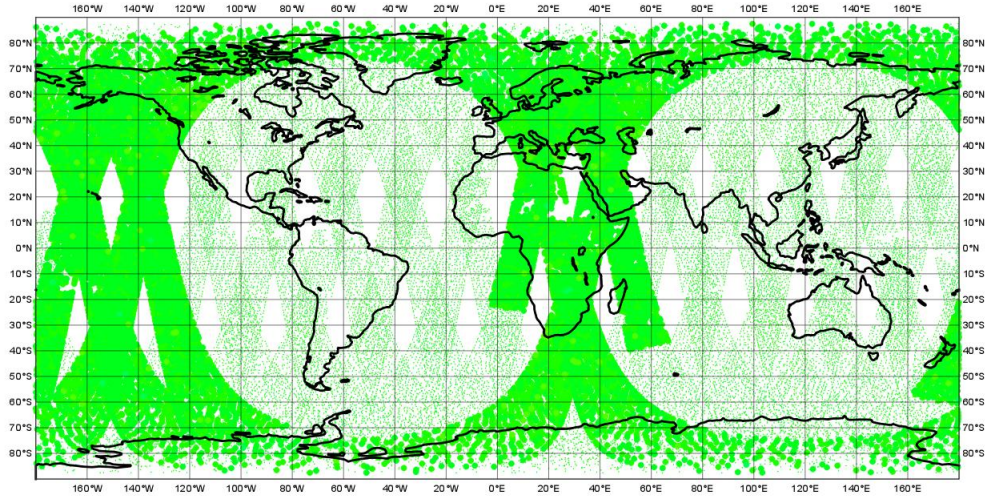

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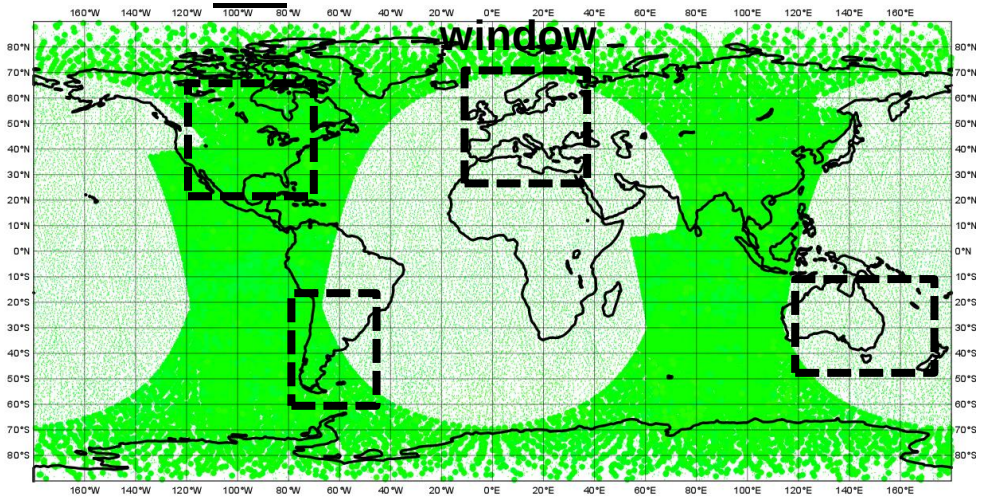

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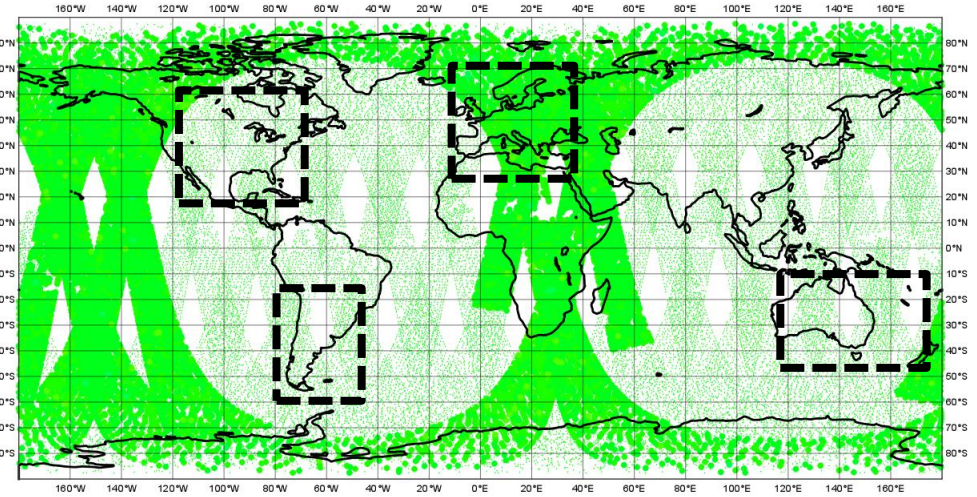
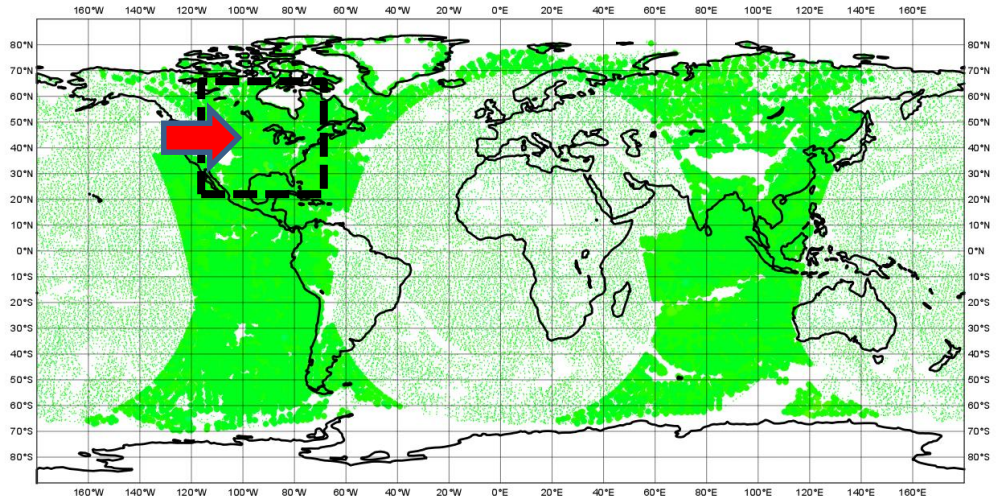


= radiosonde verification regions

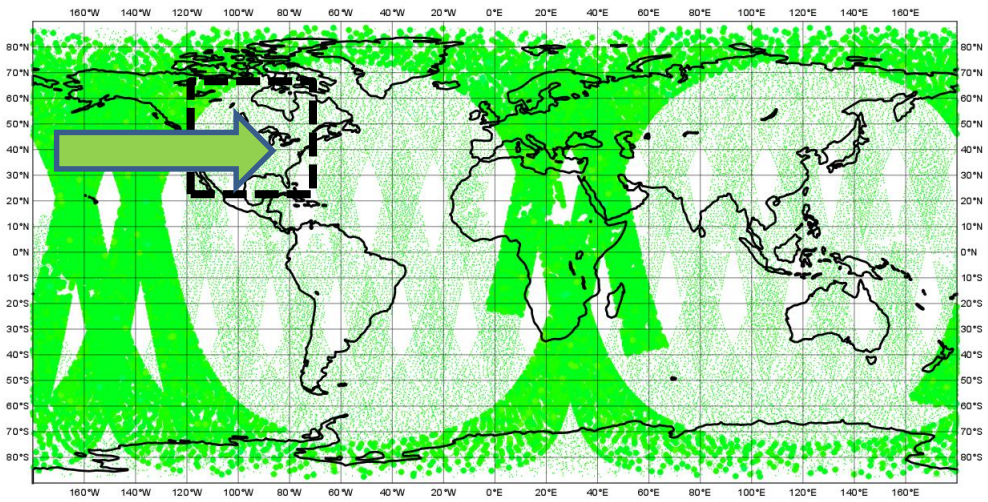
…the location of influential orbits upstream of verification regions leads to interesting variations in the relative impact of METOP v NPP… it changes with forecast range ….

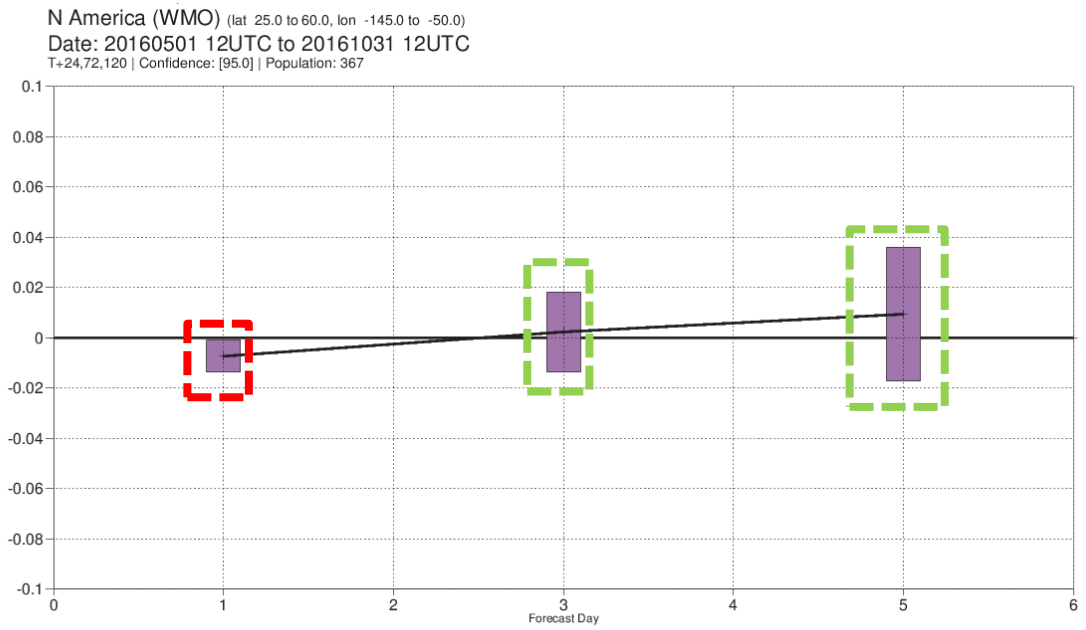
METOP* v NPP (North America verification region)

NPP last 3 hours of 00z and 12z



METOP last 3hrs of 00z and 12z 4DVAR window



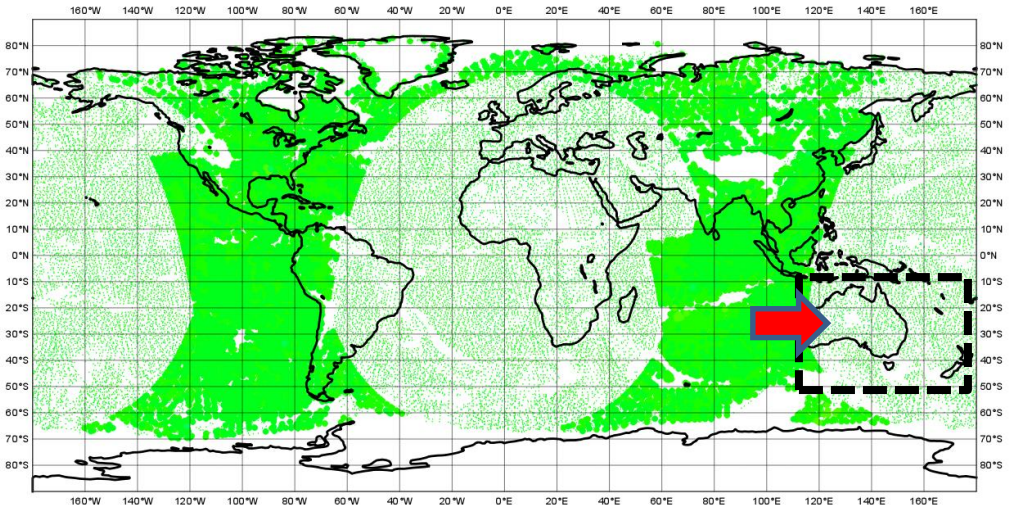


METOP > NPP

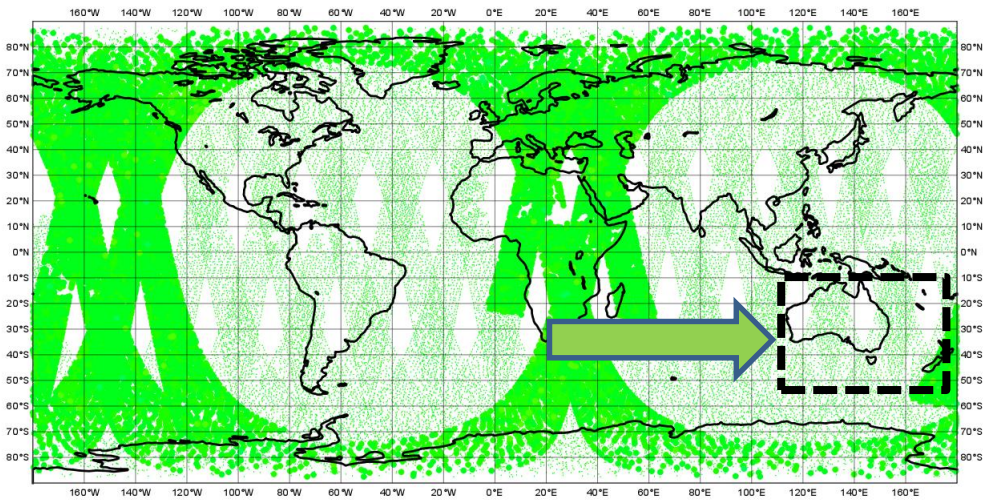
NPP > METOP

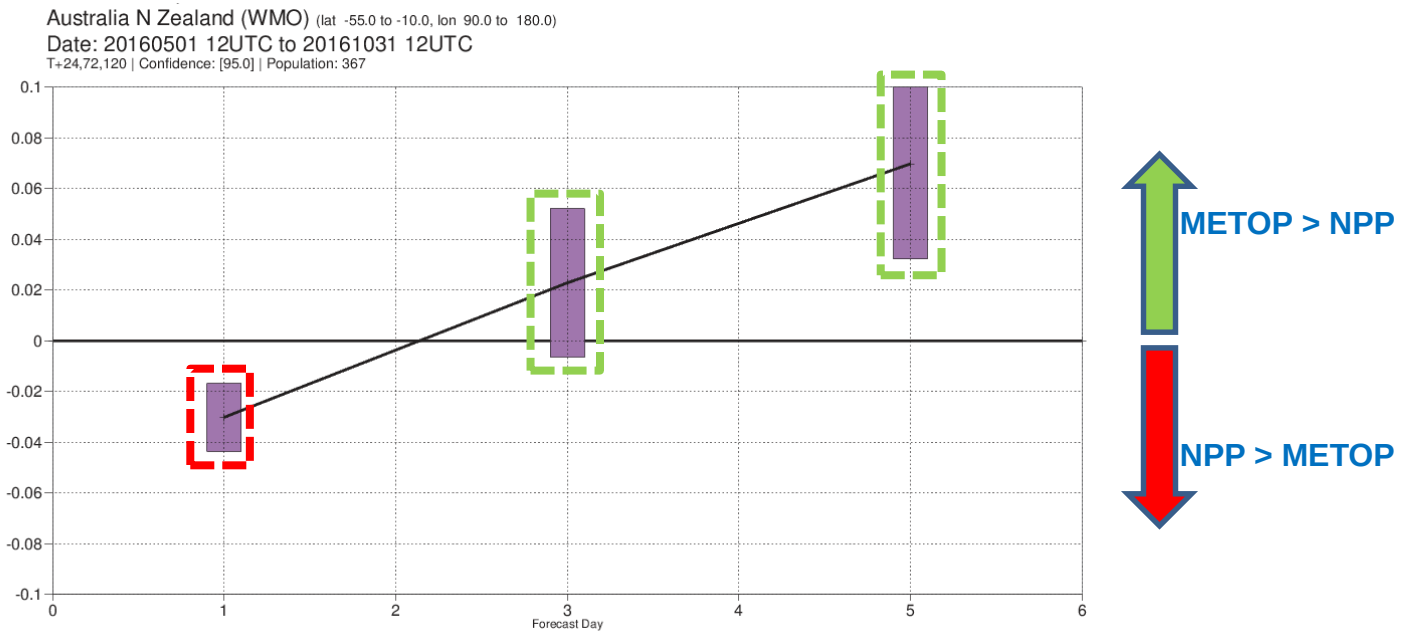
METOP* v NPP (Australia/NZ verification region)

