Data Assimilation considerations for future infrared sounder deployment

Tony McNally

Principal Scientist, ECMWF

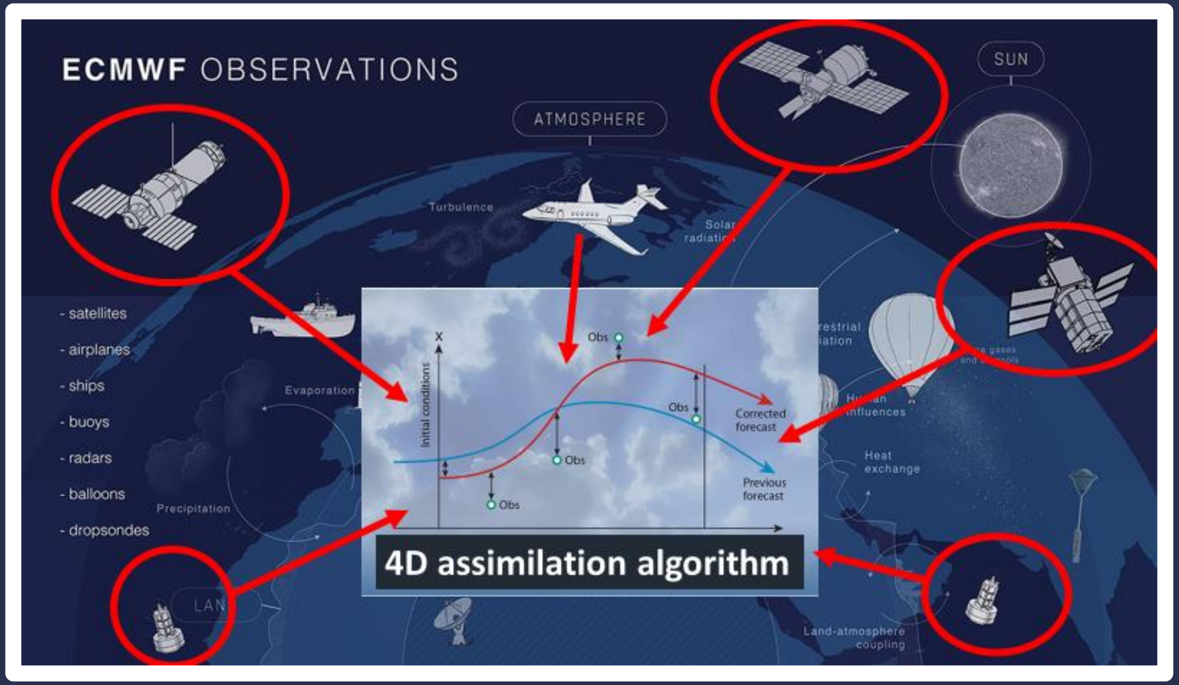
Outline

- Overview of modern NWP DA systems
- Current use and impact of IR systems at ECMWF
- What factors influence this impact ?
- Requirements for future infrared systems ?

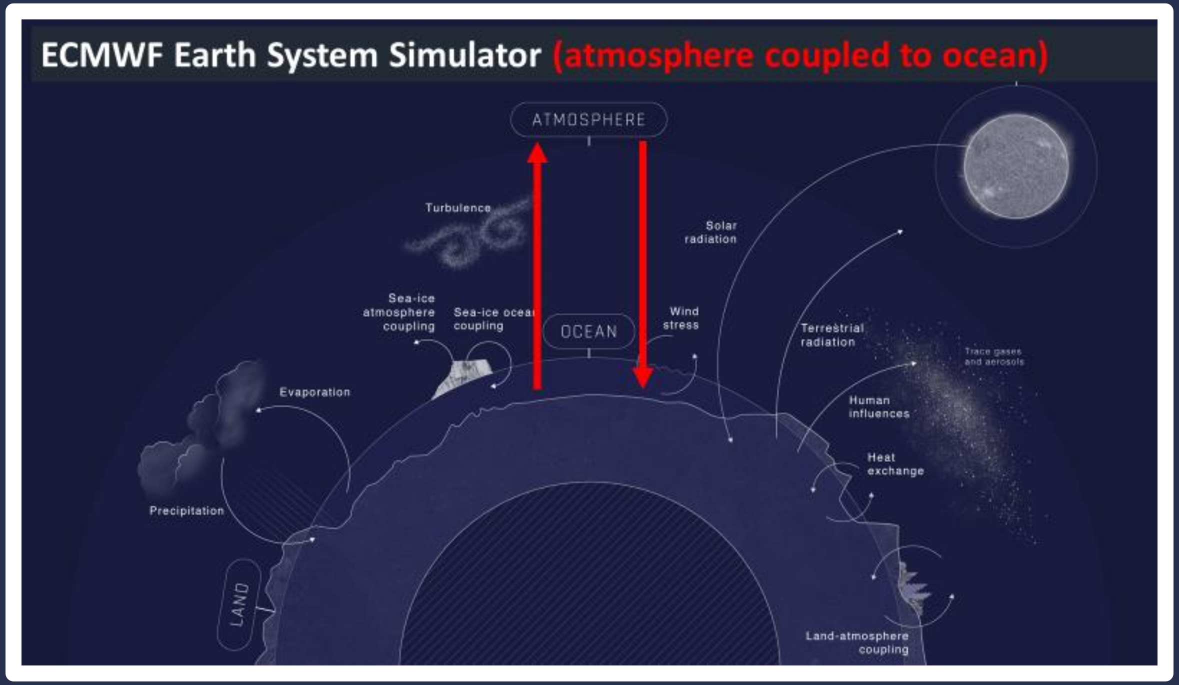
Outline

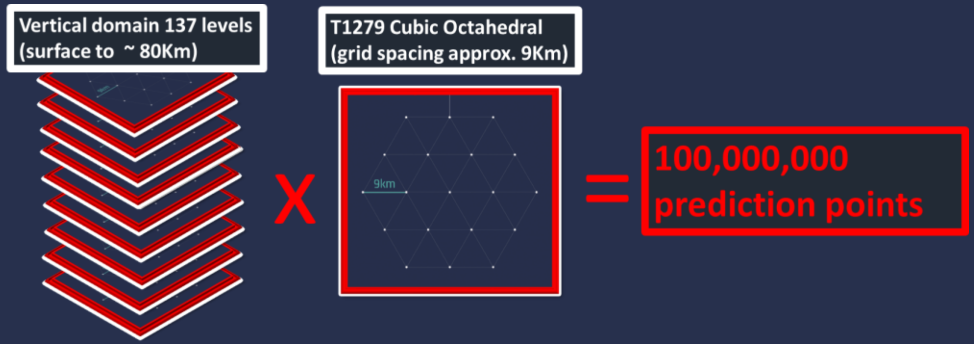
- Overview of modern NWP DA systems
- Current use and impact of IR systems at ECMWF
- What factors influence this impact ?
- Requirements for future infrared systems ?

The ECMWF Numerical Weather prediction System

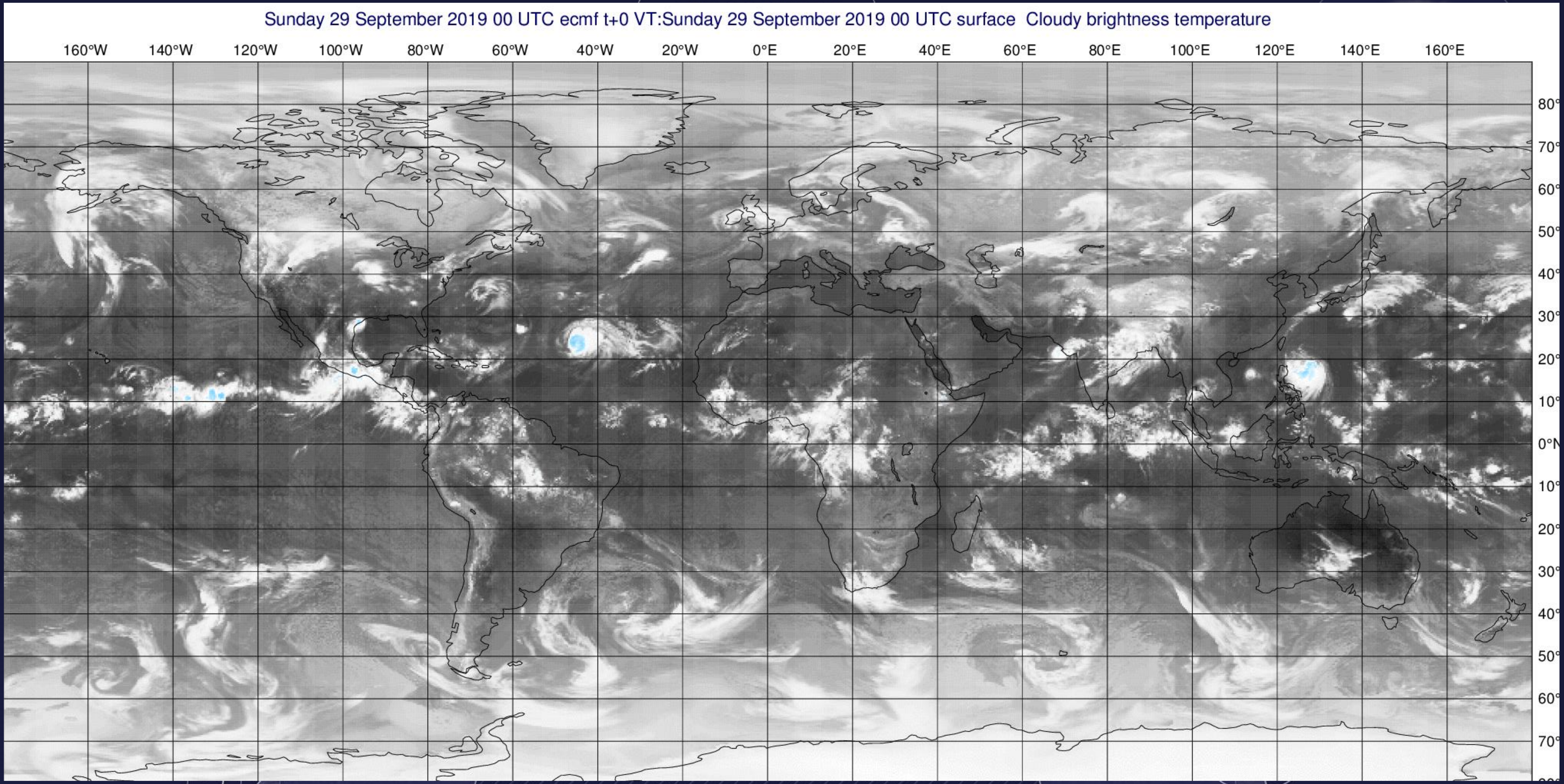


approx. 15,000,000 observations per hour





ECMWF Earth System Simulator (space view)



Land-atmosphere coupling

Modern Data Assimilation Systems

- Very well observed with a wide variety of satellite and in situ measurements
- Highly coupled to extract maximum value from observations
- Highly adaptive and learning
- Moving to extremely high spatial and temporal resolution

Modern Data Assimilation Systems

- Very well observed with a wide variety of satellite and in situ measurements
- Highly coupled to extract maximum value from observations
- Highly adaptive and learning
- Moving to extremely high spatial and temporal resolution

Current satellites use for operational global NWP

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 16 / 17 I/ABI	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 16 / 17 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 16 / 17 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)		

+ numerous marine satellites (altimeters) and composition satellites (COP)

...and some significant new arrivals!