NPP last 3 hours for 00z and 12z



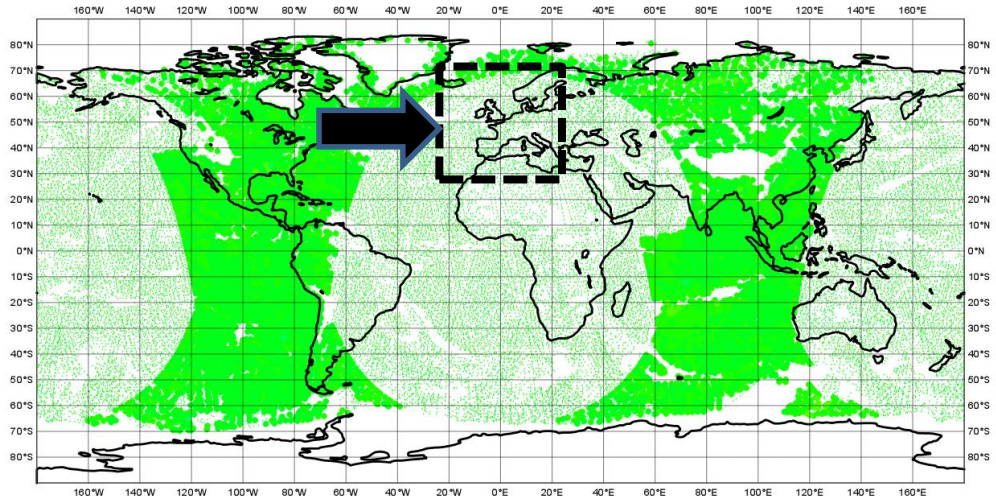
METOP last 3hrs for 00z and 12z 4DVAR window



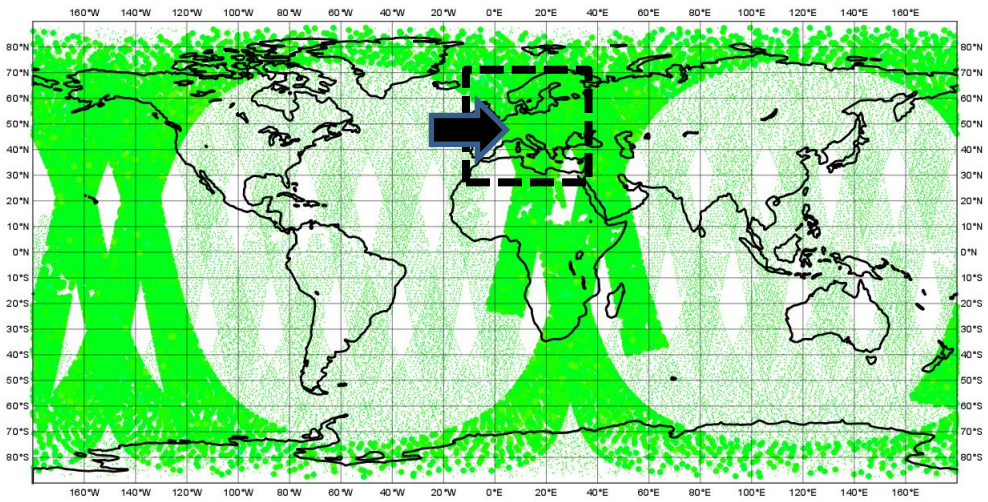


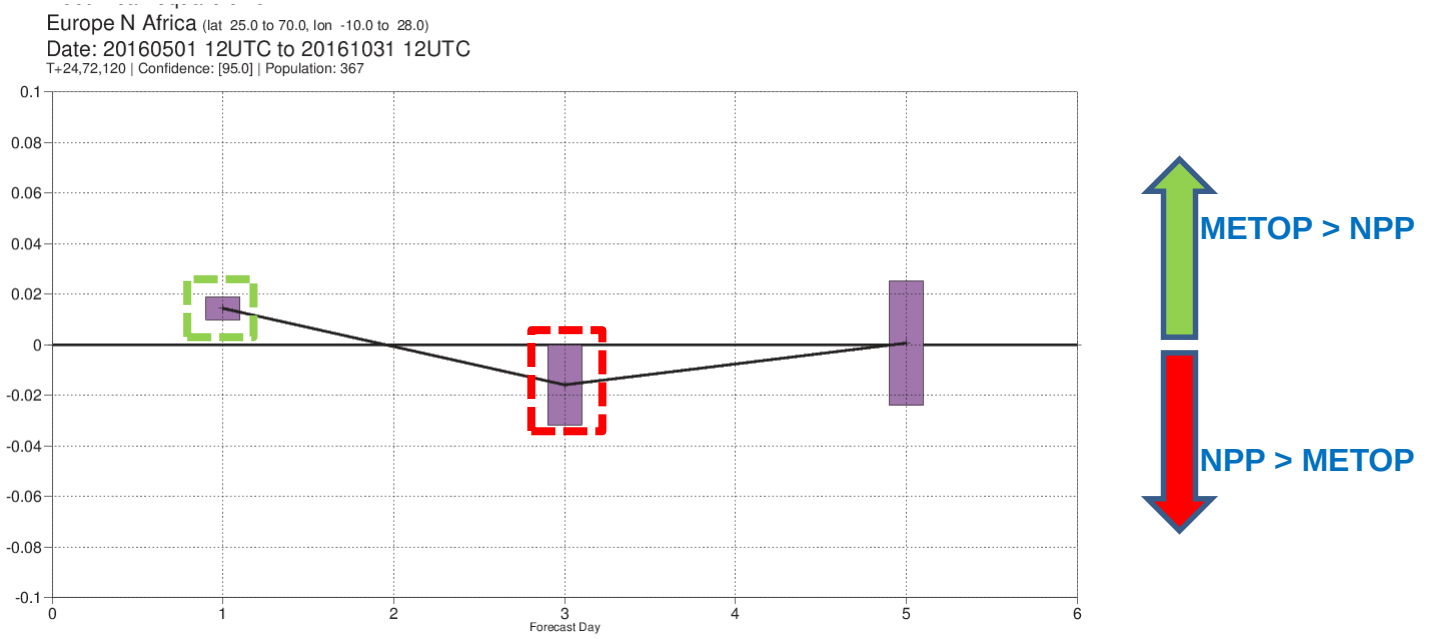
METOP* v NPP (European verification region)

NPP last 3 hours of 00z and 12z



METOP last 3hrs of 00z and 12z 4DVAR window





METOP > NPP

NPP > METOP

What factors influence an observation's value and are they captured in existing impact diagnostics ?

Intrinsic to the observation in OSE/FSOI

- Quality and quantity
- NRT availability
- coverage
- resolution
- time sampling
- uniqueness (including orbit)

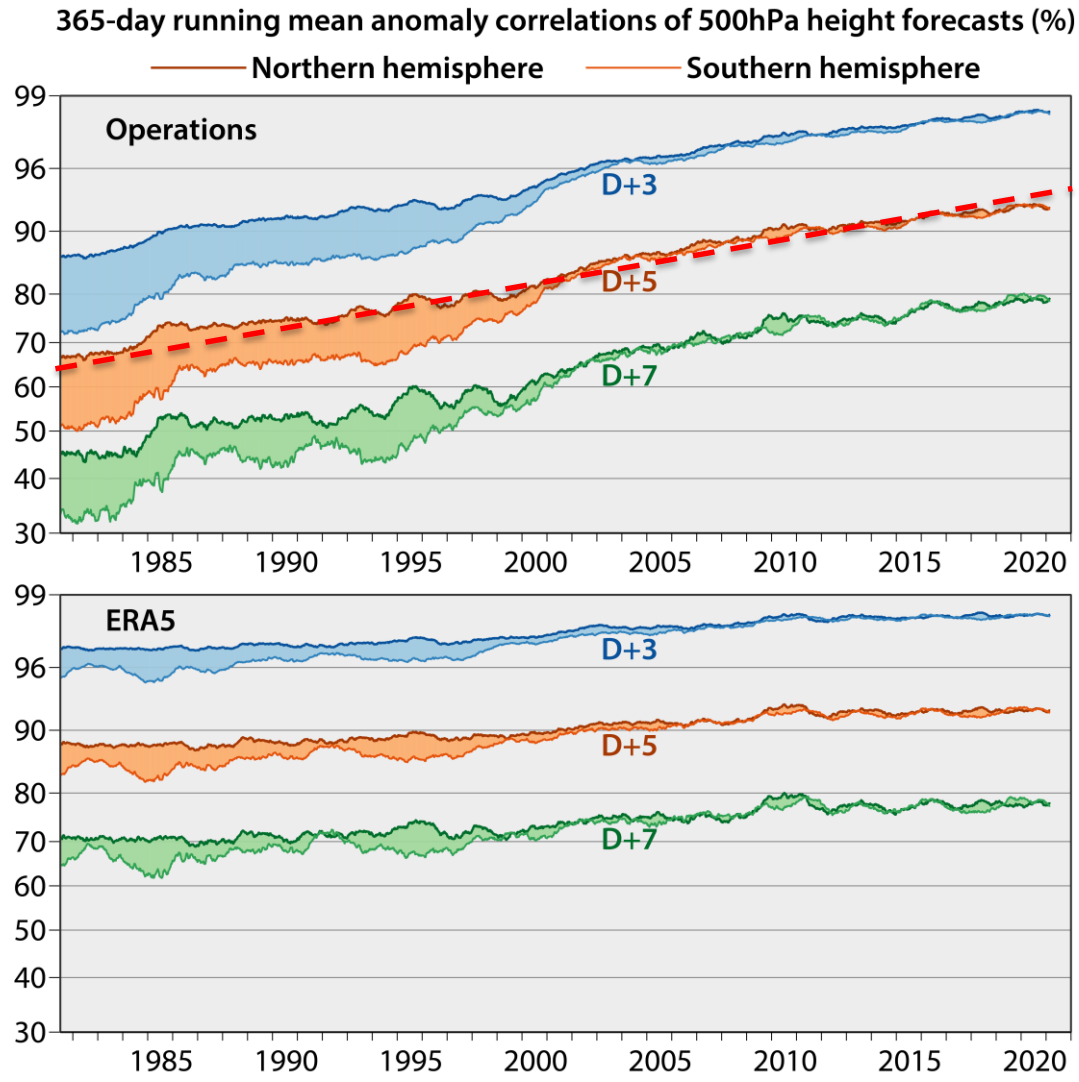
Non-intrinsic factors in OSE/FSOI

- Position in assimilation window
- Skill of DA tuning (Obs error)
- Reaction with model biases (spinup/down)
- Scope of the DA (e.g. clouds)

Value factors not captured by OSE / FSOI

- Longevity for RD investment and climate
- Useful in different applications
- Observation use for model development
- Calibration standard observations
- Prototype data (e.g. GIIRS)
- Technology demonstrations ?

Observations are critical in system development

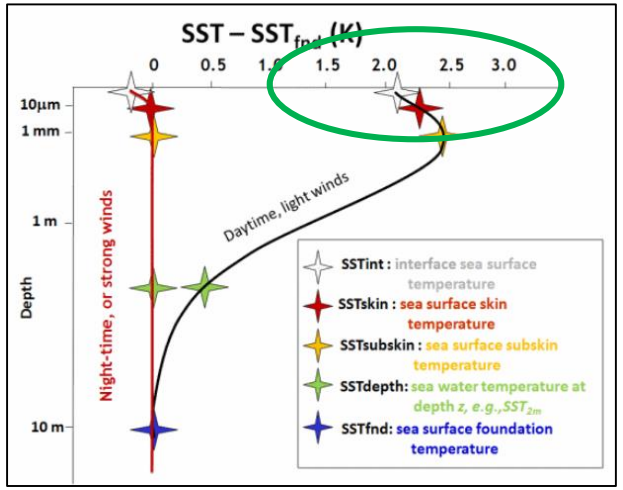


Observations are used in the design of upgrades to operational systems and for validation and testing

Much of our science is still empirical!

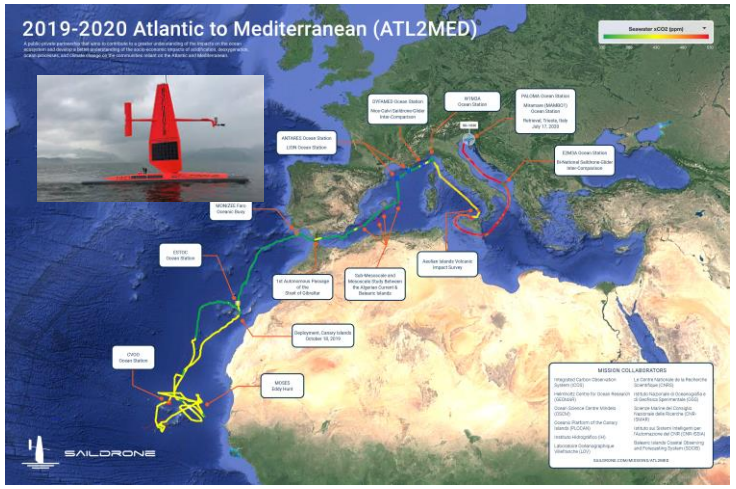
Impact on model development: Ocean skin physics

Diagnostics from assimilated and non assimilated observations give indications of how to improve our forecast model representation of ocean cool skin physics.



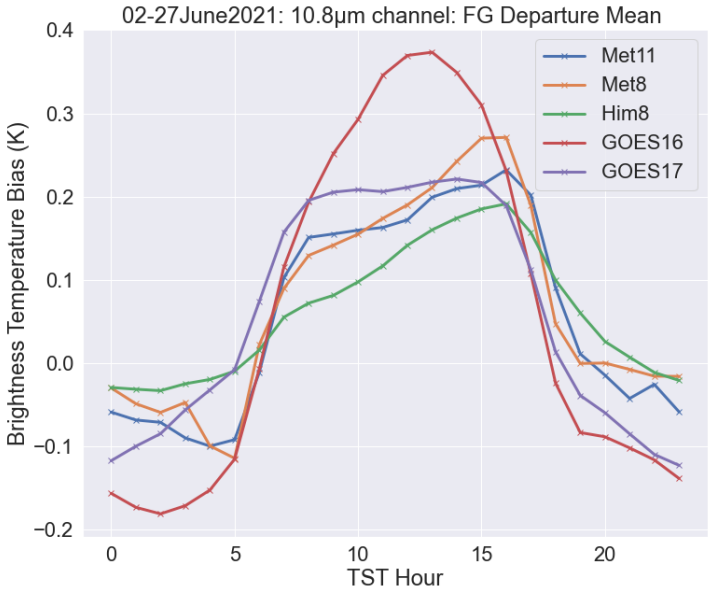
GHRSST

Saildrone data



Phil Browne / Saildrone Inc.

GEO window channels



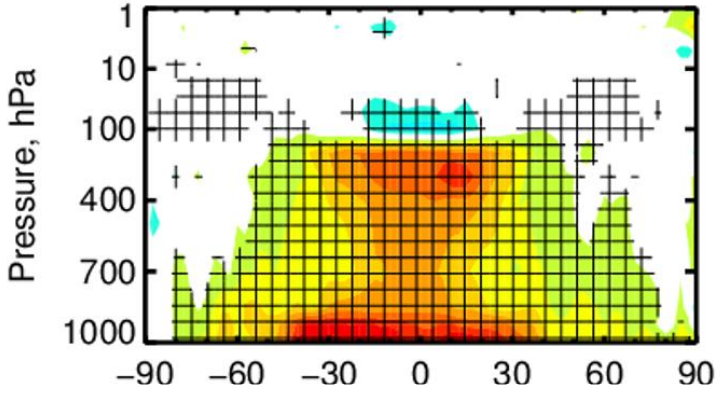
Samuel Quesada Ruiz

…which led us to question our model parameterisation of the “cool-skin”

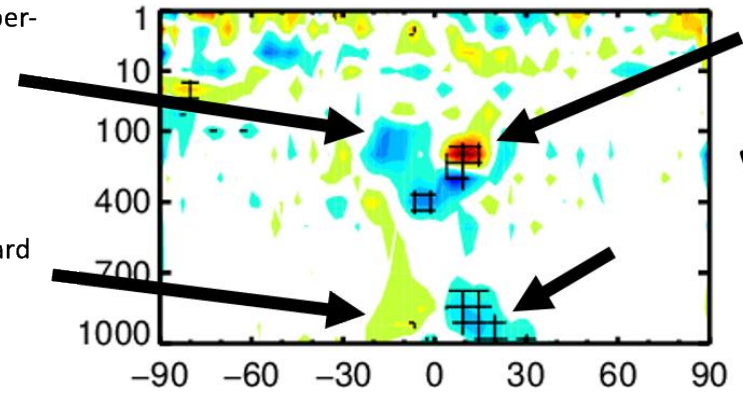
Observation driven changes to the model can have a massive impact…much larger than via assimilation!

Switching off the parameterisation had a dramatic effect on the model large scale circulation (some good some bad!)

T



V



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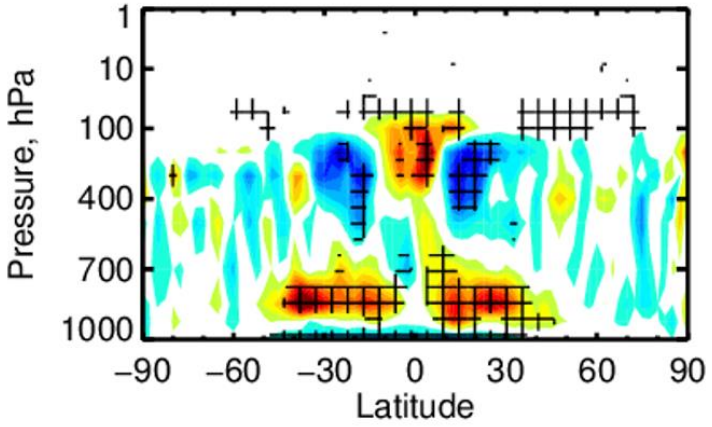

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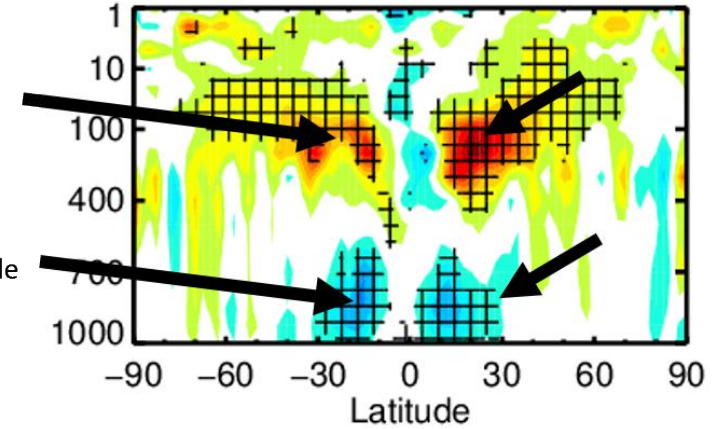

A few “holistic” thoughts on how to improve observation value…

…scientific and non-scientific…

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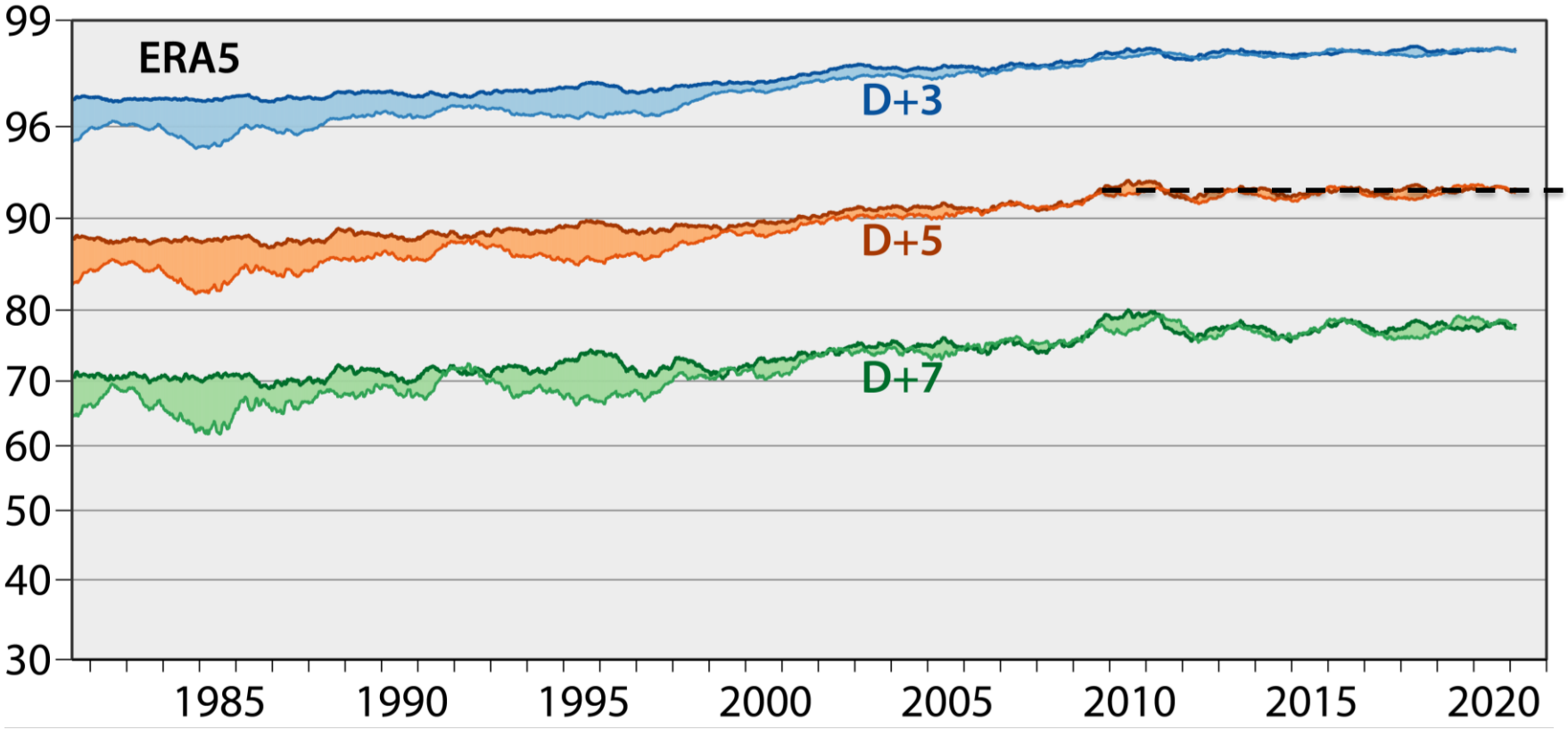
…scientific and non-scientific…



Have we levelled off recently ?

A few “holistic” thoughts on how to improve observation value…

Scientific and non-scientific…

Investing in *holistic* R+D that will scale to benefit the entire observing system…

1) Continuous DA

2) All-sky, all-surface, all-channel and all-pixel

3) Coupled prediction systems

Investing in holistic R+D that will scale to benefit the entire observing system…

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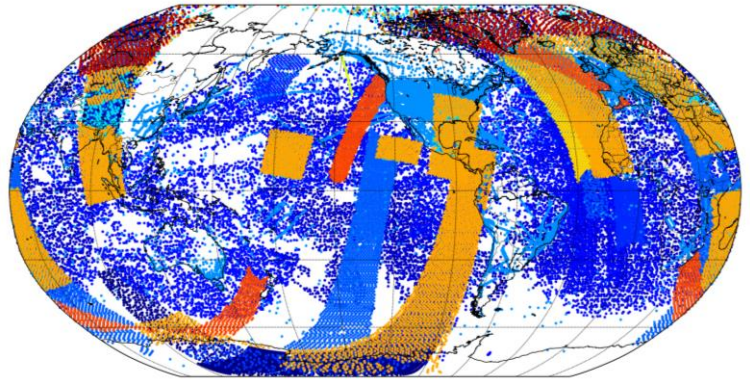
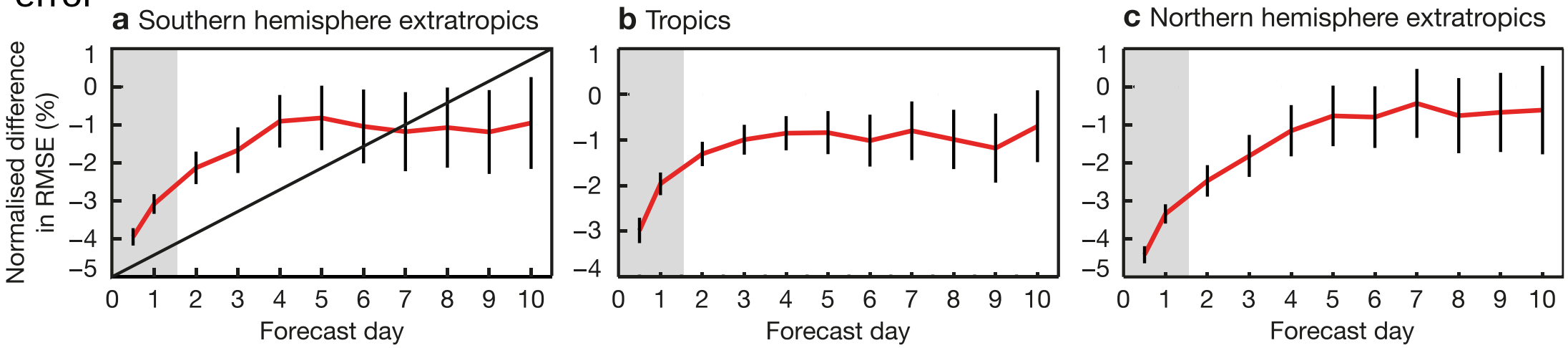
Continuous Data Assimilation

(Peter Lean's talk)



- Introduced in IFS CY46R1 (2019)
- At the time that the analysis is complete, the most recent assimilated observation is 35 minutes old compared to 120 minutes previously.
- Improved medium range forecast scores approx. 2% reduction in RMS error



Normalised difference in RMS error for vector wind

Lean, P, Hólm, EV, Bonavita, M, Bormann, N, McNally, AP, Järvinen, H. Continuous data assimilation for global numerical weather prediction. *Q J R Meteorol Soc*. 2021; 147: 273– 288.

Investing in holistic R+D that will scale to benefit the entire observing system…

1) Continuous DA

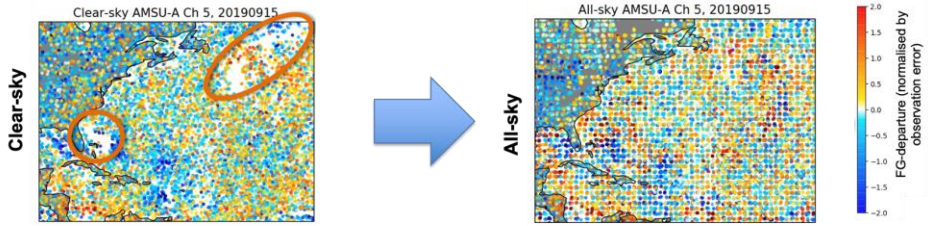
2) All-sky, all-surface, all-channel and all-pixel

3) Coupled prediction systems

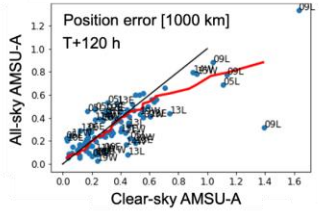
All-sky, all-channel, all surface and all-pixels

All sky …AMSUA microwave

The all-sky technology developed to use microwave imagers in cloudy and precipitating regions has recently been extended to AMSUA



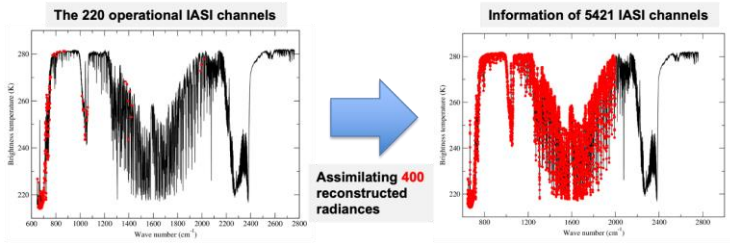
The additional MW data that can now be used in meteorologically active regions shows a clear benefit on mean scores, but also some **severe weather** predictions (storm Humberto above)



(Dave Duncan EUMETSAT Fellow)

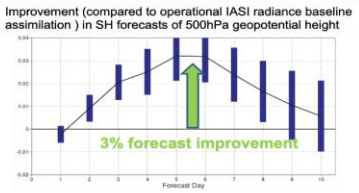
All channel…IASI hyperspectral infrared

Technology is being developed to use the full IASI longwave and midwave spectrum using radiances reconstructed from truncated principal components



By assimilating the full IASI LW/MW spectrum via reconstructed radiances derived from truncated PCA we can extract even more information from these observations.

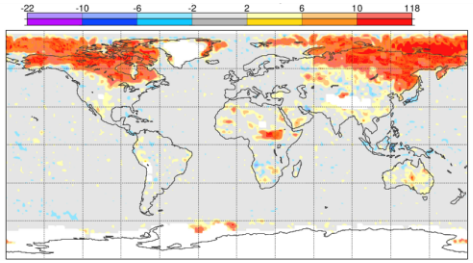
Latest results show PCA/RR consistently outperforming traditional radiance channels assimilation

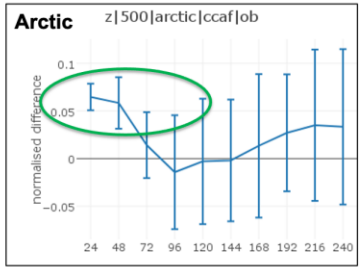


Marco Matricardi EUMETSAT WP

All surface …microwave data over land and ice

A new 2D approach for analyzing skin temperature and emissivity has been developed which is particularly beneficial for the assimilation of microwave radiances with a sensitivity to surface emission / reflection





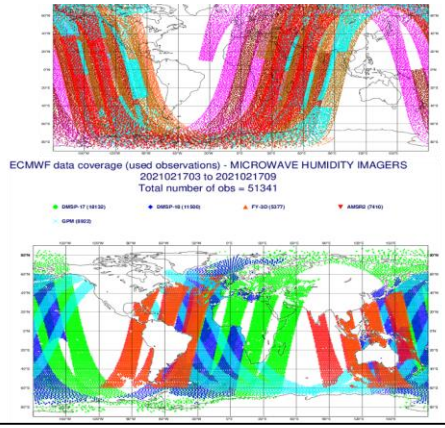
Applied to AMSUA, many more observations can be used (e.g. in the arctic) with significant localised improvements in forecast quality

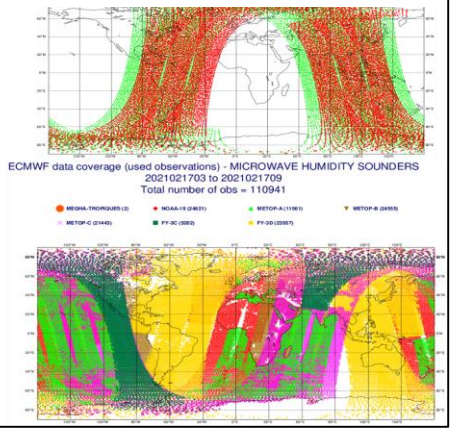
Seb Massart

All pixels, super-obbing, thin or spatial correlation ?

We currently use only 5-10% of our satellite data!