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 (MODI GOES 16 / 17 I/ABI 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 16 / 17 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 (MWH HIMAWARI 8 (AHI) GCOM-W (AMSR
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)		

+ numerous marine satellites (altimeters) and composition satellites (COP)

Doppler wind LIDAR

Microwave constellations

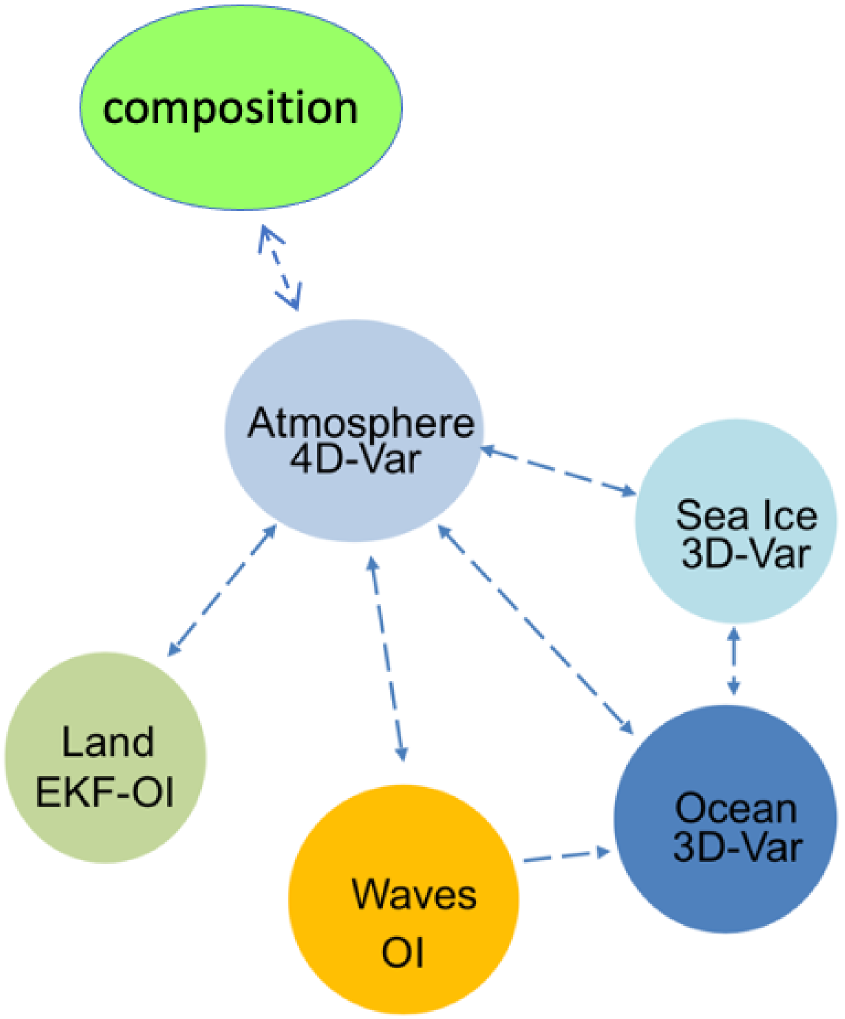
GEO Hyper-spectral IR

Commercial GPS-RO

Modern Data Assimilation Systems

- Very well observed with a wide variety of satellite and in situ measurements
- Highly coupled to extract maximum value from observations
- Highly adaptive and learning
- Moving to extremely high spatial and temporal resolution

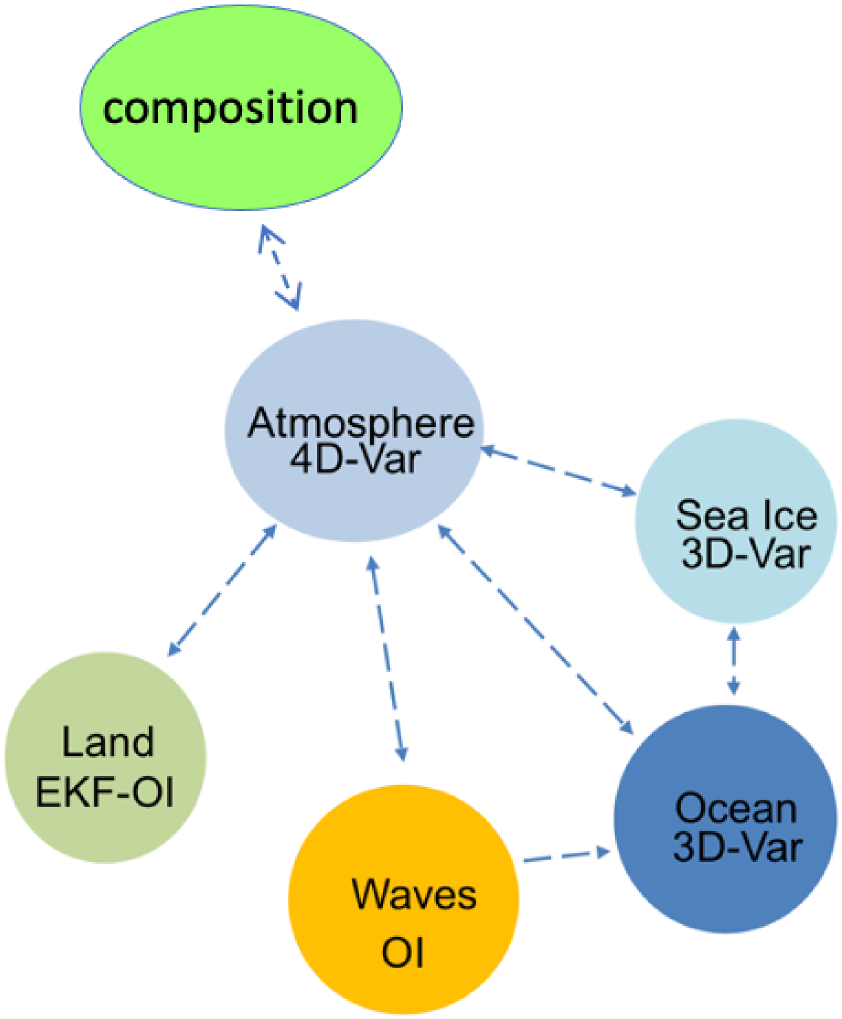
Coupled DA and forecasting systems



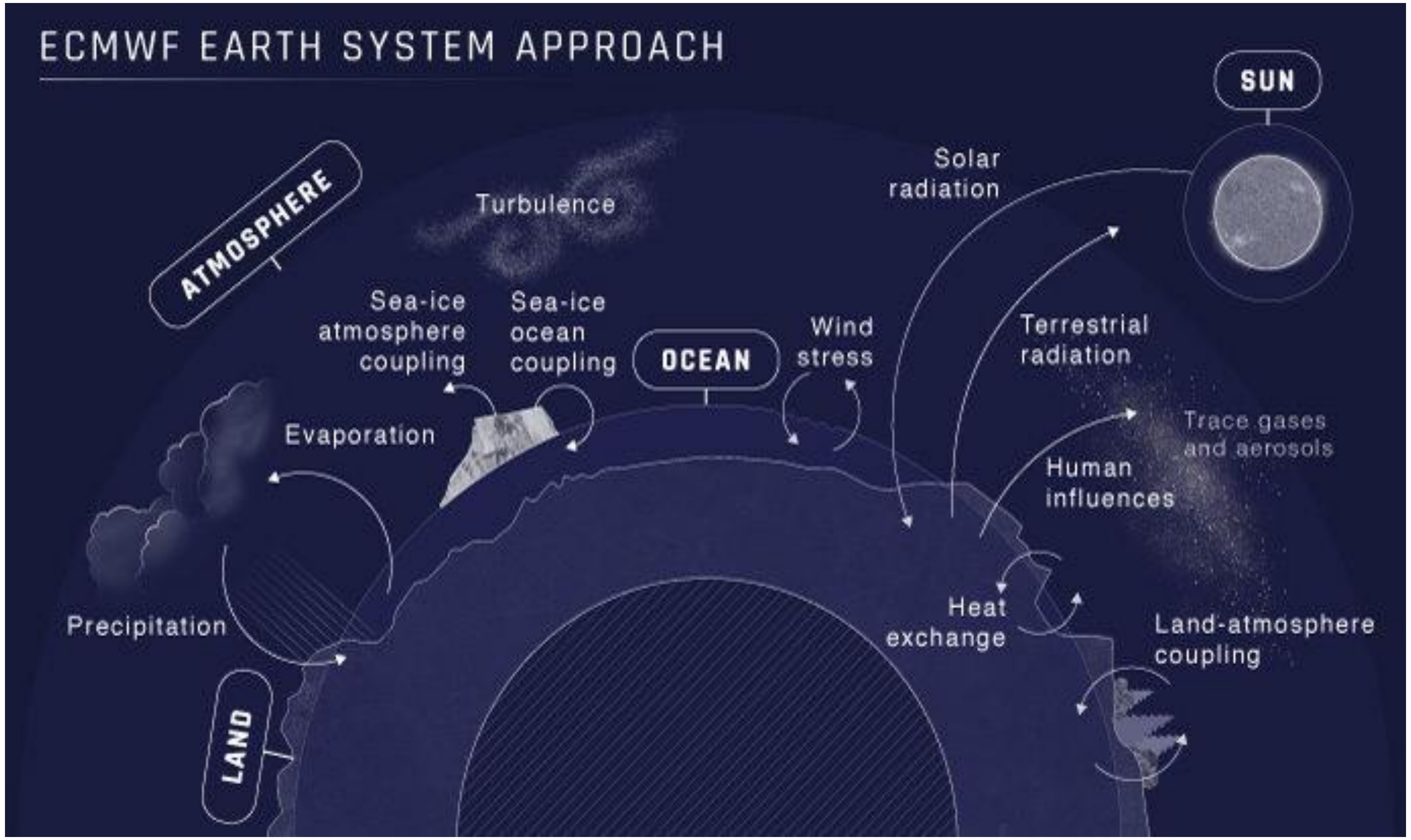
In the real world these components of the Earth system interact …

…so they must interact in our prediction systems!