Jo Waller's talk





Investing in holistic R+D that will scale to benefit the entire observing system…

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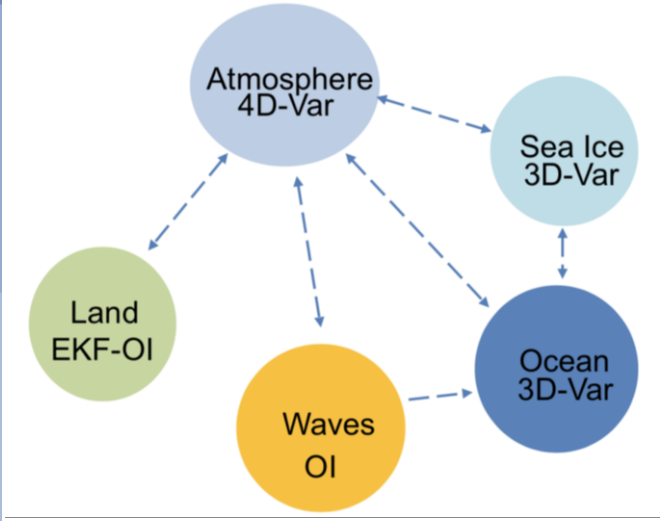
2) All-sky, all-surface, all-channel and all-pixel

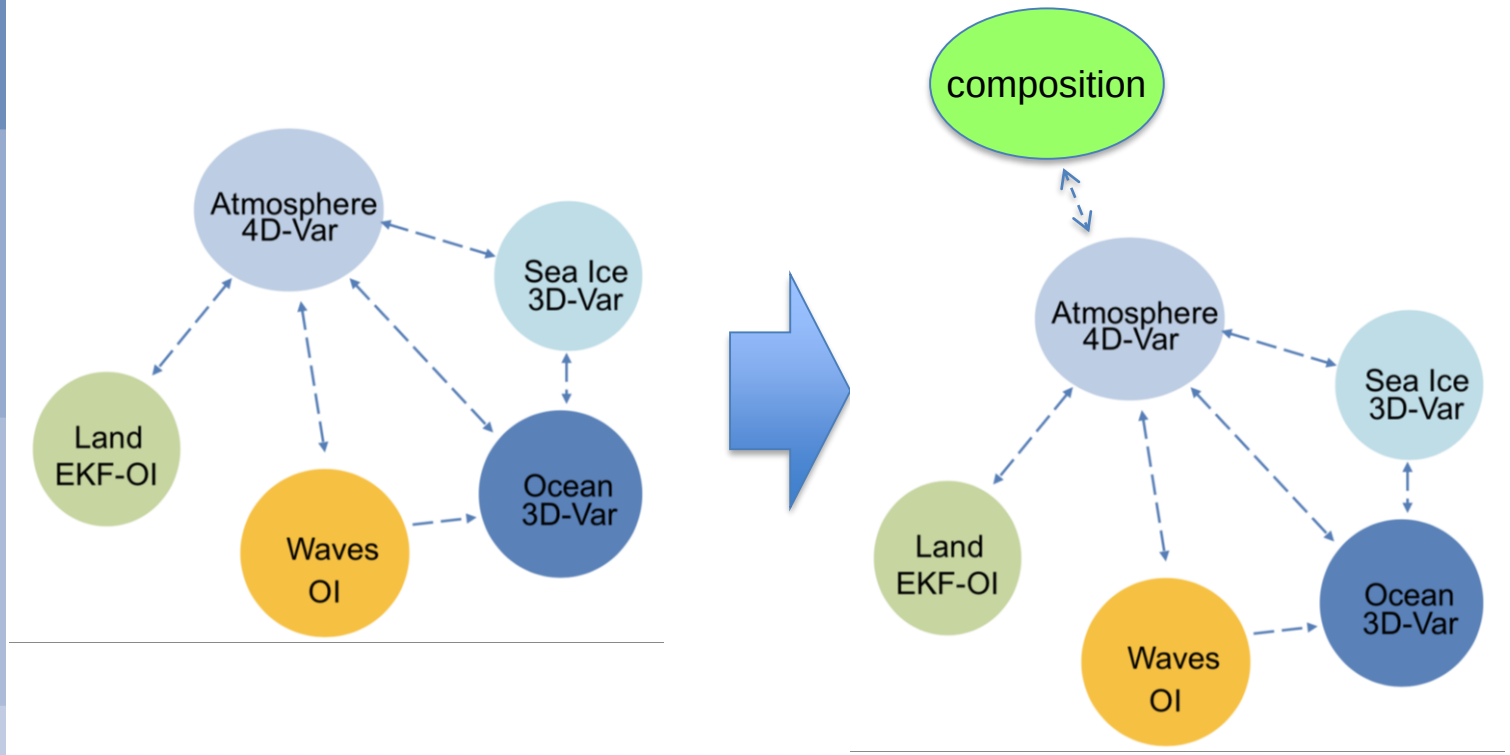
3) Coupled prediction systems

Coupled prediction systems – for NWP

(Patricia de Rosnay's talk)

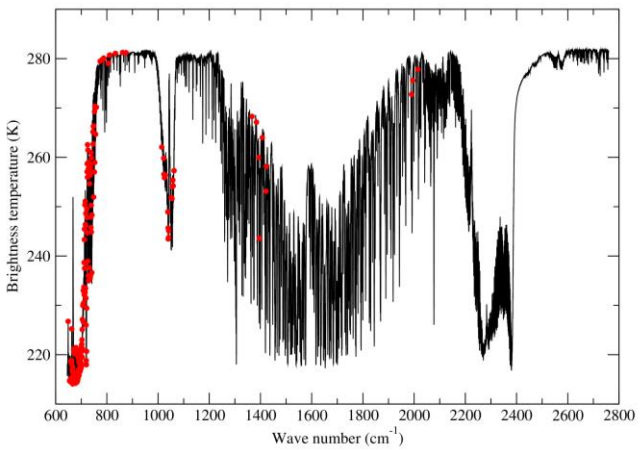


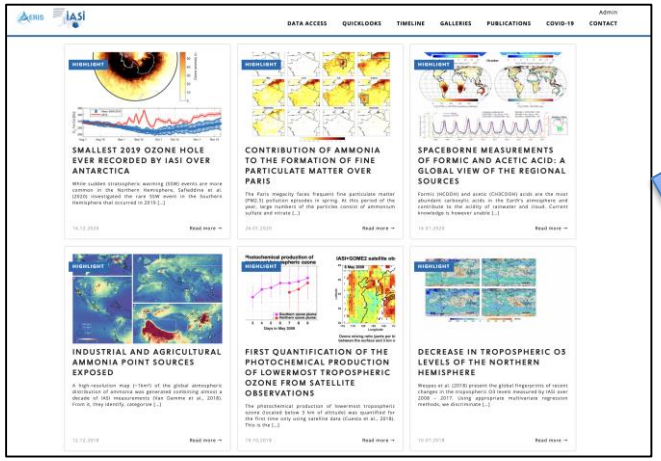
Coupled prediction systems – and composition



An observation's value increases in coupled prediction systems…

An observation's value increases in coupled prediction systems…e.g. IASI composition





composition

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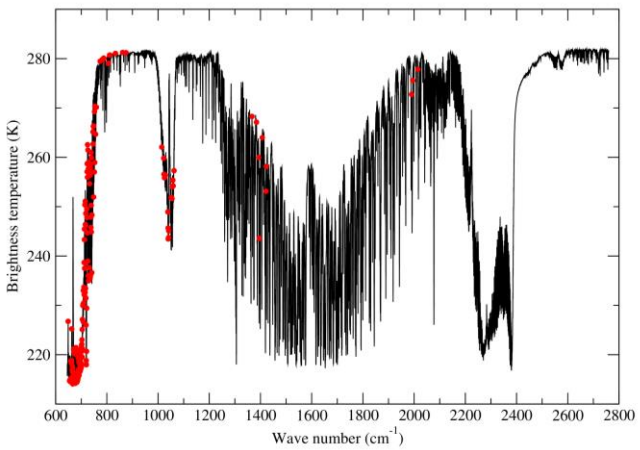
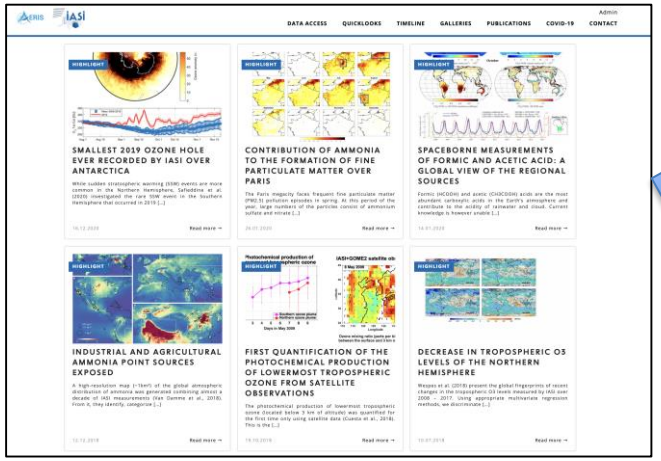
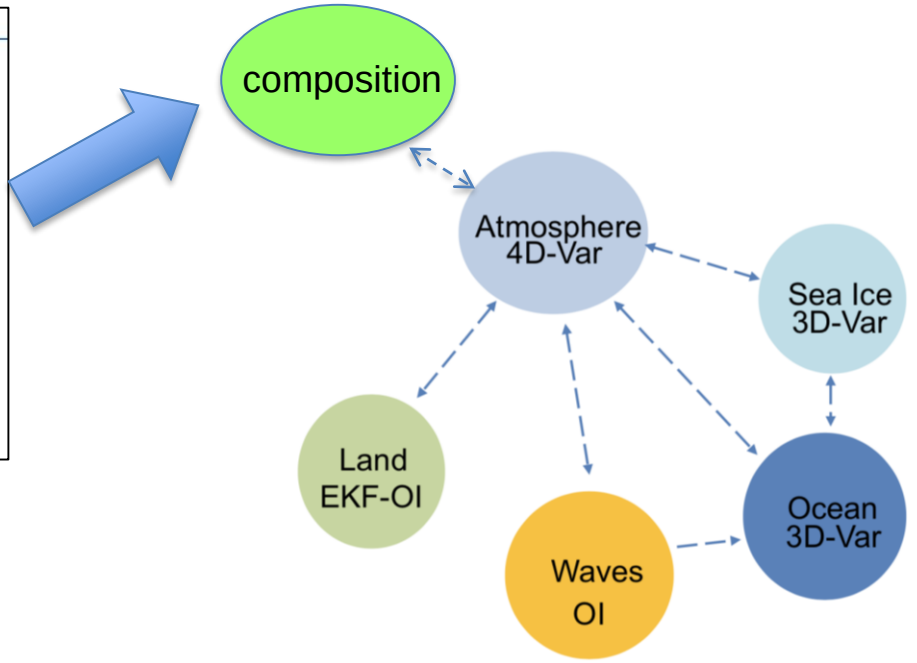
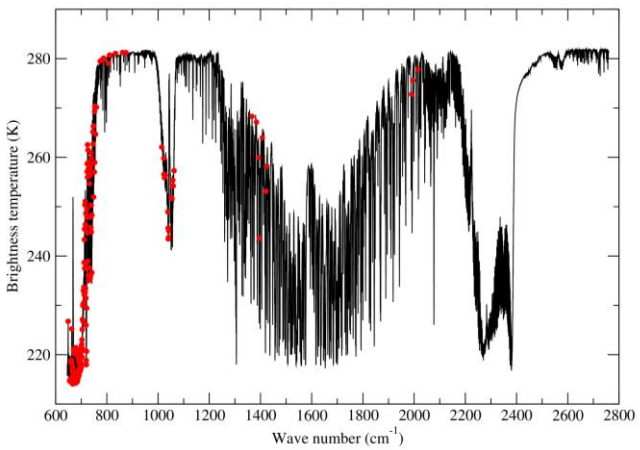
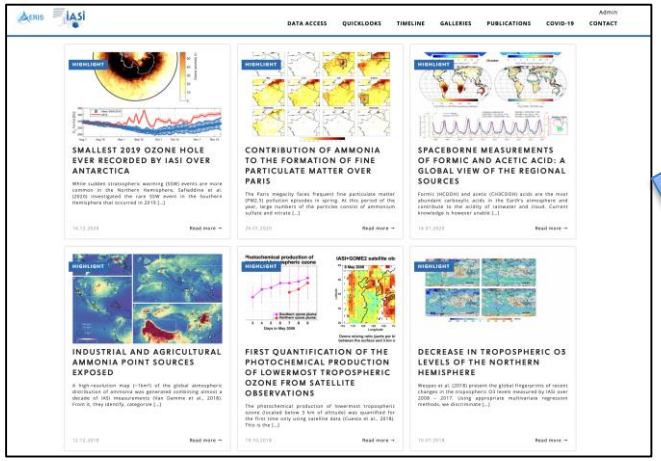


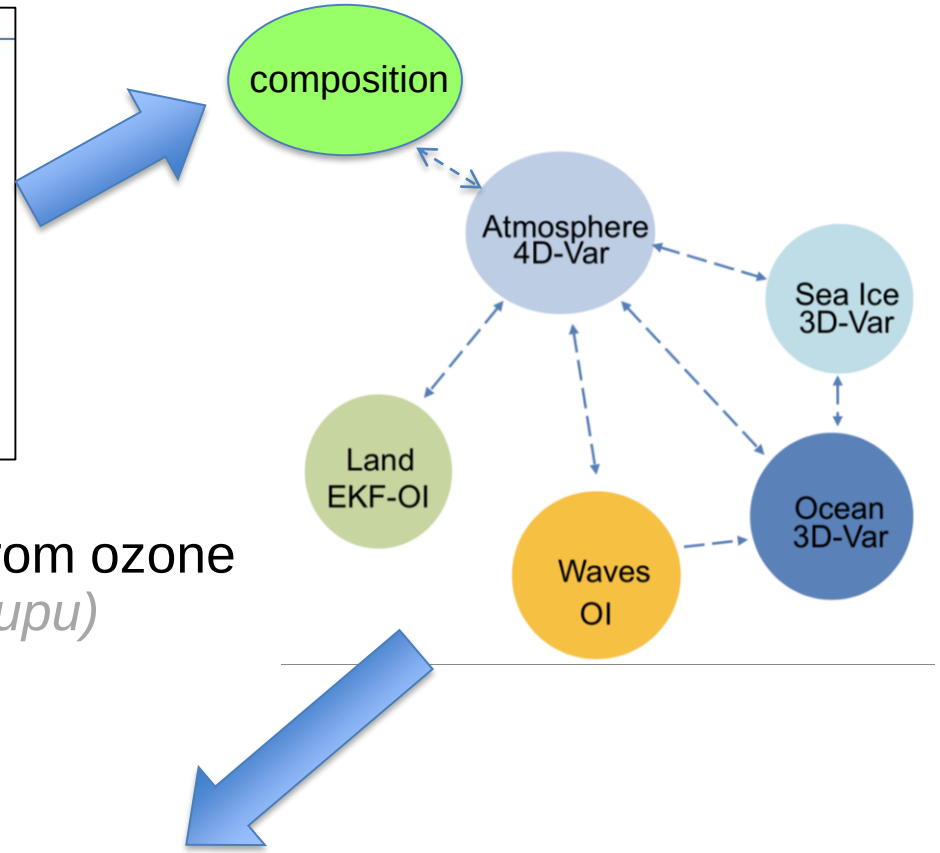




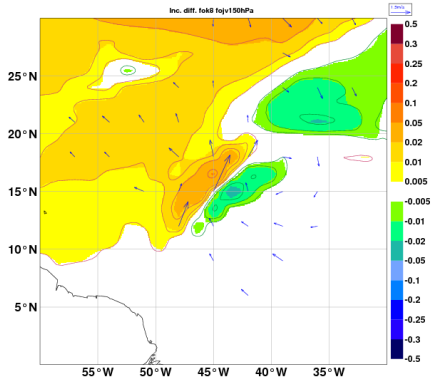
An observation's value increases in coupled prediction systems…produces wind information