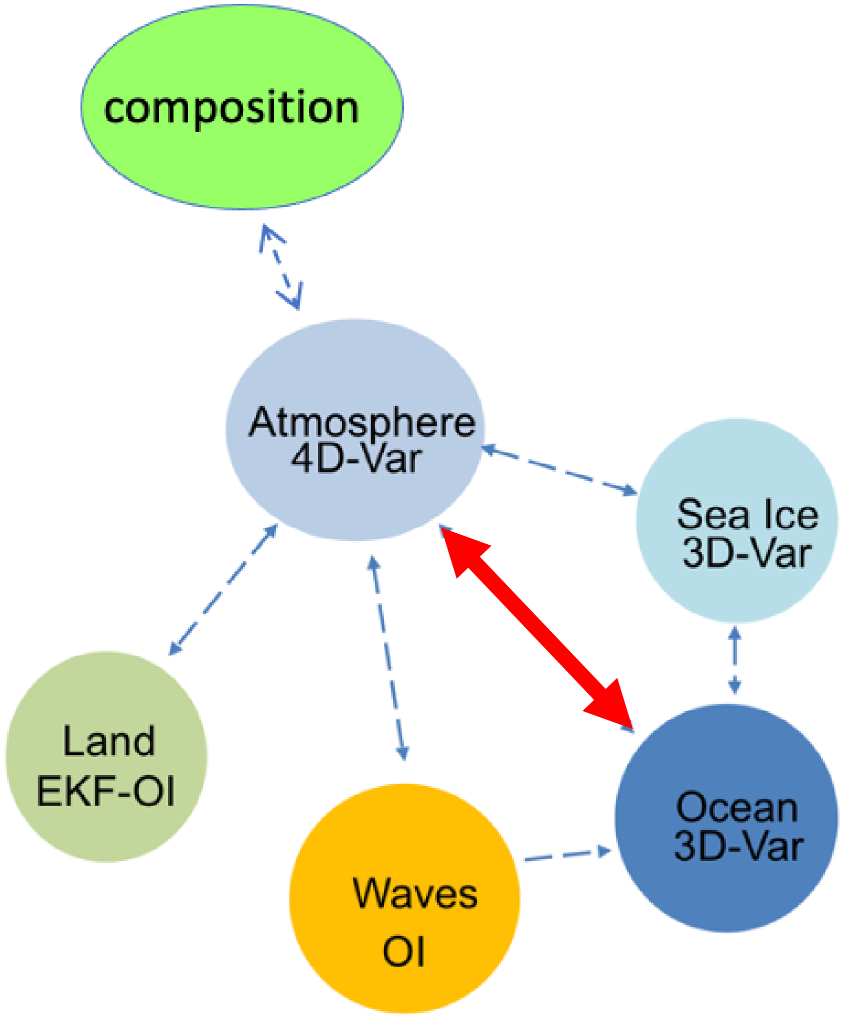
Coupled DA and forecasting systems

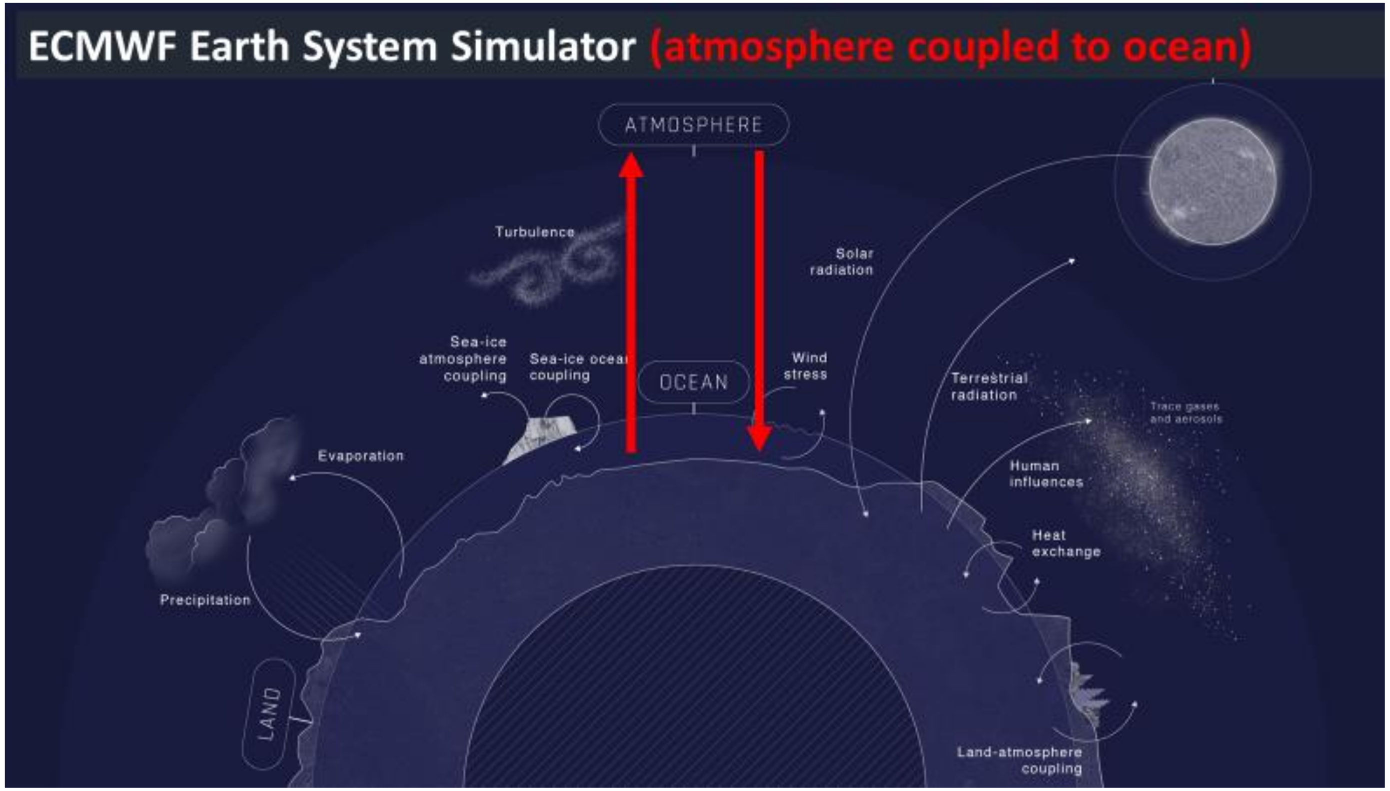


An observation's influence and value increases in coupled prediction systems…perhaps far beyond what was originally intended…



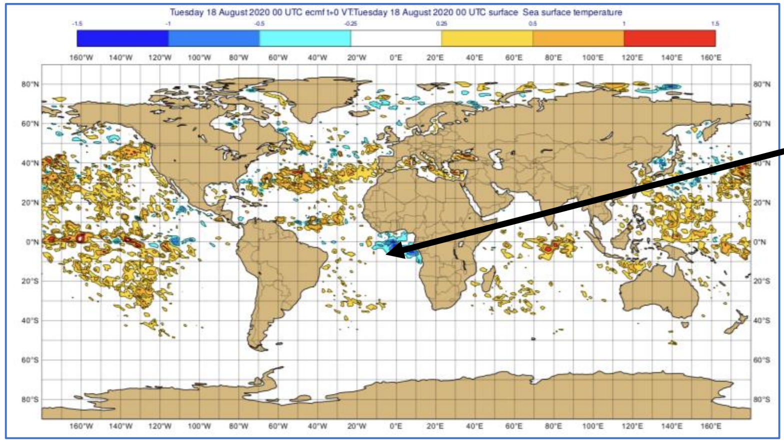
Coupled atmosphere and ocean…



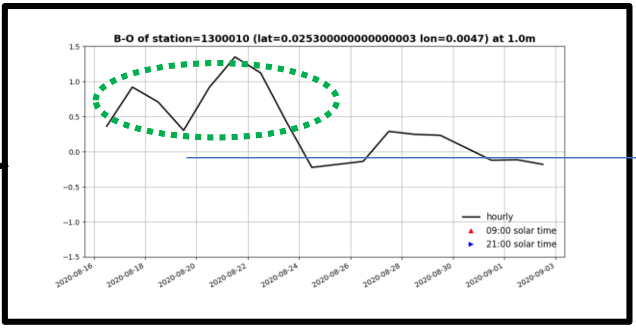


IASI, CrIS and AIRS influence the ocean subsurface

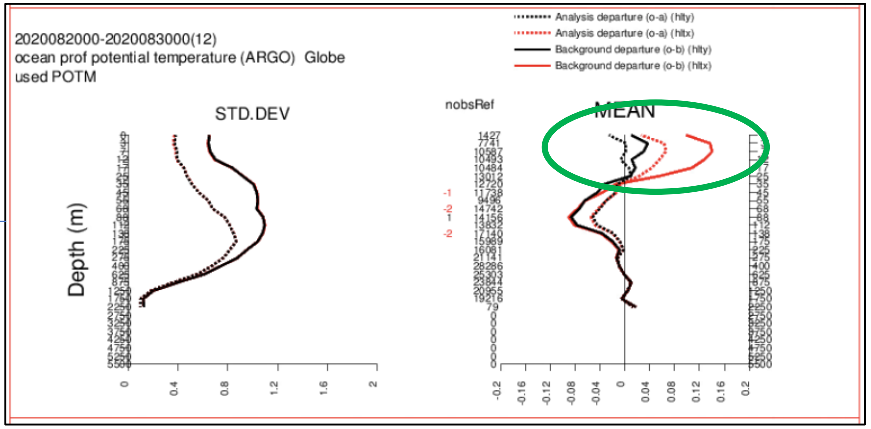
NEMOVAR SST changes forced by 3x IASI, 2x CrIS and AIRS radiances after 2 weeks of assimilation



Moored buoys

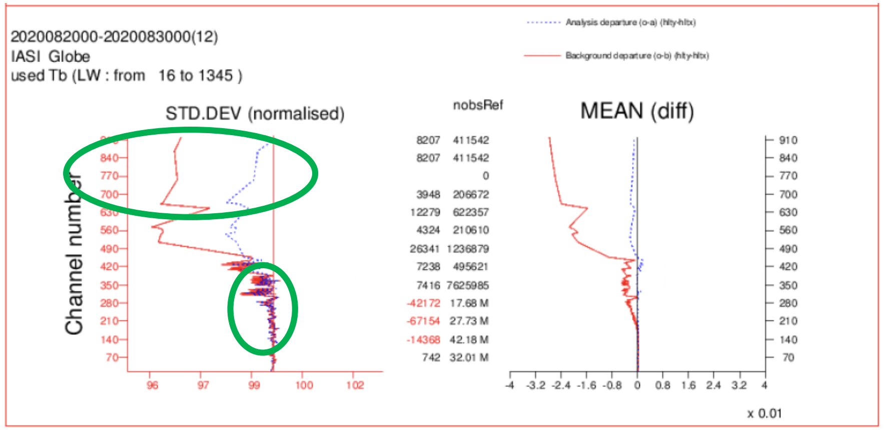


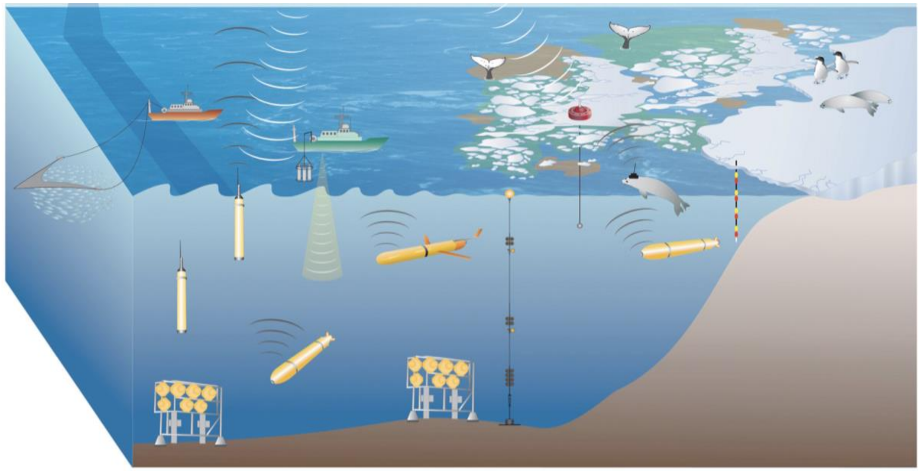
ARGO floats



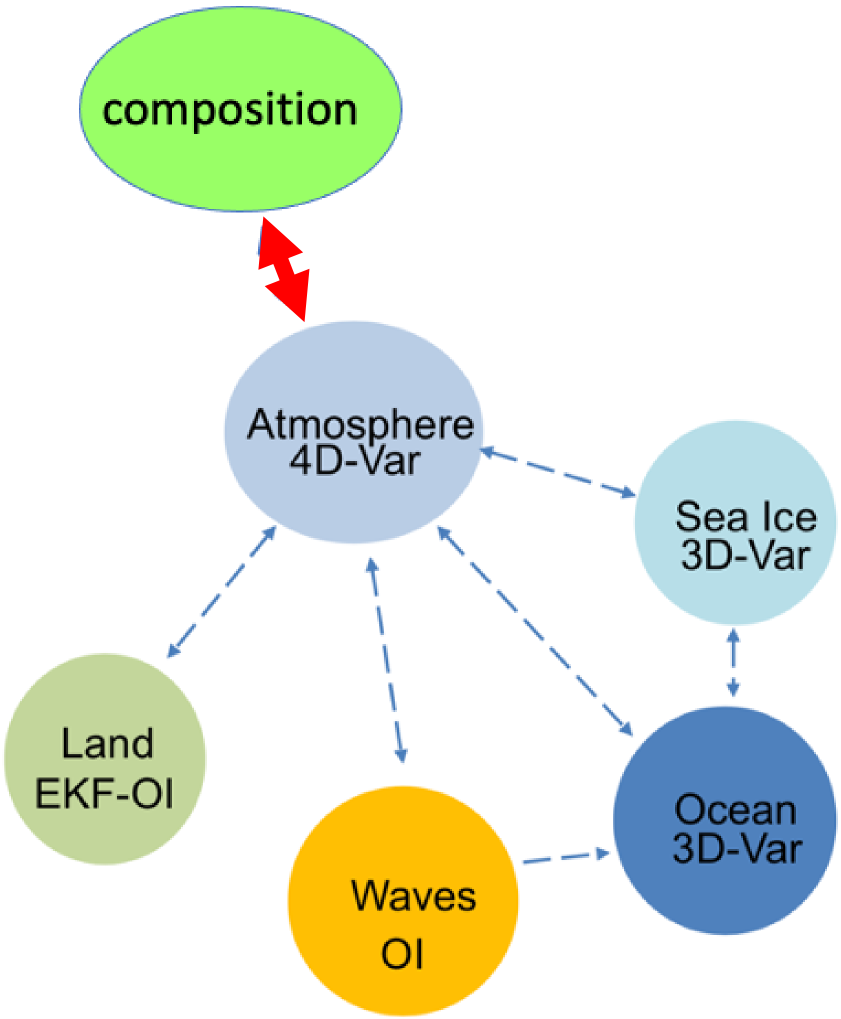
Assimilating infrared radiances in coupled 4D-Var / NEMOVAR produces a better ocean surface **and** sub-surface (verified by in situ ocean observations) which simultaneously feeds back to **improved atmospheric weather forecasts**

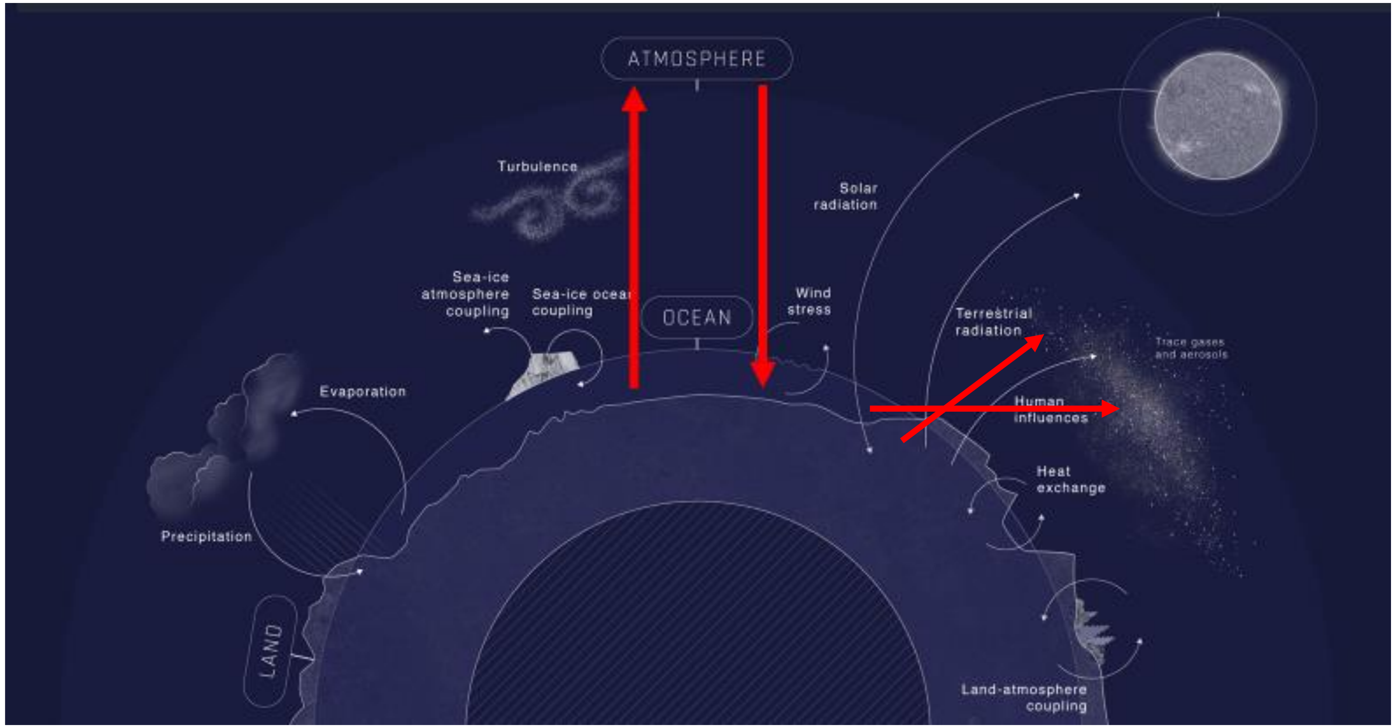
Changes have ***memory*** in the ocean and feed back to improve radiance use in the atmosphere





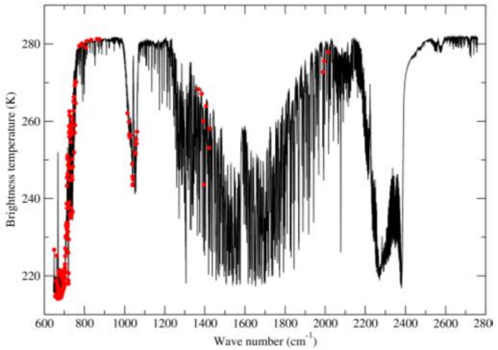
Coupled atmospheric composition…

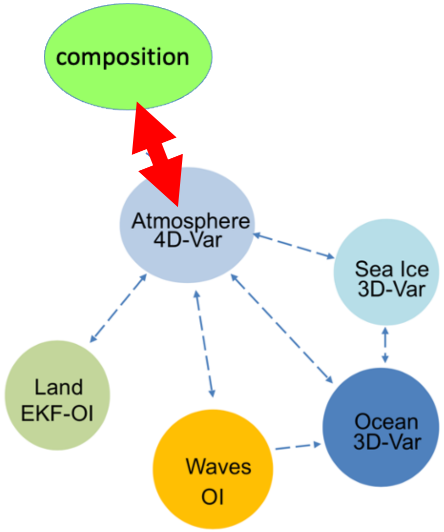




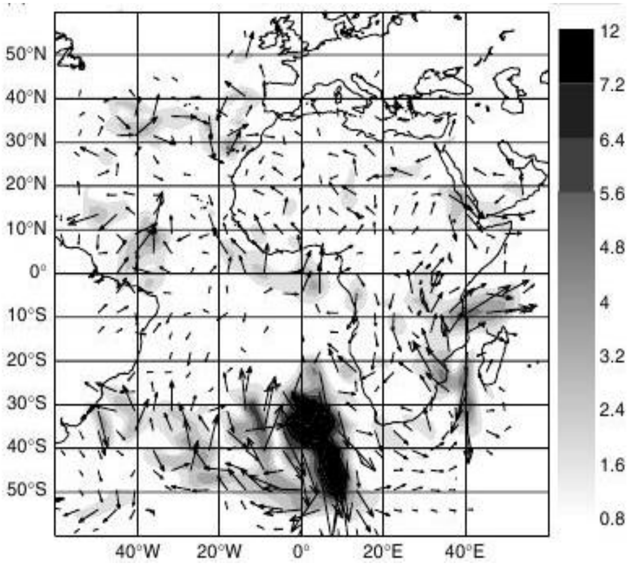
Infrared radiances produce wind information