Advection wind tracing from ozone in the stratosphere. *(C Lupu)*



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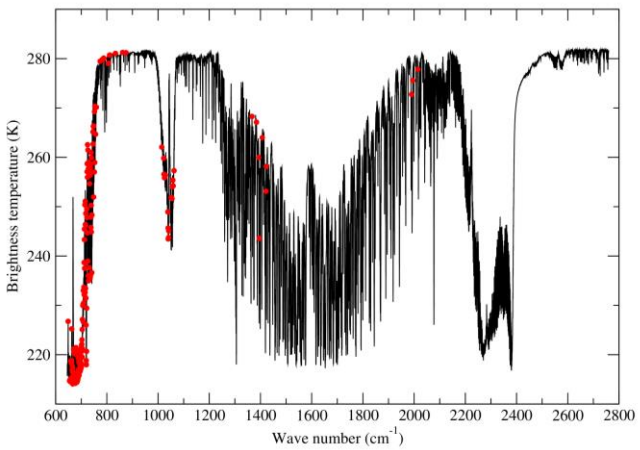
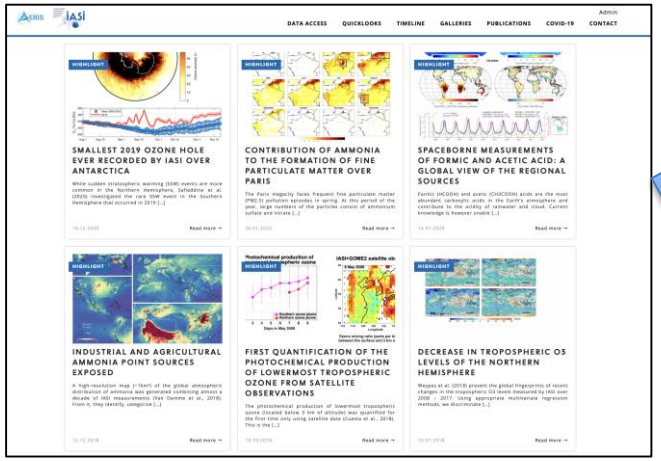
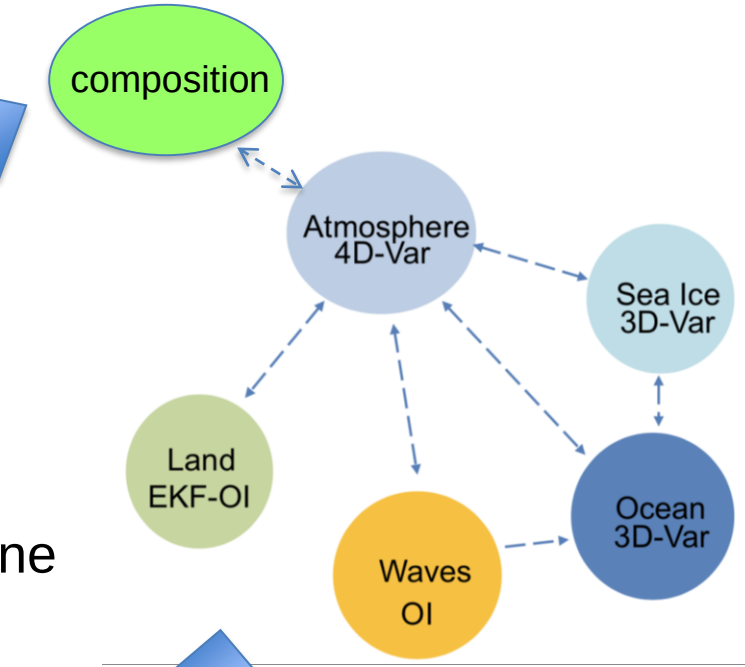
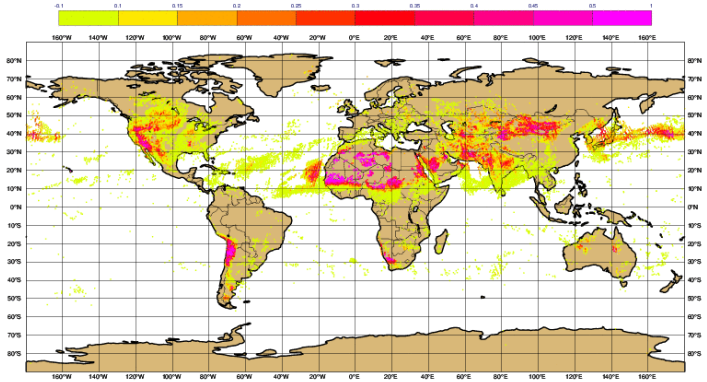


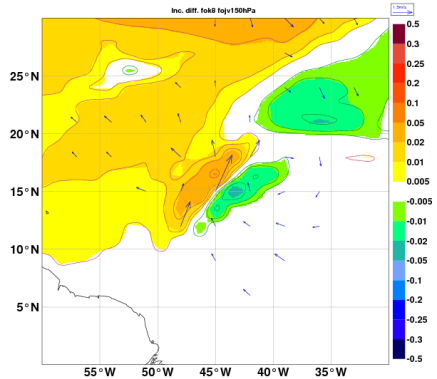




Advection wind tracing from dust aerosol ?

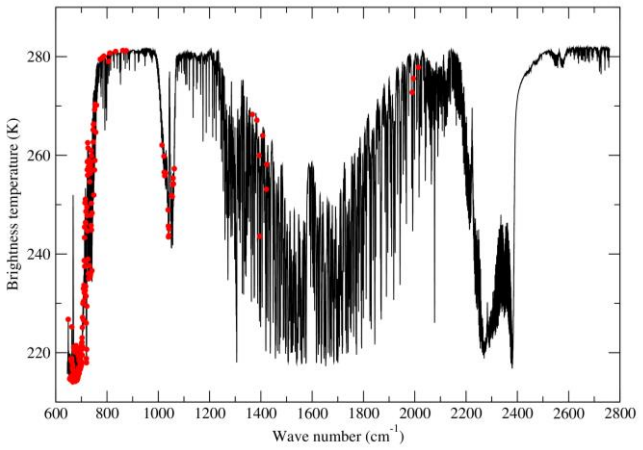


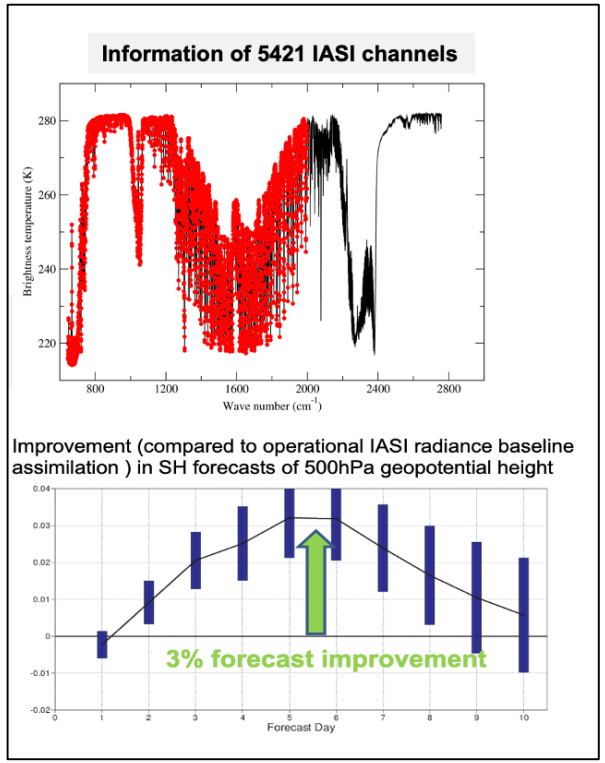
Advection wind tracing from ozone in the stratosphere. *(C Lupu)*

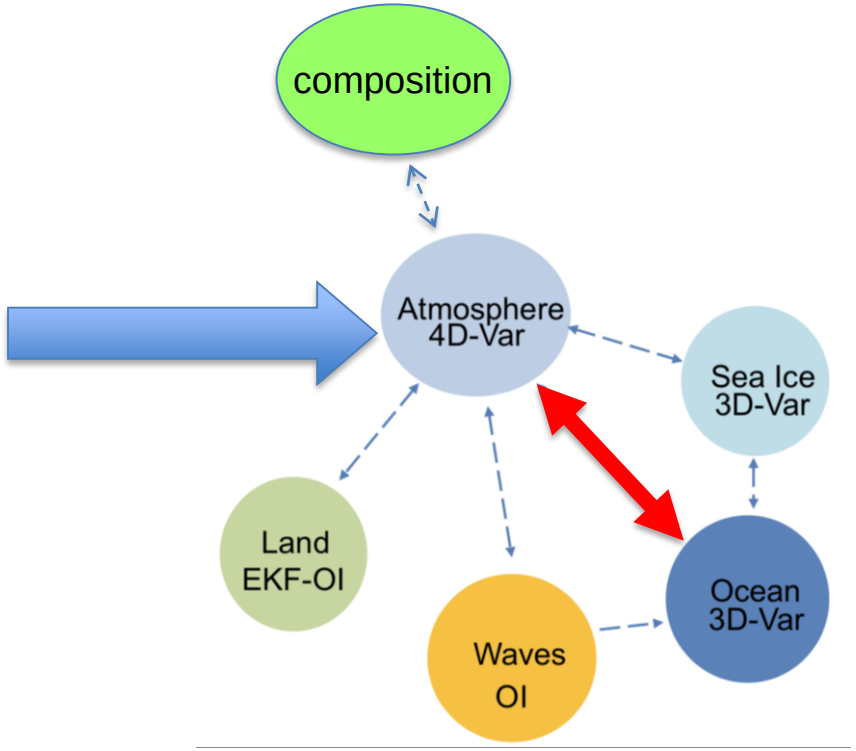


An observation's value increases in coupled prediction systems…

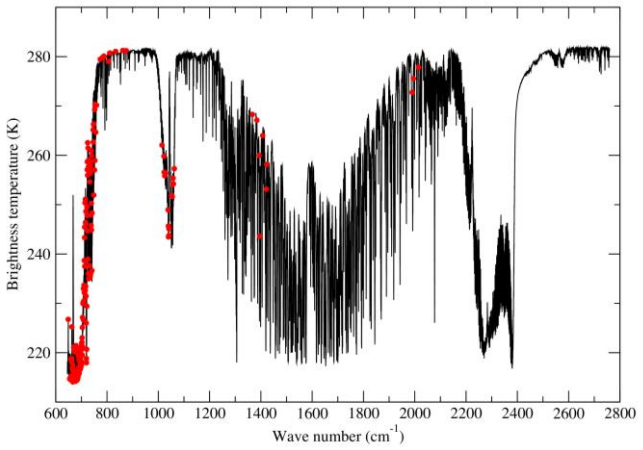
An observation's value increases in coupled prediction systems…e.g. IASI atmospheric NWP information

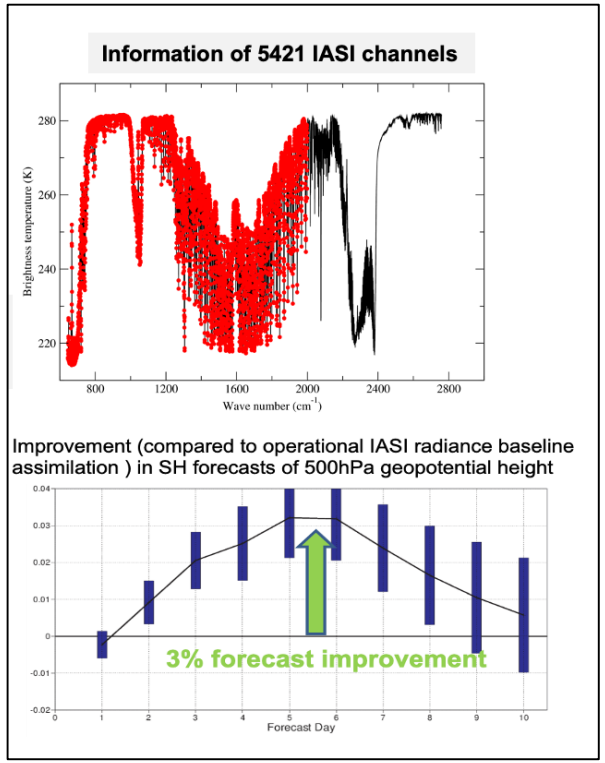


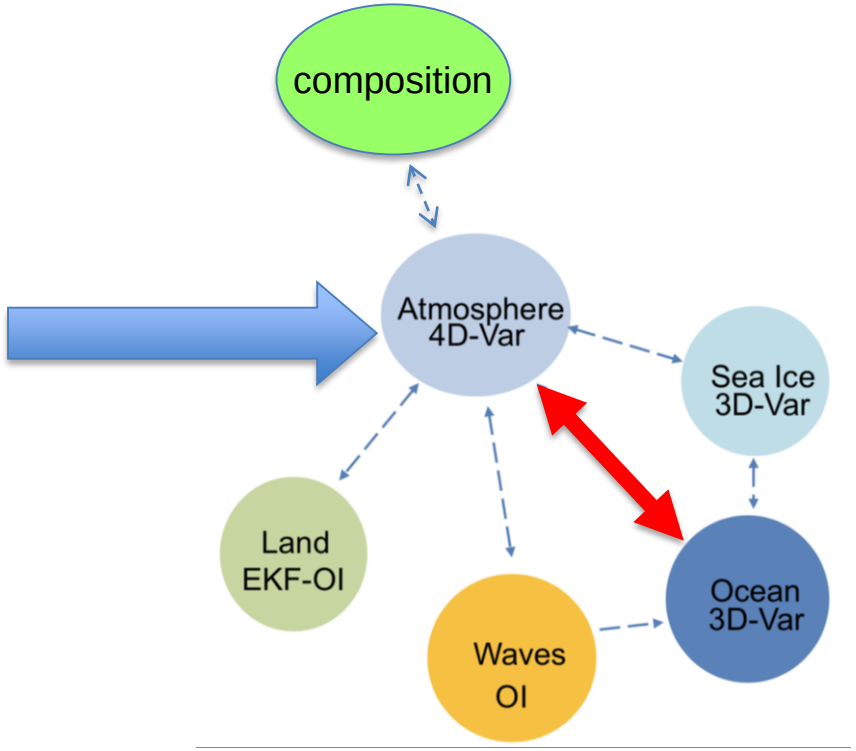




An observation's value increases in coupled prediction systems…goes in to the ocean





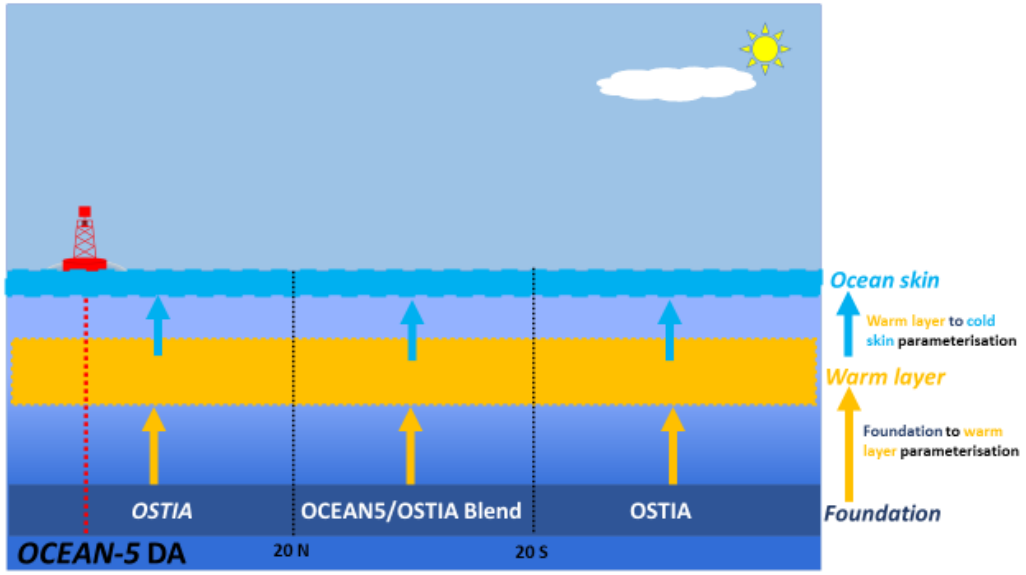


Coupled ocean SST assimilation

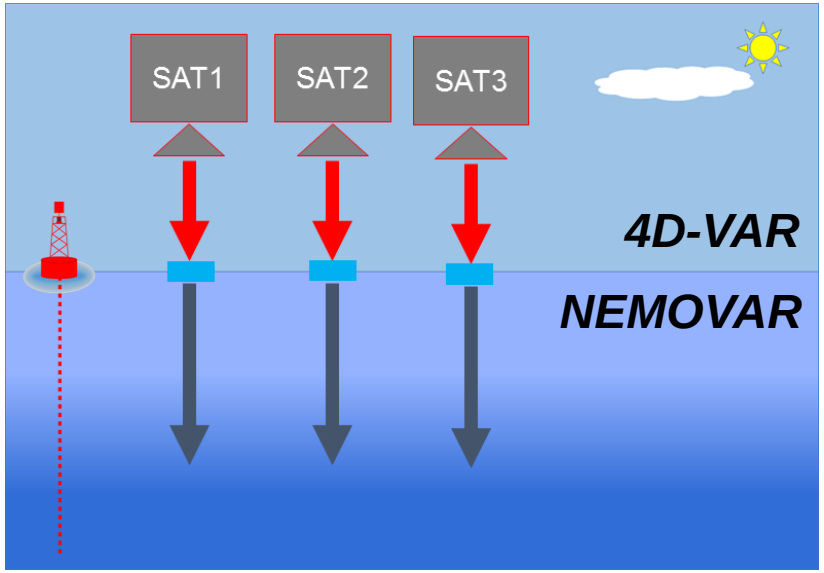
Tony McNally, Phil Browne, David Fairburn, Hao Zou, Seb Massart, Marcin Chrust, + …

The ocean surface can no longer be treated as a lower boundary condition of the atmosphere or an upper boundary condition of our ocean, it is at the **centre** of our coupled DA / FC system and must be treated as such.