IR radiances assimilated in 4D-Var

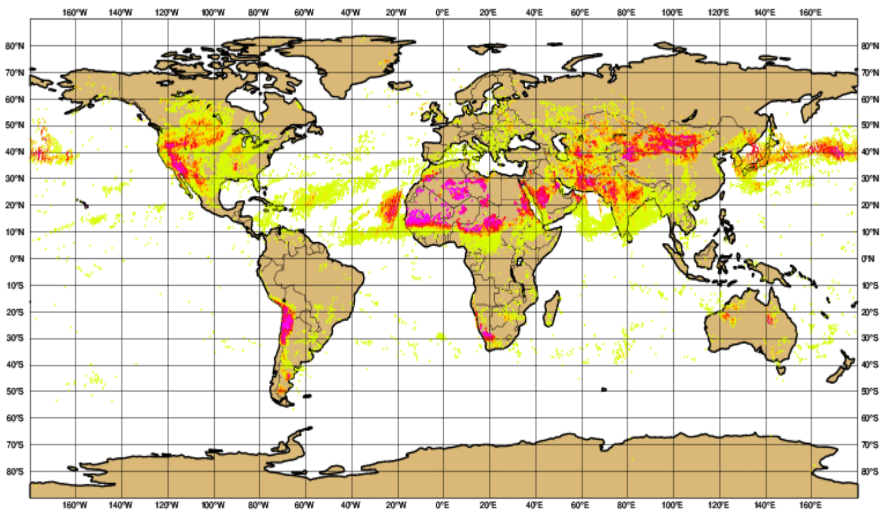




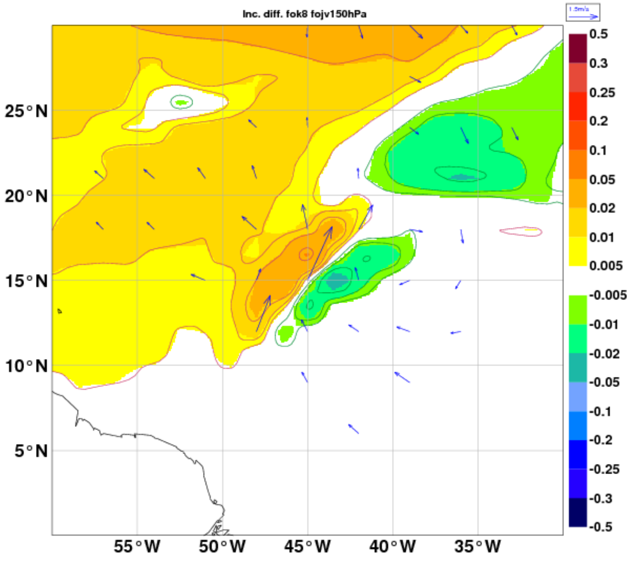
Wind tracing from water vapour



Wind tracing from dust aerosol



Wind tracing from ozone



Modern Data Assimilation Systems

- Very well observed with a wide variety of satellite and in situ measurements
- Highly coupled to extract maximum value from observations
- Highly adaptive and learning
- Moving to extremely high spatial and temporal resolution

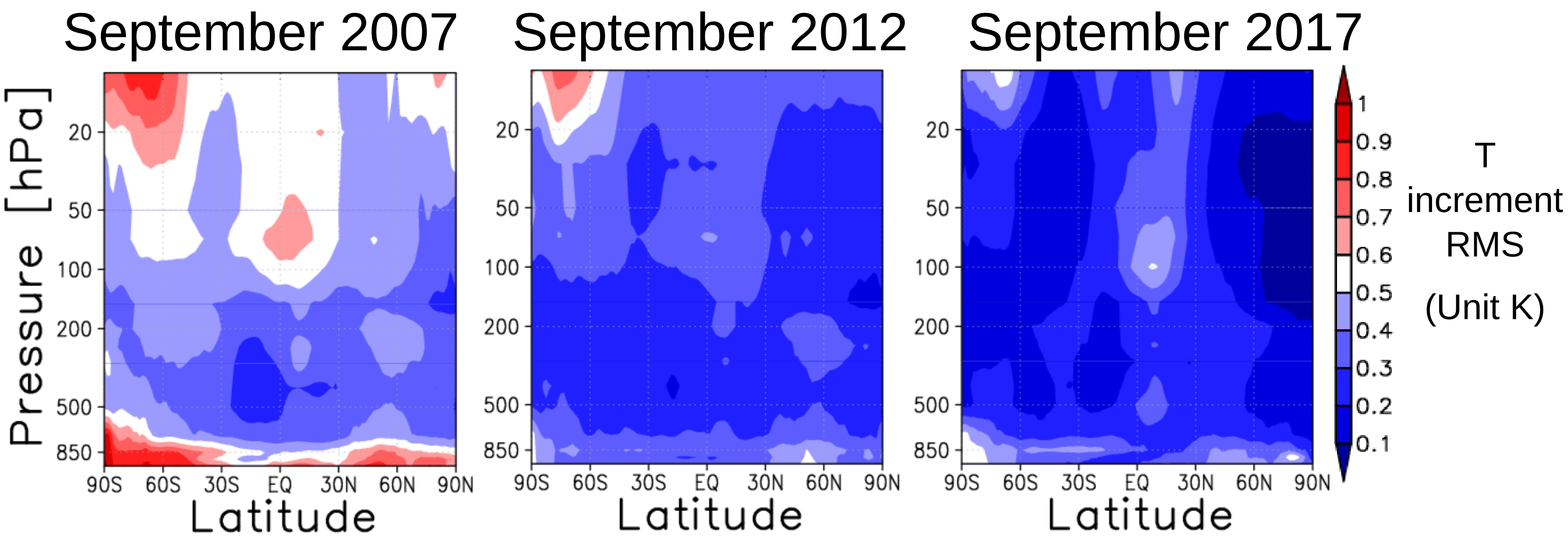
Modern DA systems are highly adaptive and learning

When observation is introduced to a modern DA system a number of things can result:

- 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 random errors** via an adaptive cycling EDA
- Adjust **observation random errors** via adaptive estimation (soon)

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.

We're looking for weaker signals than ever before



Analysis increments keep getting smaller

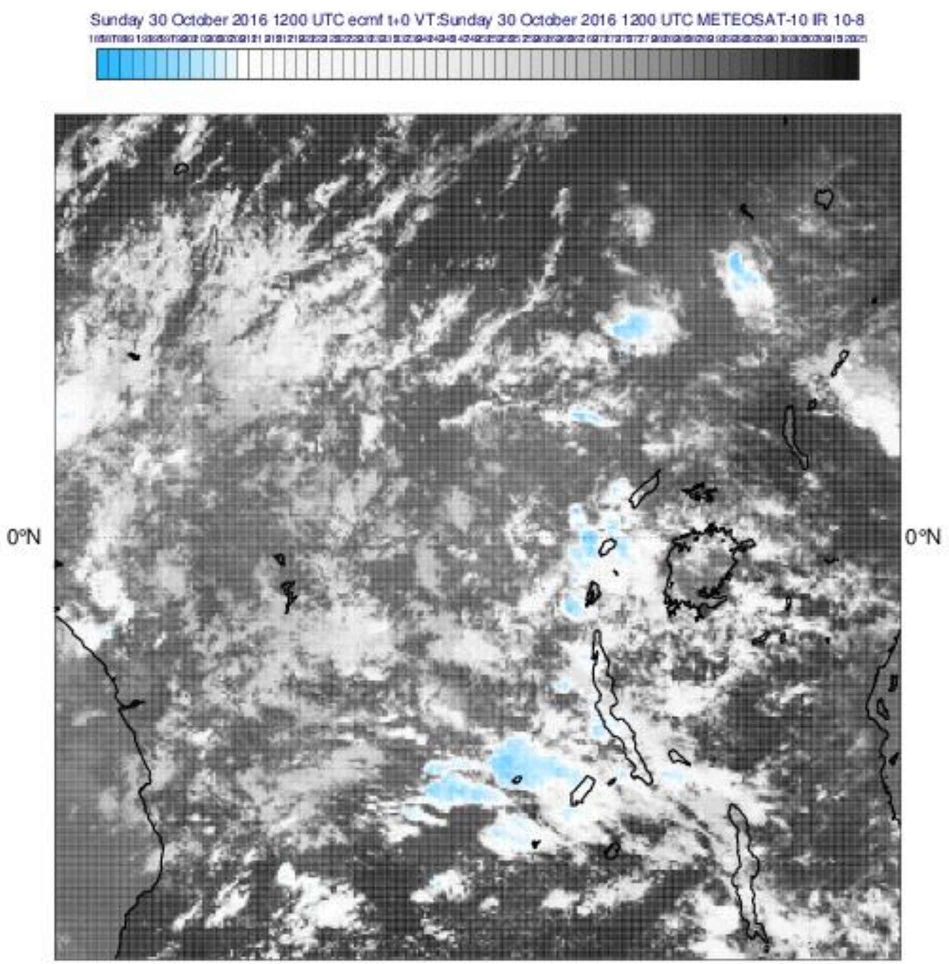
→ We can't afford missing as large cloud effects as we used to