SST constrained by OSTIA



SST constrained by 4D-Var SKT

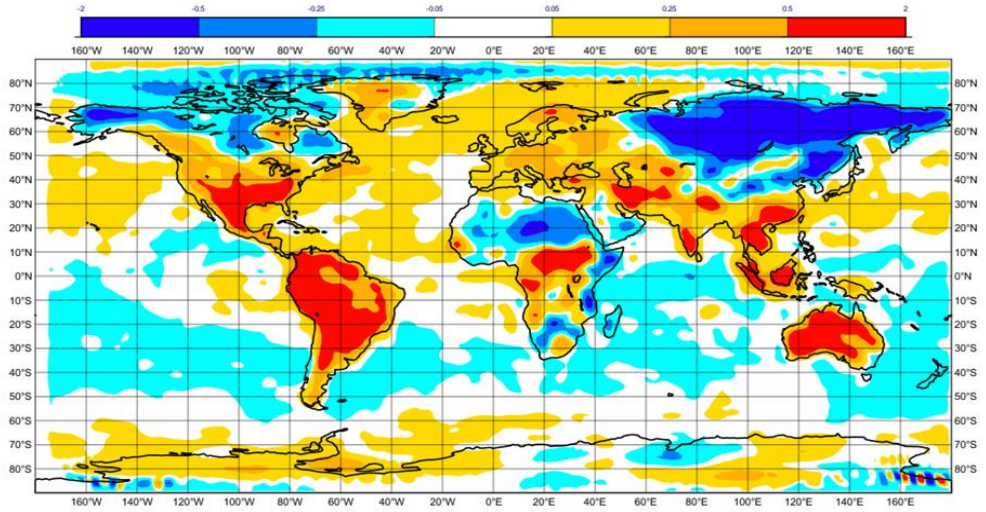


The new system will avoid unnecessary external / internal mapping and conversion of satellite information …and improve operational scheduling

Coupled ocean SST assimilation

Skin temperature increments driven by satellites in 4D-Var (**IASI**, CrIS, SLSTR, AMSRE, SEVIRI, ABI, AHI) will be explicitly coupled (via outer loop model integration) to the upper layer of the NEMO ocean.

4D-Var (SKT) increments

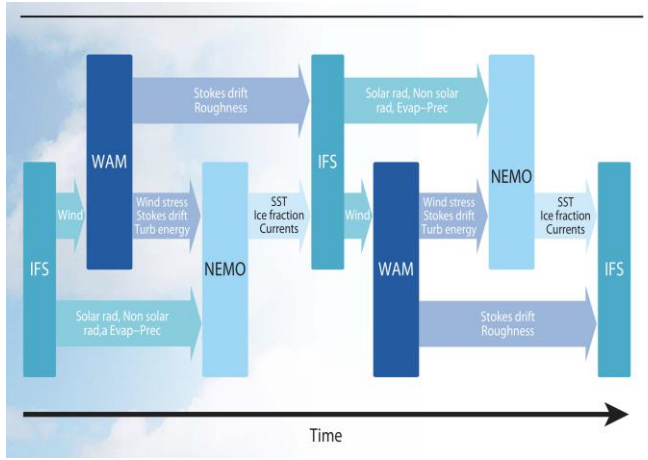


…	….
133	850
134	900
135	950
136	1000
137	1013

2m

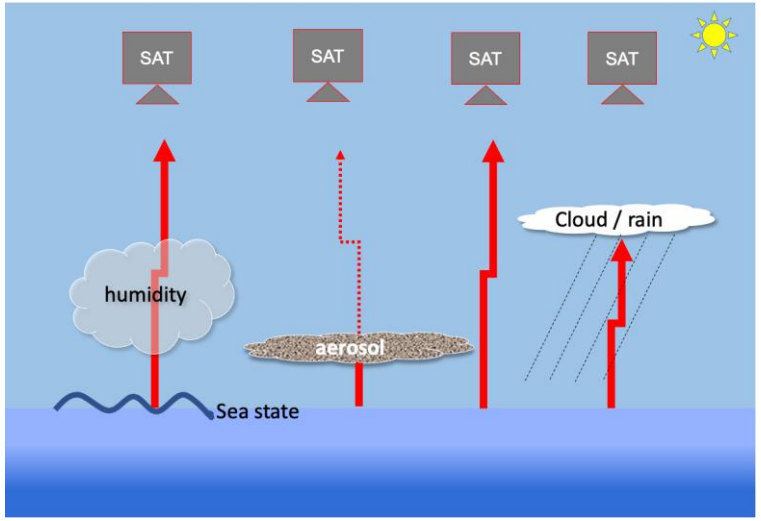
skin

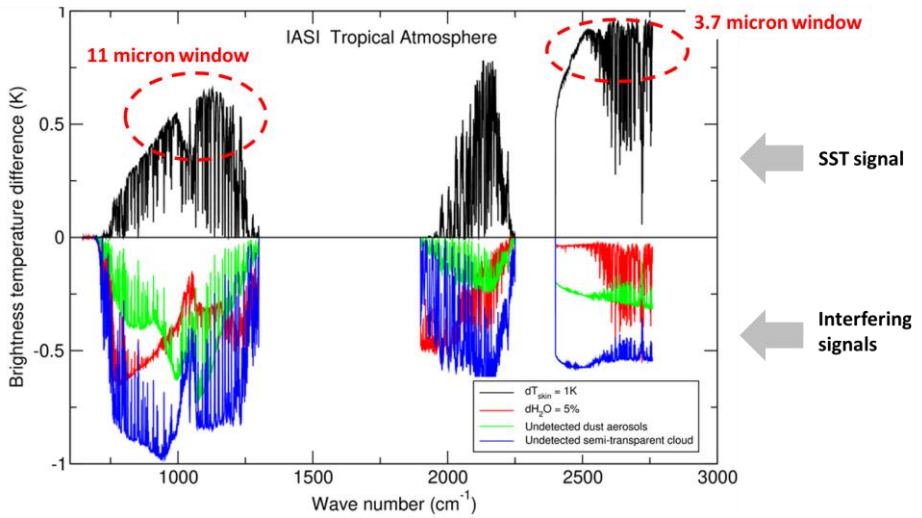
1	0.51	0.00
2	1.56	1.02
3	2.67	2.10
4	3.86	3.25
5	5.14	4.49
6	6.54	5.83
7	8.09	7.30
8	9.82	8.93
9	11.77	10.77
10	13.99	12.85
11	16.53	15.22
12	19.43	17.93
13	22.76	21.04
14	26.56	24.60
…	…	….

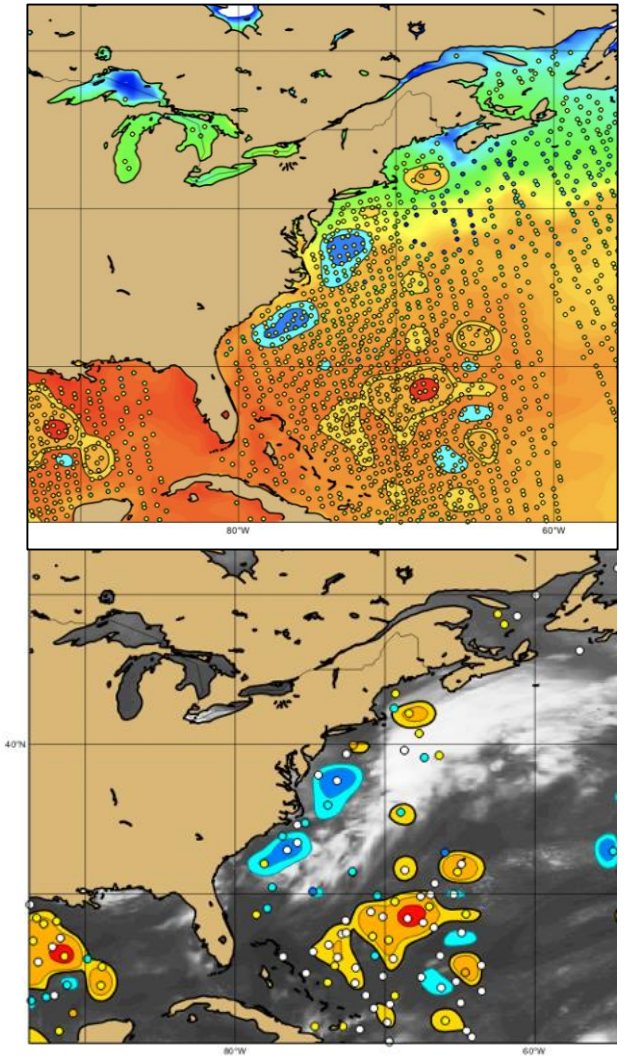


Coupled ocean SST assimilation…IASI

IASI contains hyper-spectral information that allows us to separate the ocean surface emission (SKT) signal from atmospheric interferences – this best done inside an atmospheric 4D-Var

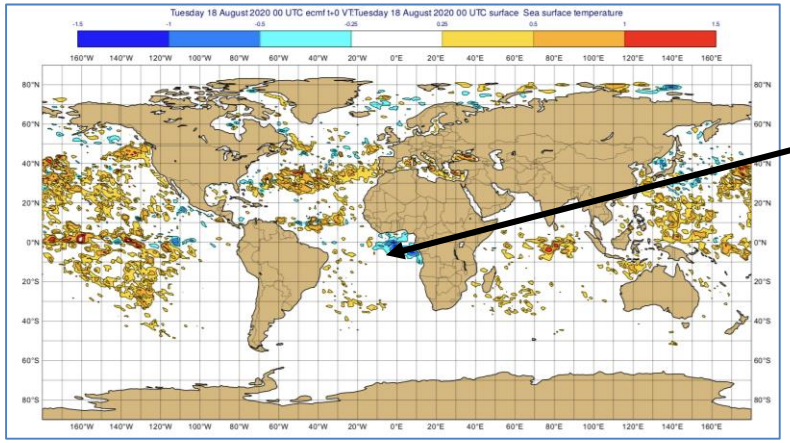


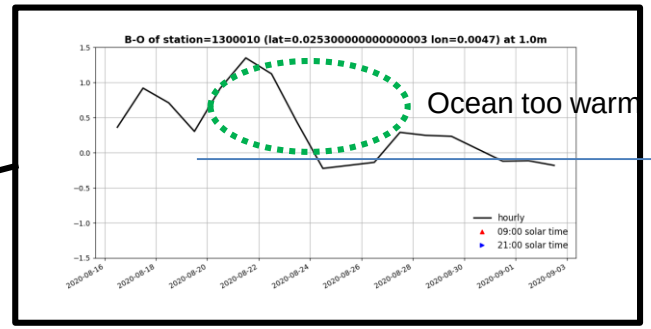


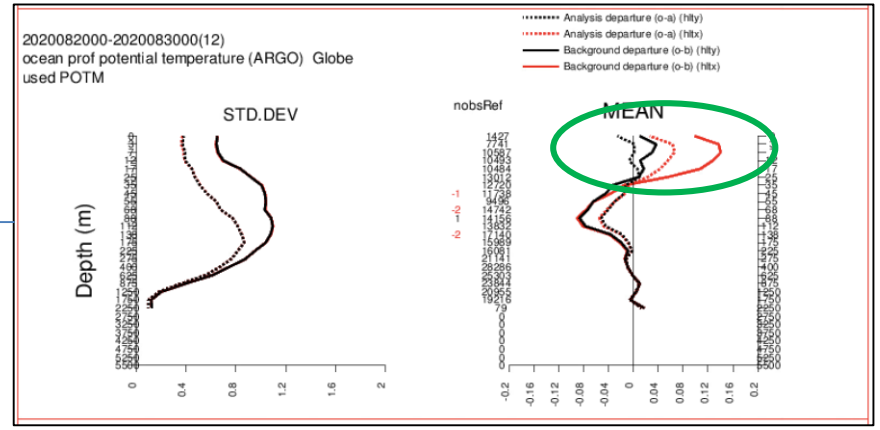


Coupled assimilation: IASI adds value to the ocean!

NEMOVAR SST changes forced by IASI radiances after 2 weeks of assimilation

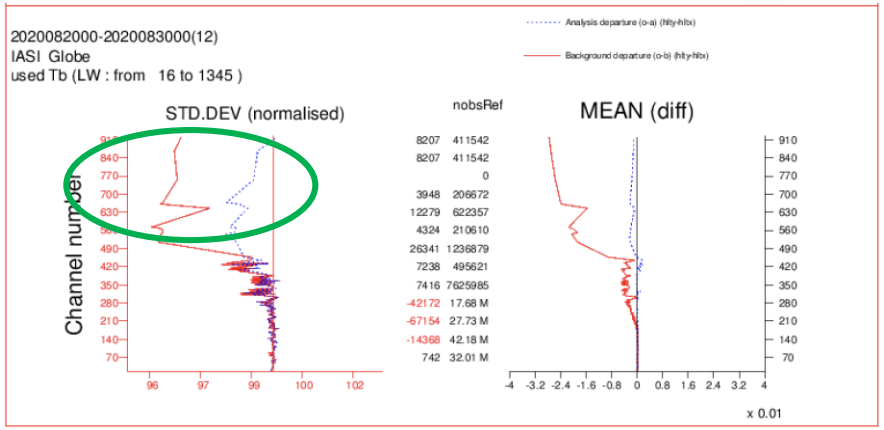


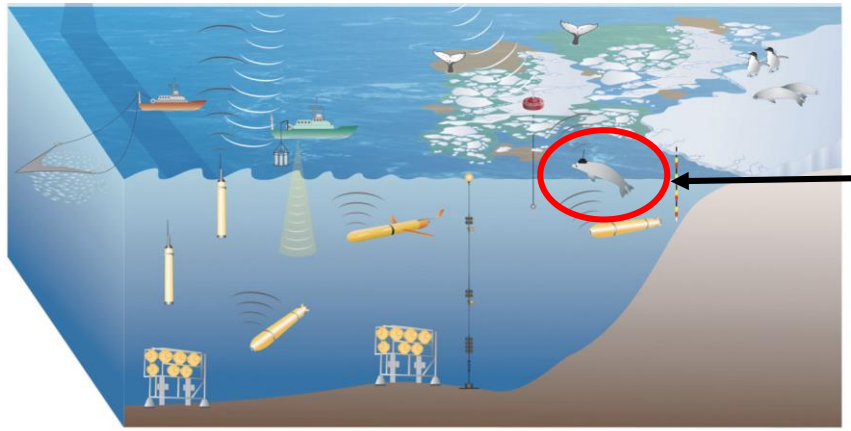


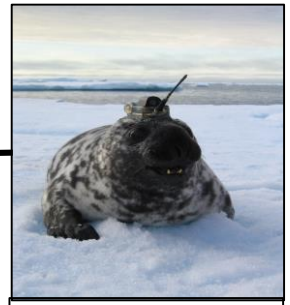


Assimilating IASI radiances in 4D-Var / NEMOVAR produces a better fit to surface and sub-surface **in situ observations** which simultaneously **anchor the IASI assimilation**

Changes have ***memory*** in the ocean improving the fit to IASI radiances in 4D-Var

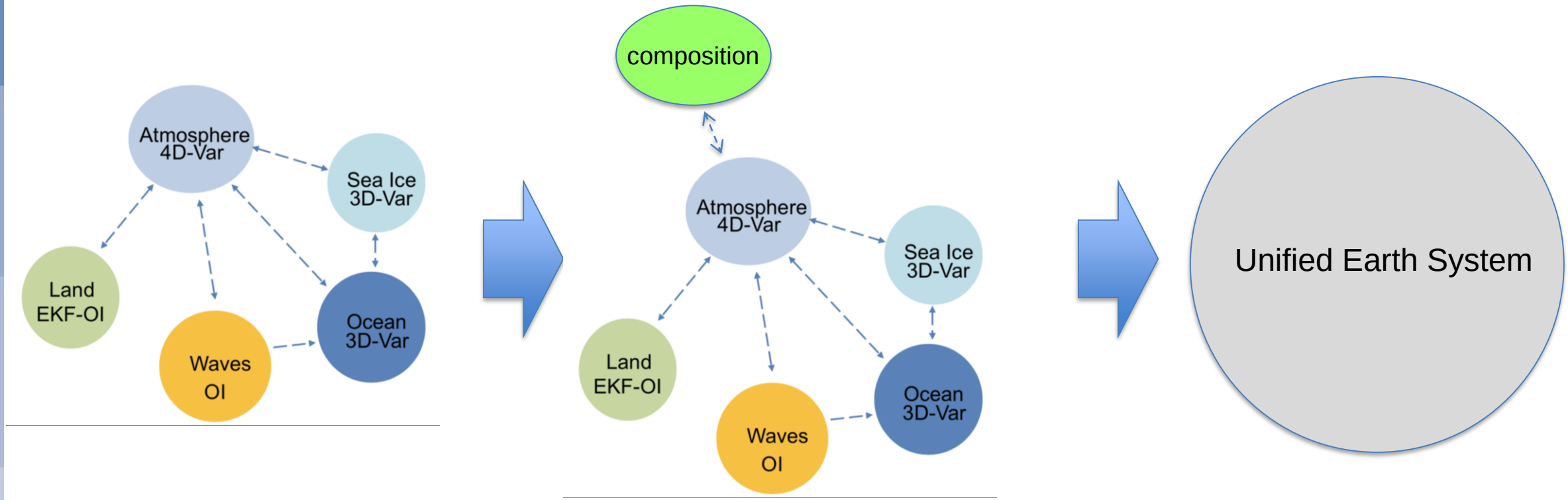






Phil Browne's pet sea lion!

Coupled prediction systems – the future ?



A few “holistic” thoughts on how to improve observation value…

Scientific and **non-scientific**…

Greater coordination in data exploitation

1) Timely data collection and data sharing

2) Satellite orbit deployment

3) More coordinated R+D

Greater coordination in data exploitation

1) Timely data collection and data sharing

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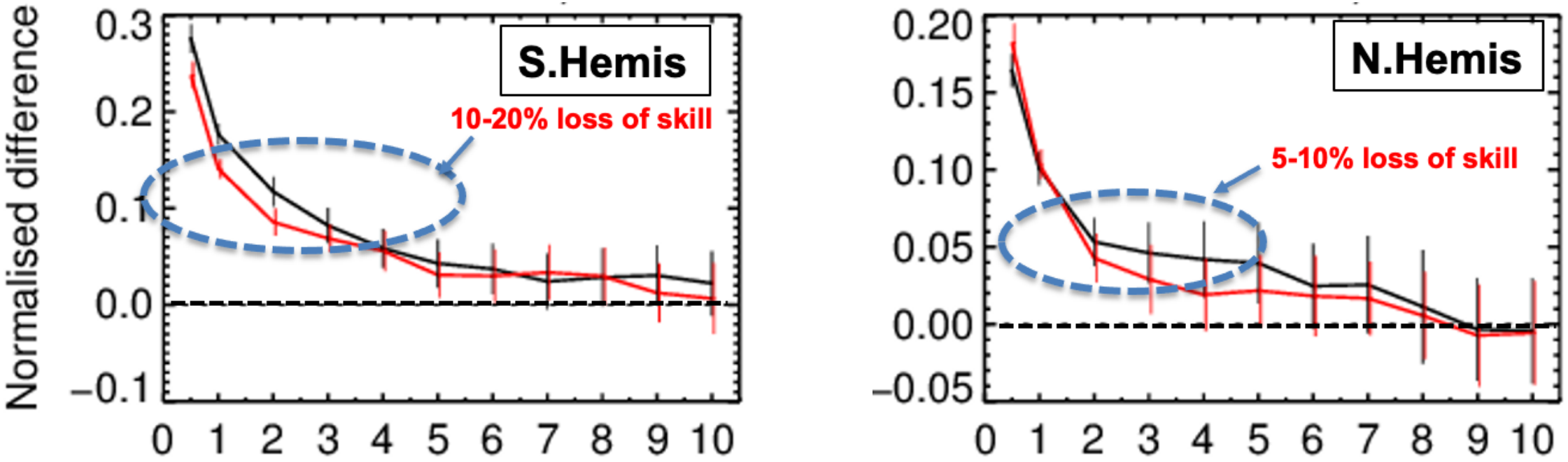
Contributions of Europe vs US vs ASIA

OBSERVATION	CONTROL (ECMWF OPS)	EUROPE	USA	ASIA
Atmospheric Motion Vectors	METOP A,B,C,DUAL (AVHRR) METEOSAT 8,11 (SEVIRI) HIMAWARI 8 (AHI) NPP, NOAA 20 (VIIRS) NOAA 15,18,19 (AVHRR) GOES 15,16 (I/ABI) AQUA (MODIS)	METOP A,B,C + DUAL (AVHRR) METEOSAT 8,11 (SEVIRI)	NPP, NOAA 20 (VIIRS) NOAA 15,18,19 (AVHRR) AQUA (MODIS) GOES 15,16 (ABI)	HIMAWARI 8 (AHI)
Atmospheric Sounding radiances	METOP A,B,C (AMSU/MHS/IASI) NPP, NOAA 20 (ATMS/CrIS) NOAA 15,18,19 (AMSU/MHS) AQUA (AMSUA/AIRS) FY3-B,C,D (MWHS/MWHS2) METEOSAT 8,11 (SEVIRI) HIMAWARI 8 (AHI) GOES 15,16 (I/ABI) GCOM-W (AMSR-2) GPM (GMI) DMSP 17,18 (SSM/IS)	METOP A,B,C (AMSU/MHS/IASI) METEOSAT 8,11 (SEVIRI)	NPP, NOAA 20 (ATMS/CrIS) NOAA 15,18,19 (AMSU/MHS) AQUA (AMSUA/AIRS) GOES 15,16 (I/ABI) DMSP 17,18 (SSM/IS)	FY3-B,C,D (MWHS/MWHS2) HIMAWARI 8 (AHI) GCOM-W (AMSR-2)
GPS-RO	METOP A,B,C (GRAS) COSMIC TERRASAR / TANDEM FY3 (GNOS) KOMPSAT5 (GNOS)	METOP A,B,C (GRAS)	COSMIC*	FY3 (GNOS) KOMPSAT5
Scatterometer	METOP 3,4,5 (ASCAT)	METOP A,B,C (ASCAT)		

The importance of US – EU data exchange

use all satellites
use only EUM satellites
use only US satellites

Medium-range forecast error degradation compared to **control** (500hPa)



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

Greater coordination in data exploitation

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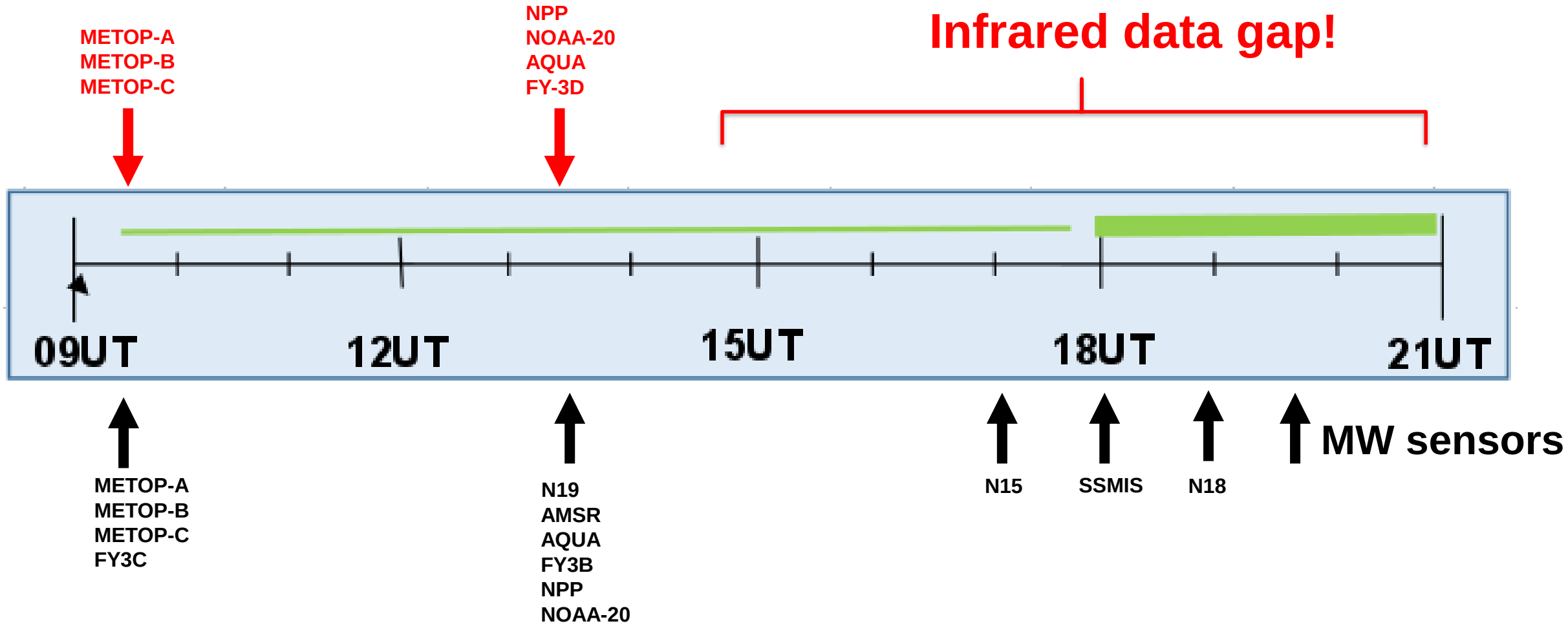
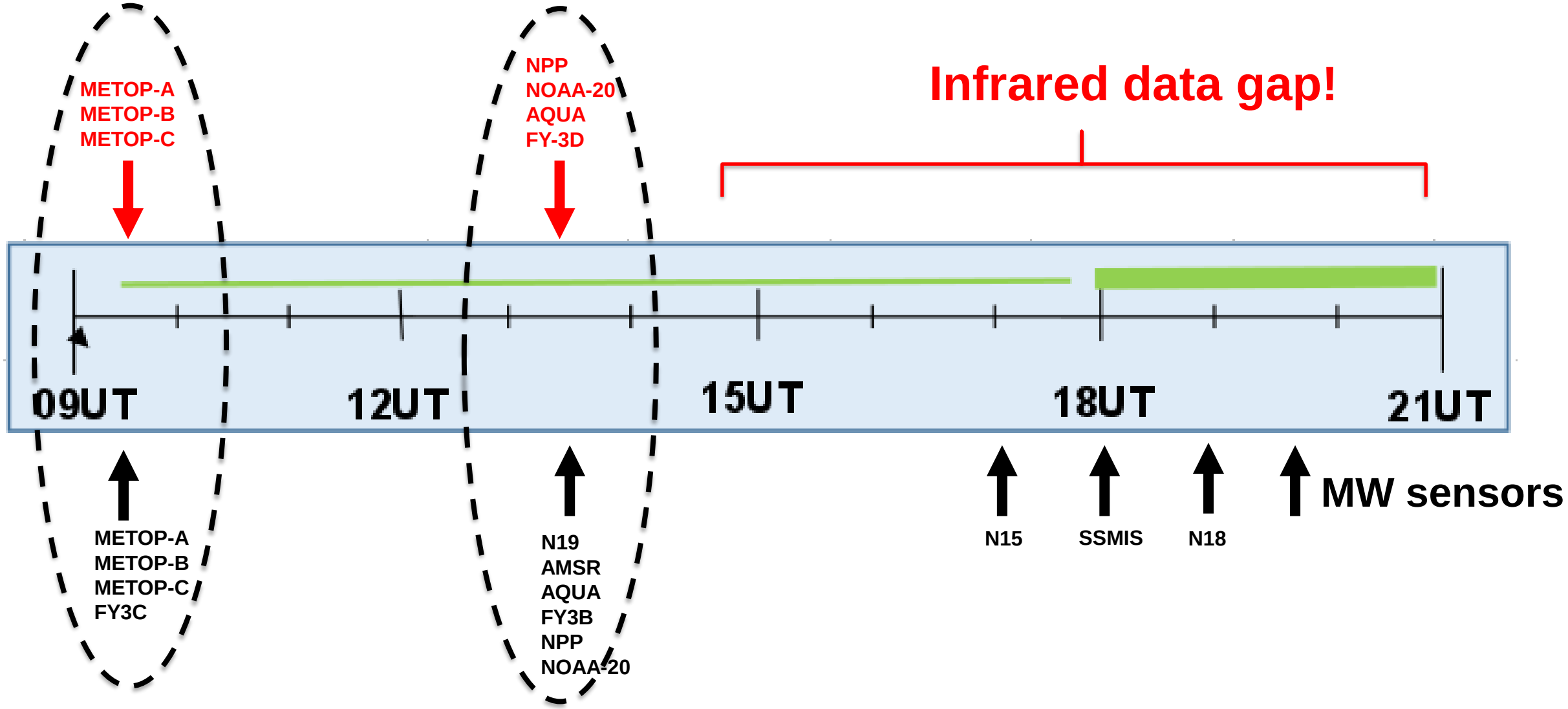
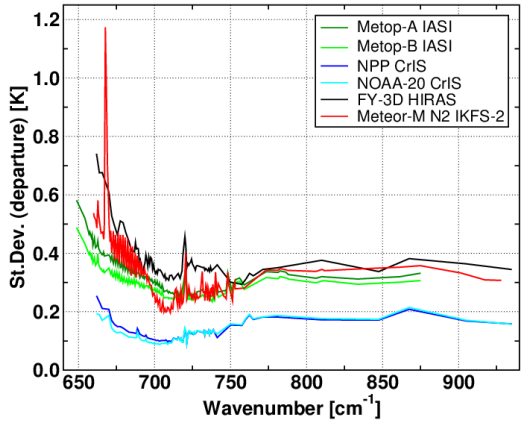
Satellite orbit deployment



Satellite orbit deployment - do we really need resilience at 09:30 / 13:30 ?