Modern Data Assimilation Systems

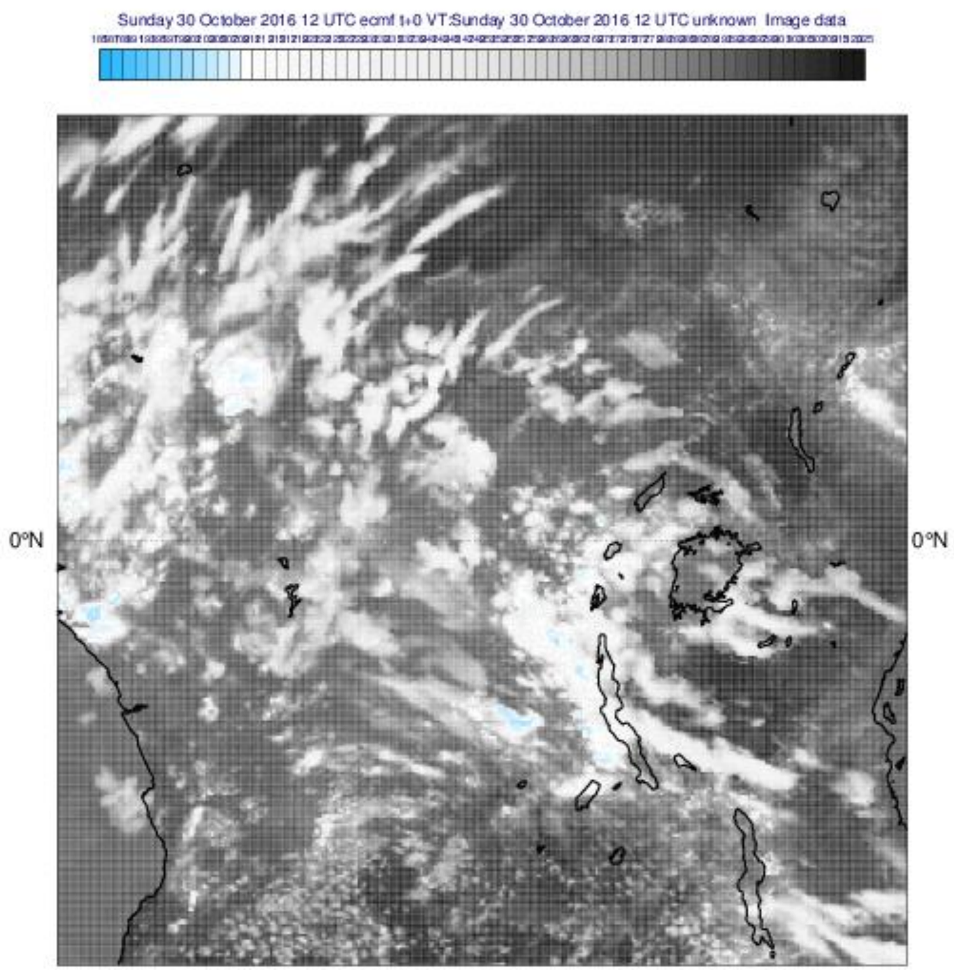
- Very well observed with a wide variety of satellite and in situ measurements
- Highly coupled to extract maximum value from observations
- Highly adaptive and learning
- Moving to extremely high spatial and temporal resolution

Global NWP systems (FC/DA) are moving to Km scale

MET-11 SEVIRI real Observations



Simulated from TCO7999 model (~1.25Km)

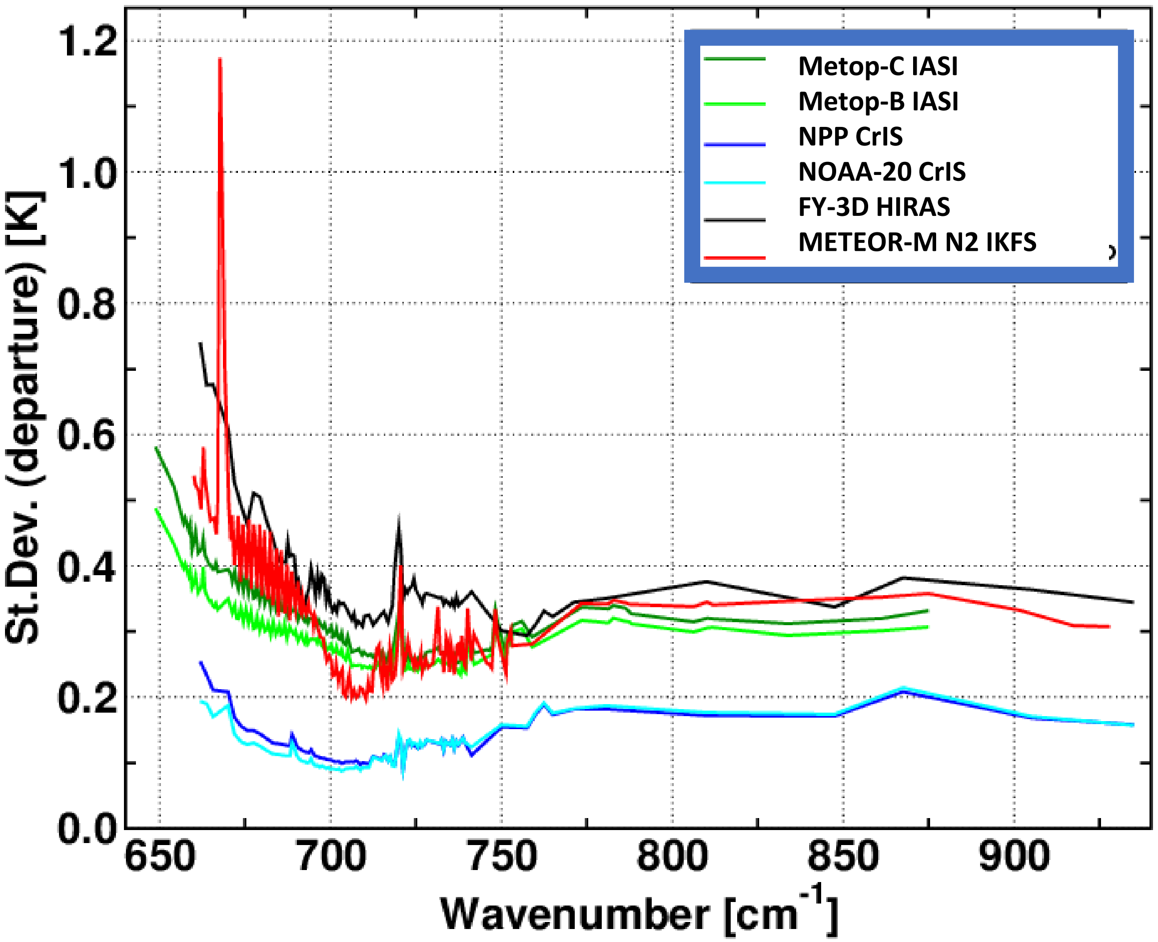


Outline

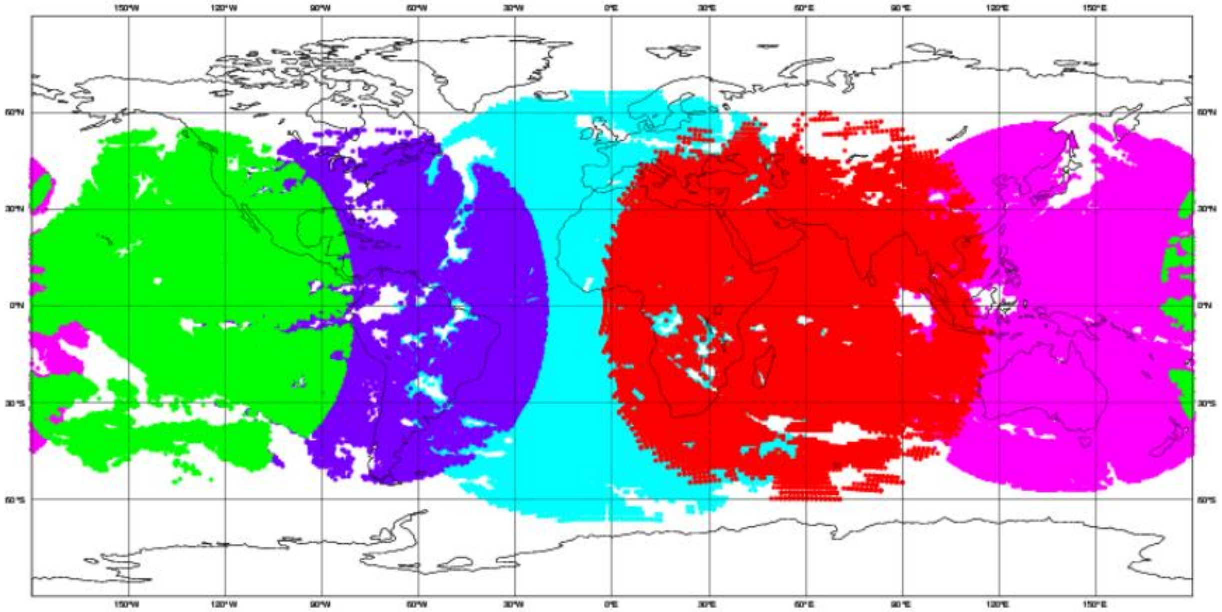
- Overview of modern NWP DA systems
- Current use and impact of IR systems at ECMWF
- What factors influence this impact ?
- Requirements for future infrared systems ?

Infrared data currently used (or pre-operational)