Satellite orbit deployment – some improvement soon…



IR sensors

METOP-A
METOP-B
METOP-C

NPP
NOAA-20
AQUA
FY-3D

METEOR

FY-3E

09UT
12UT
15UT
18UT
21UT

METOP-A
METOP-B
METOP-C
FY3C

N19
AMSR
AQUA
FY3B
NPP
NOAA-20

N15

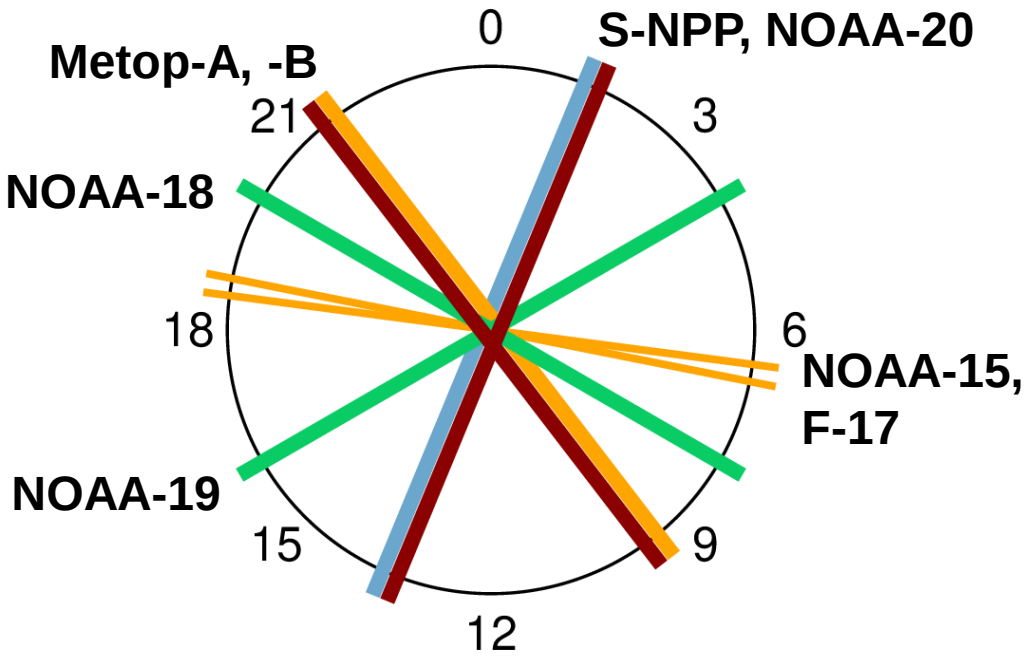
SSMIS

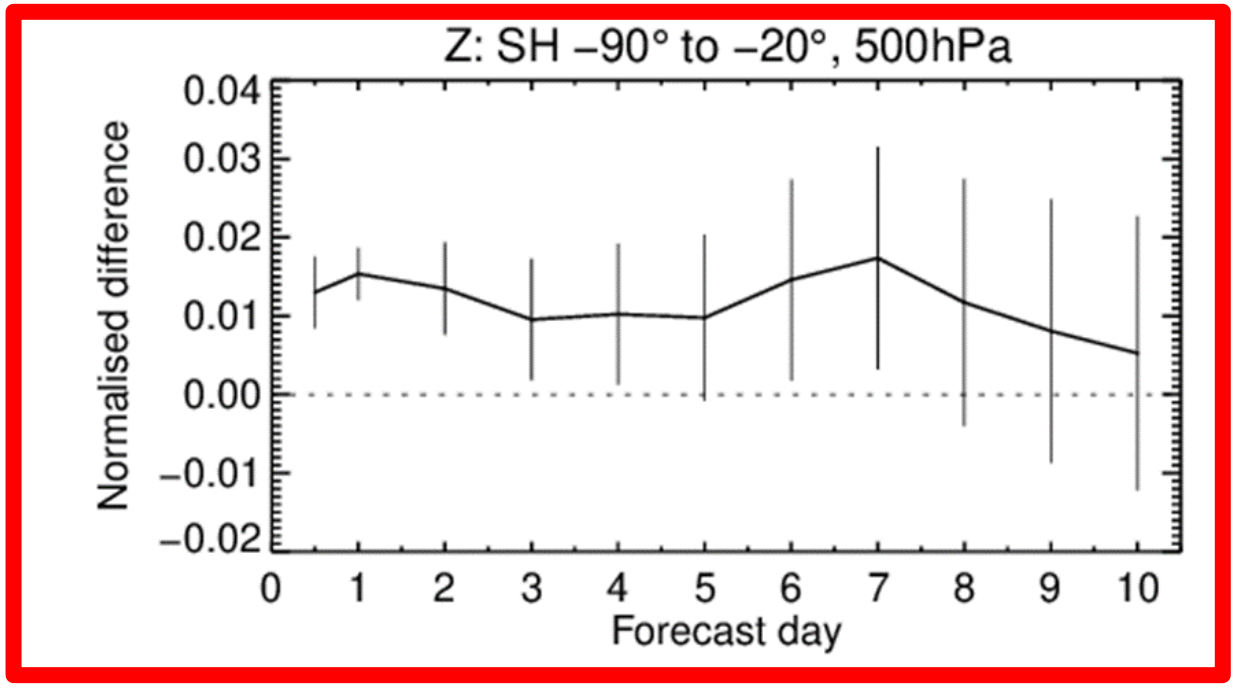
N18

MW sensors

Satellite orbit deployment – some improvement soon…but do we need more ?

Combined benefit of **old NOAA satellites** (that have drifted unplanned in to different orbital planes) is significant





Niels Bormann

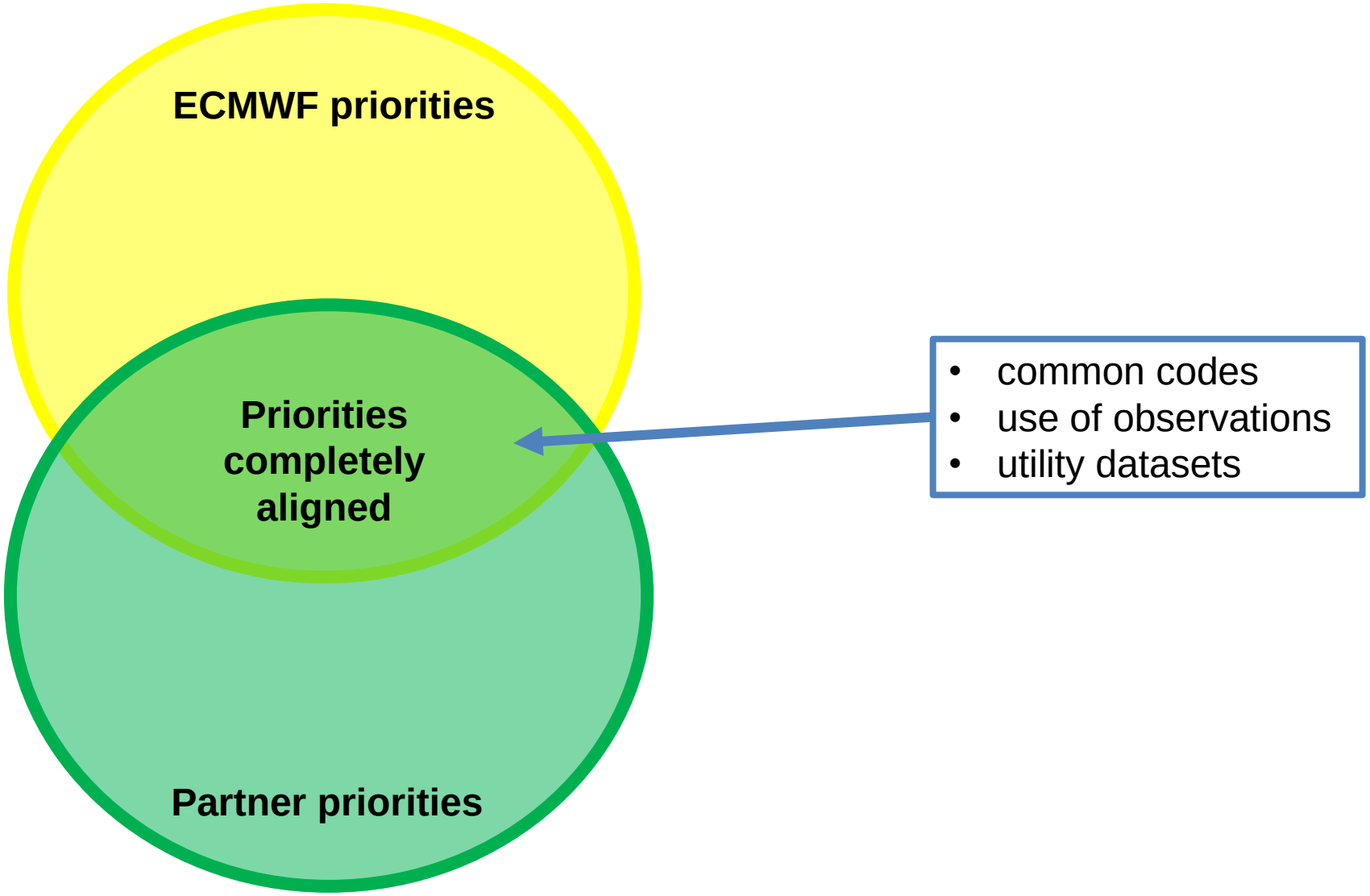
Greater coordination in data exploitation

1) Timely data collection and data sharing

2) Satellite orbit deployment

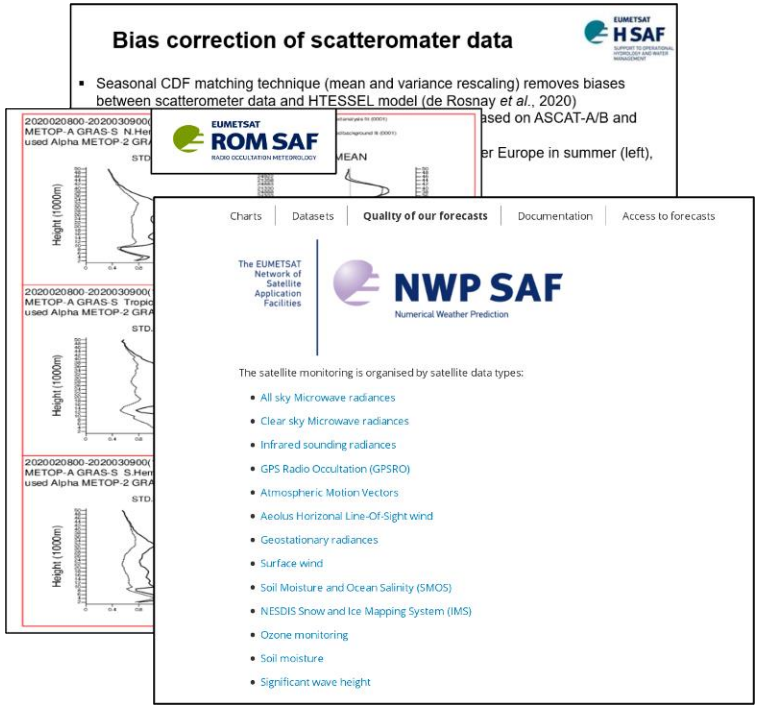
3) More coordinated R+D

Greater coordination in data exploitation

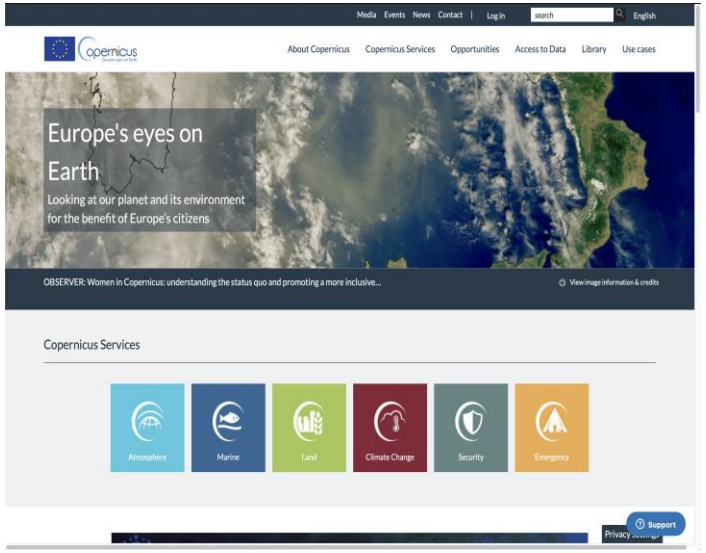


Greater coordination in data exploitation

EUMETSAT SAFs



EU Copernicus



EU Destination Earth

We cannot afford independent parallel under-exploitation of satellite observations

Greater coordination: explicit code sharing

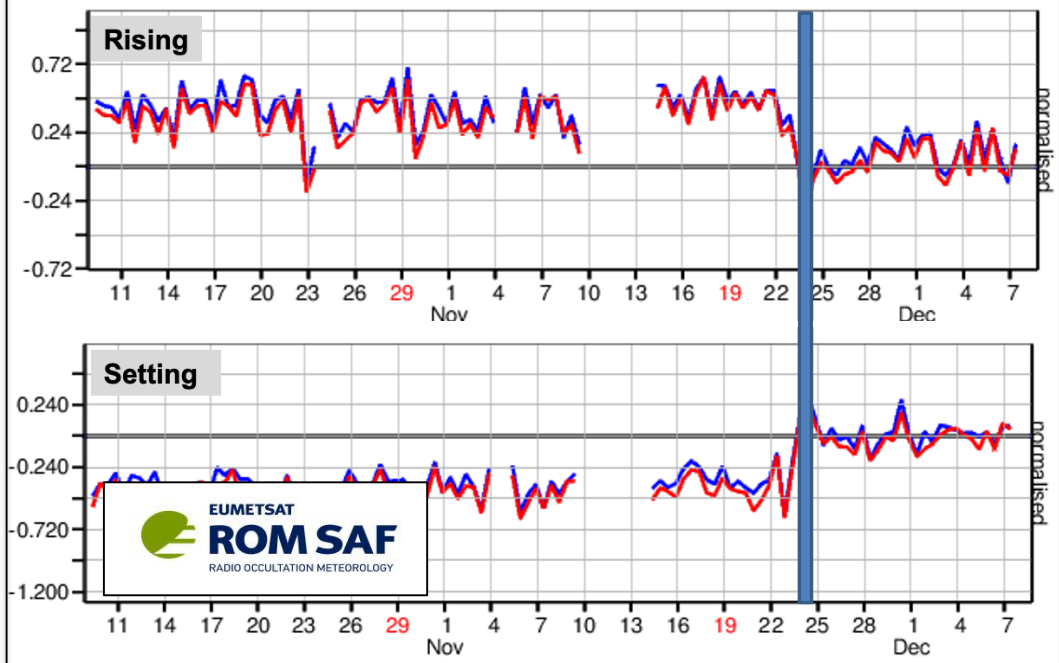
EUMETSAT NWP SAF NUMERICAL WEATHER PREDICTION	Operations Report 1.1.21 – 30.6.21	Doc ID : NWPSAF-MO-AD-100 Version : 1.0 Date : 20.07.2021

Table 2: User-registrations statistics for NWP SAF deliverables.

Deliverable	New registrations 1.1.21-30.6.21	Total registrations up to 30.6.21	Member States (total)	Others (total)
AAPP v8	27	363	126	237
AWDP v3*	15	272	74	198
CADS v3	30	71	18	53
CWDP v0.9*	11	124	32	92
IASI PCA-based compression package	5	247	70	177
MWIPP v1	11	89	27	62
NWPSAF 1D-Var v1	3	432	120	312
OPS-LRS v8	14	186	53	133
PenWP v2*	1	222	58	164
RADSIM v2	18	458	160	298
RADSIM v3	13	13	3	10
RTTOV v12	5	1501	524	977
RTTOV v13	190	318	109	209
SSMIS PP v1	0	209	49	160
Total	**343**	**4505**	**1423**	**3082**

- GNOS processing update (late November 2017)
- Result of specific collaboration between ROM-SAF and CMA
- Beneficial now (FY-3C) and for the future (FY…)

Data quality monitoring of GPS-RO data from GNOS



(Sean Healy, ROM SAF)

Summary

- We have excellent diagnostics to measure impact. But all are fallible – highly context specific – open to interpretation and misinterpretation – and possibly not always representing the wider **value** of an observation.

- Observations can add value via assimilation (in different ways!) and via system development – the latter is difficult to quantify but can be **very significant**!

- There are exciting scientific developments in progress aimed at enhancing the value we extract from observations - **coupled Earth system assimilation** may revolutionise observation exploitation!

- We can similarly enhance observation value through **non-scientific means** - with improved observation sharing and deployment and properly resourcing and coordinating our R+D

What did you do this morning ?