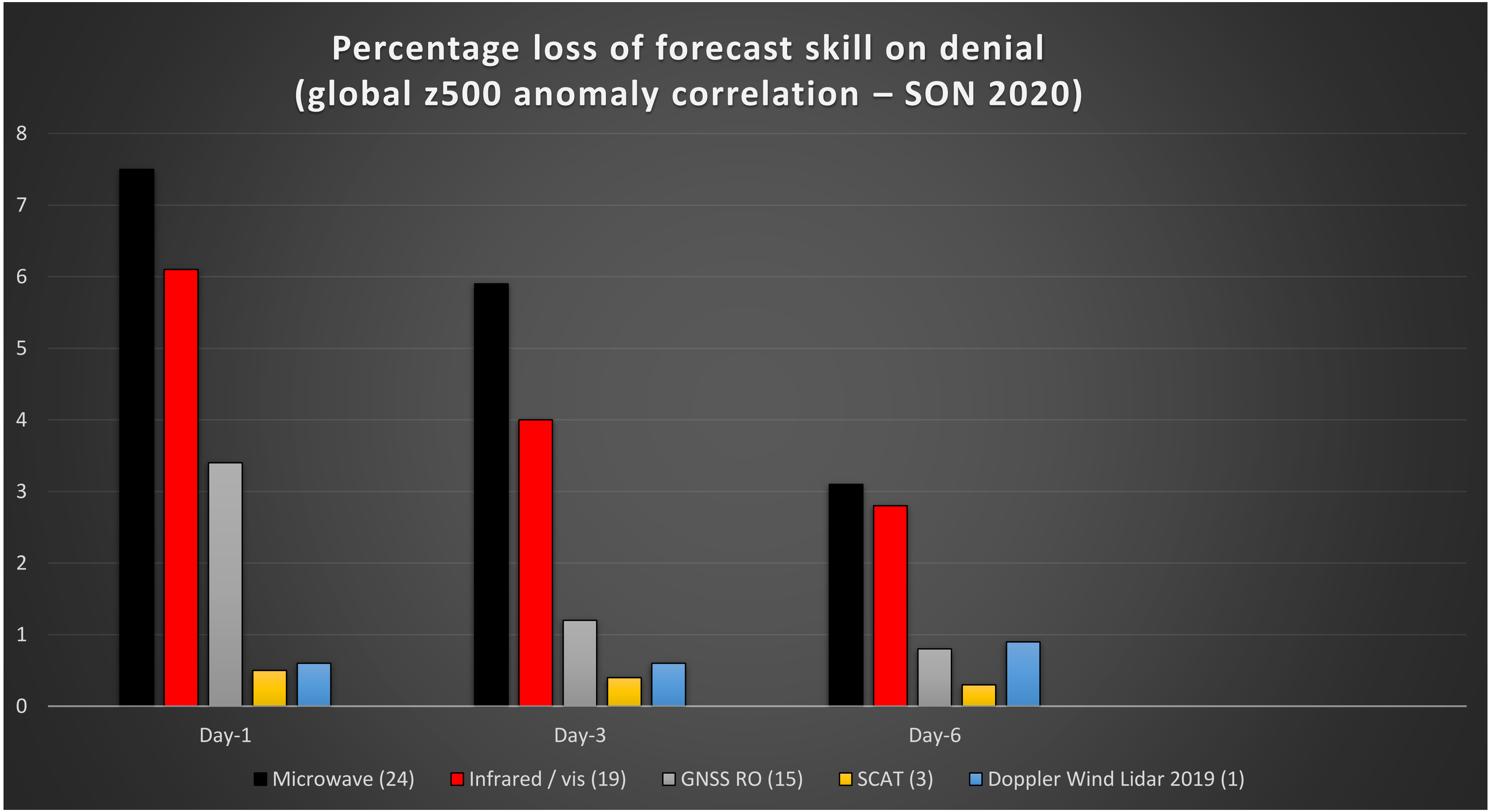
LEO Hyper-spectral IR



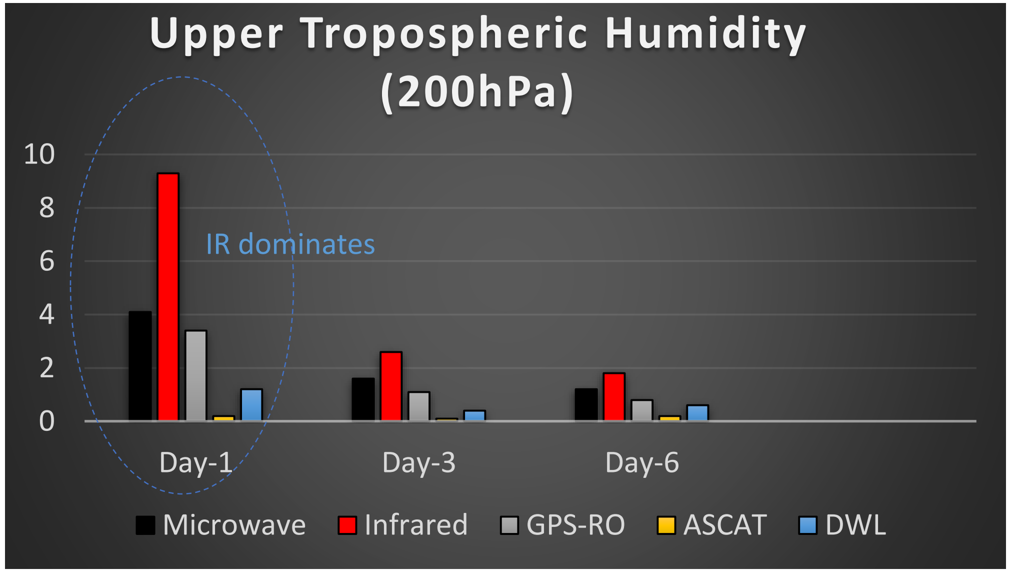
GEO low-spectral resolution IR

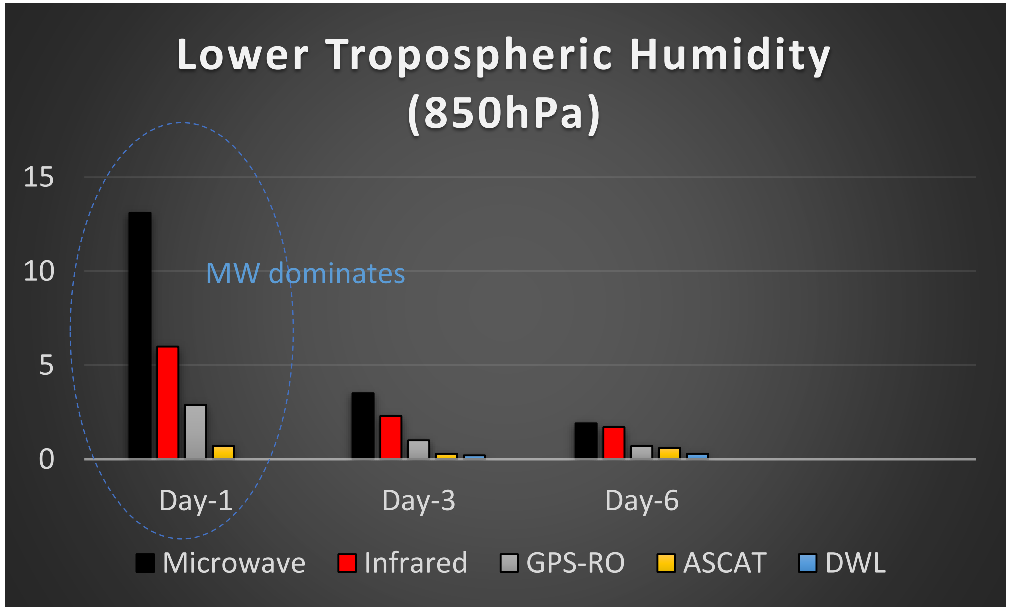


Impact on Z500 of removing all infrared data

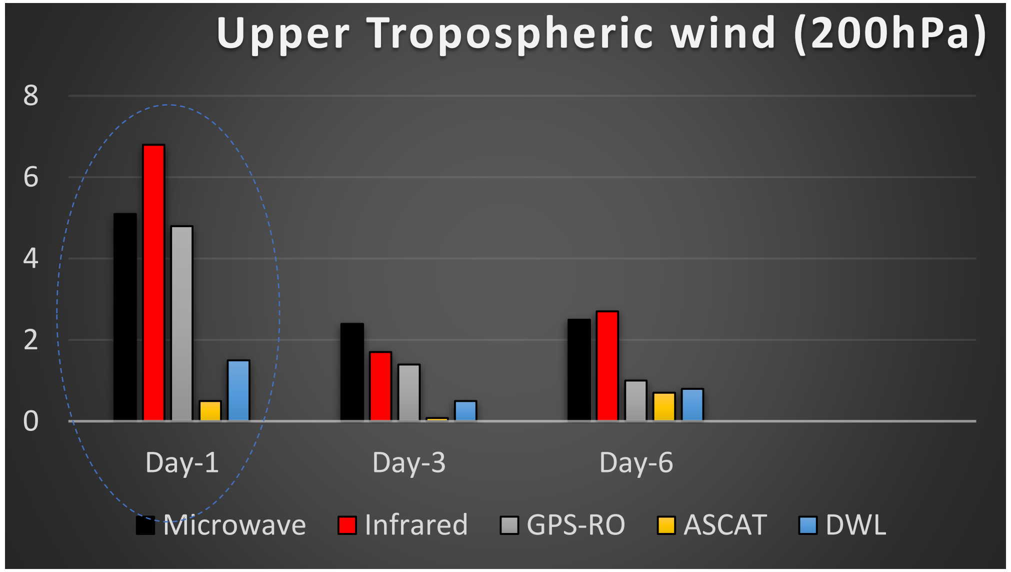


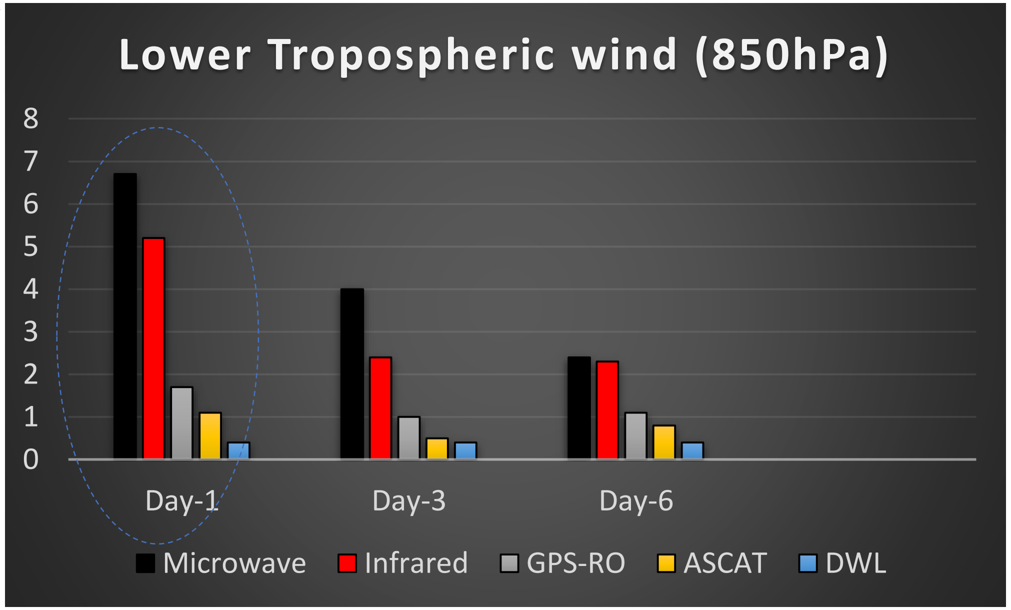
Impact on wind of removing all infrared data



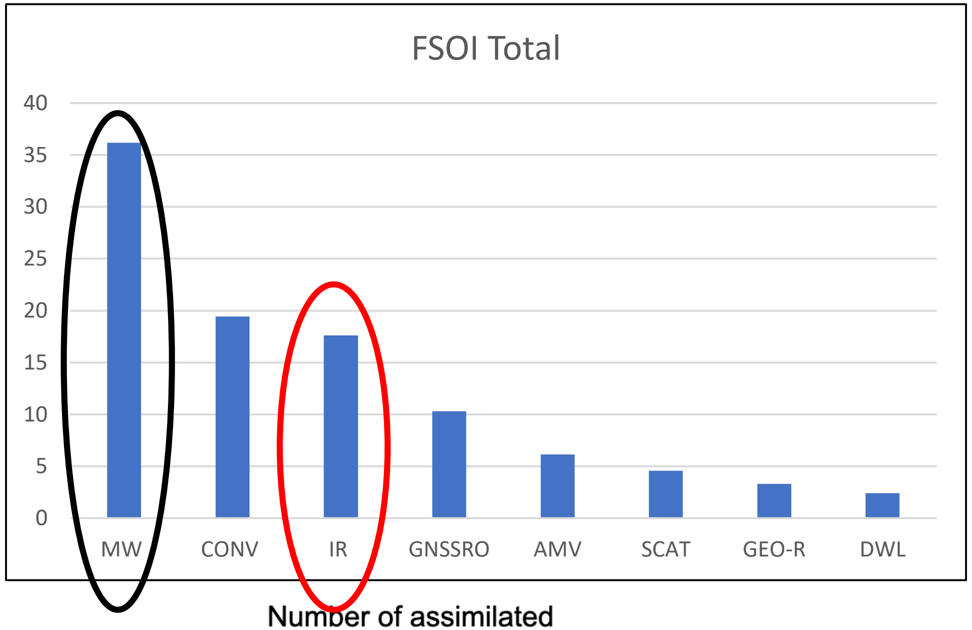


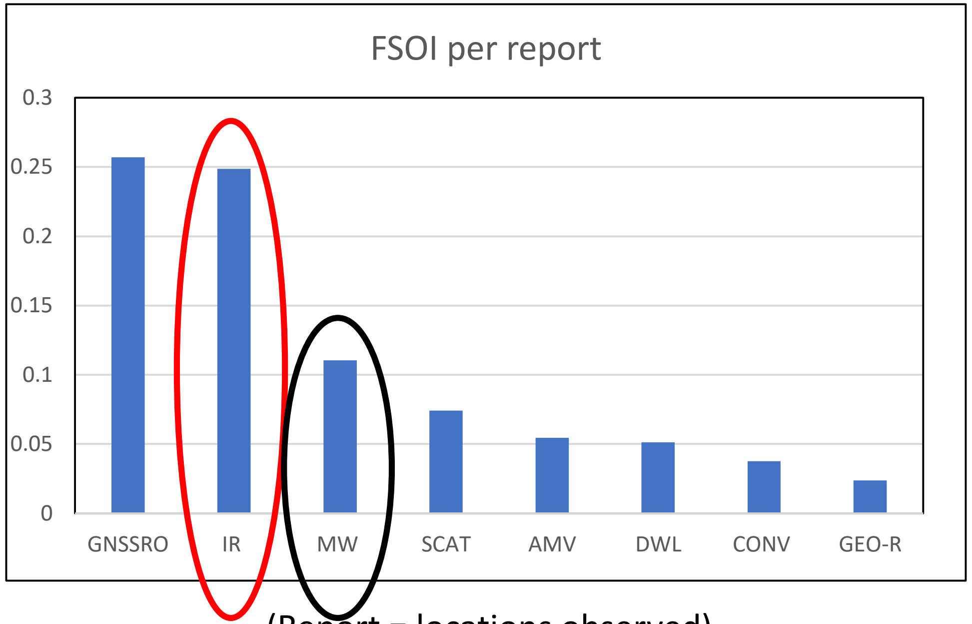
humidity skill translates to wind skill





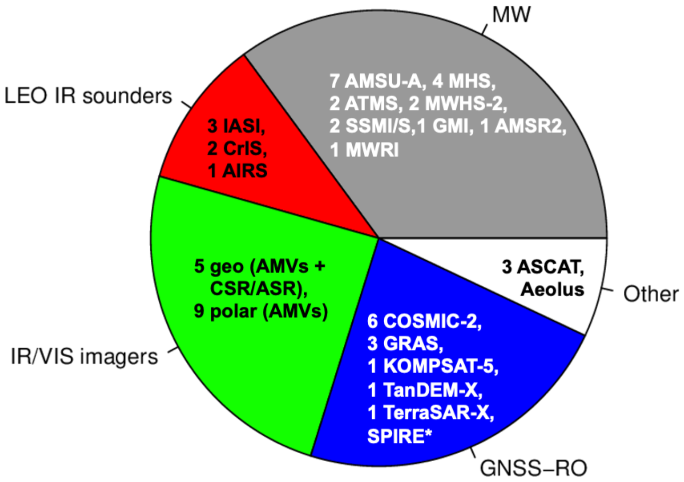
Total impact vs impact per radiance spectrum





(Report = locations observed)

Number of assimilated satellite instruments



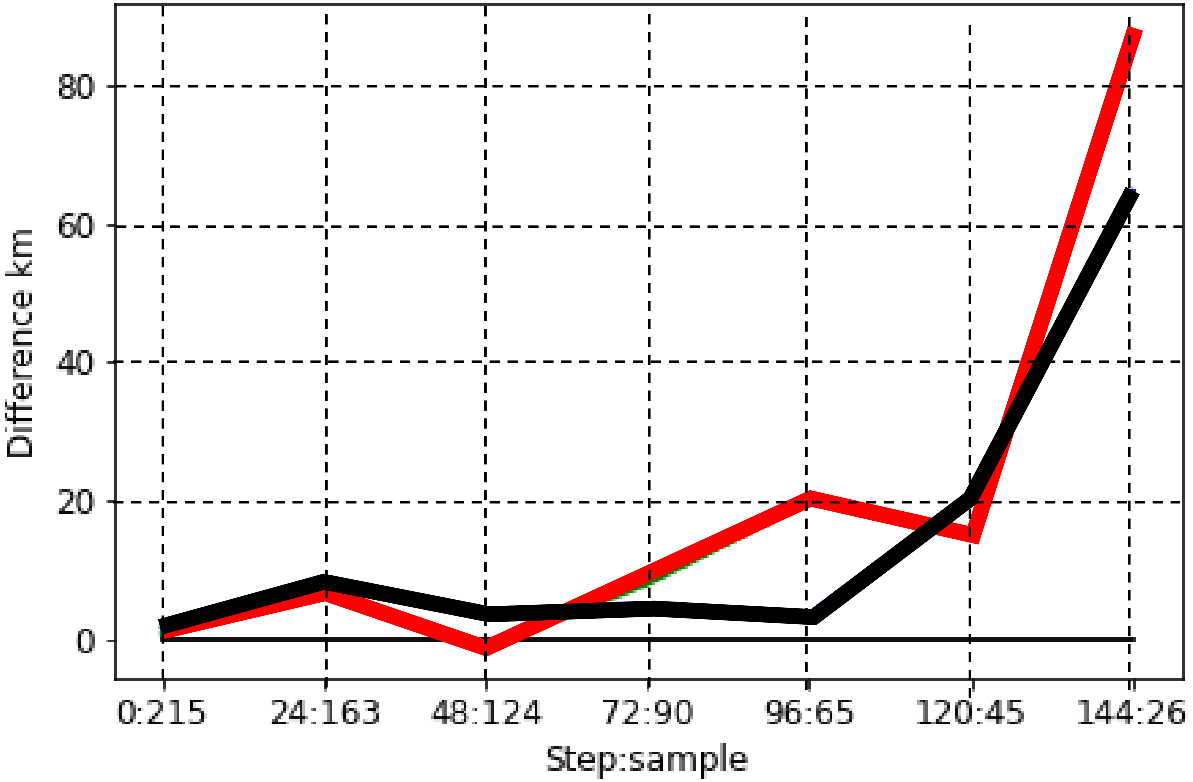
Due to the number of sensors microwave data have the largest total impact, but one infrared spectrum is significantly more influential than a microwave sounding.

Impact of MW and IR 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 <u>not</u> statistically significant)

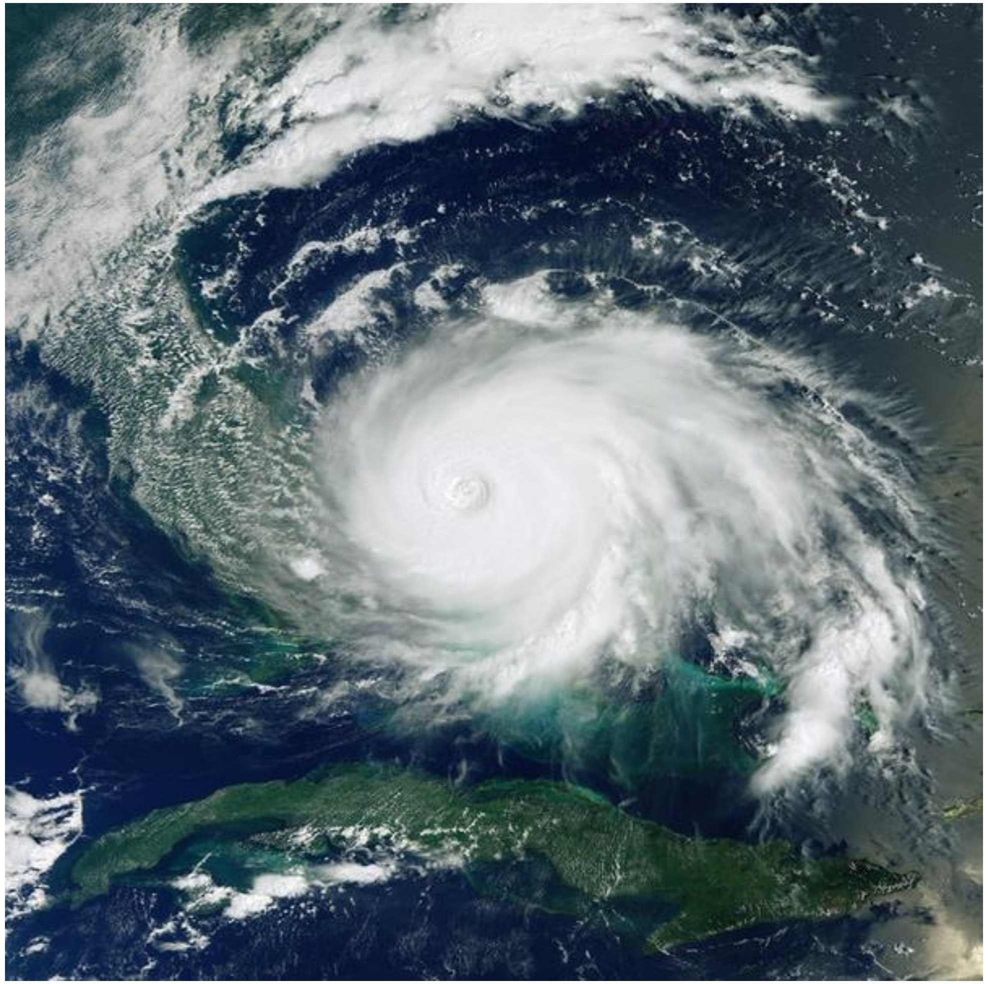
RMS loss of accuracy in forecast cyclone position (km) for the 2020 Atlantic Cyclone season from IR/MW denial



*Individual case studies consistently show a dramatic impact from denying **<u>all</u>** satellites!*

Hurricane Dorian

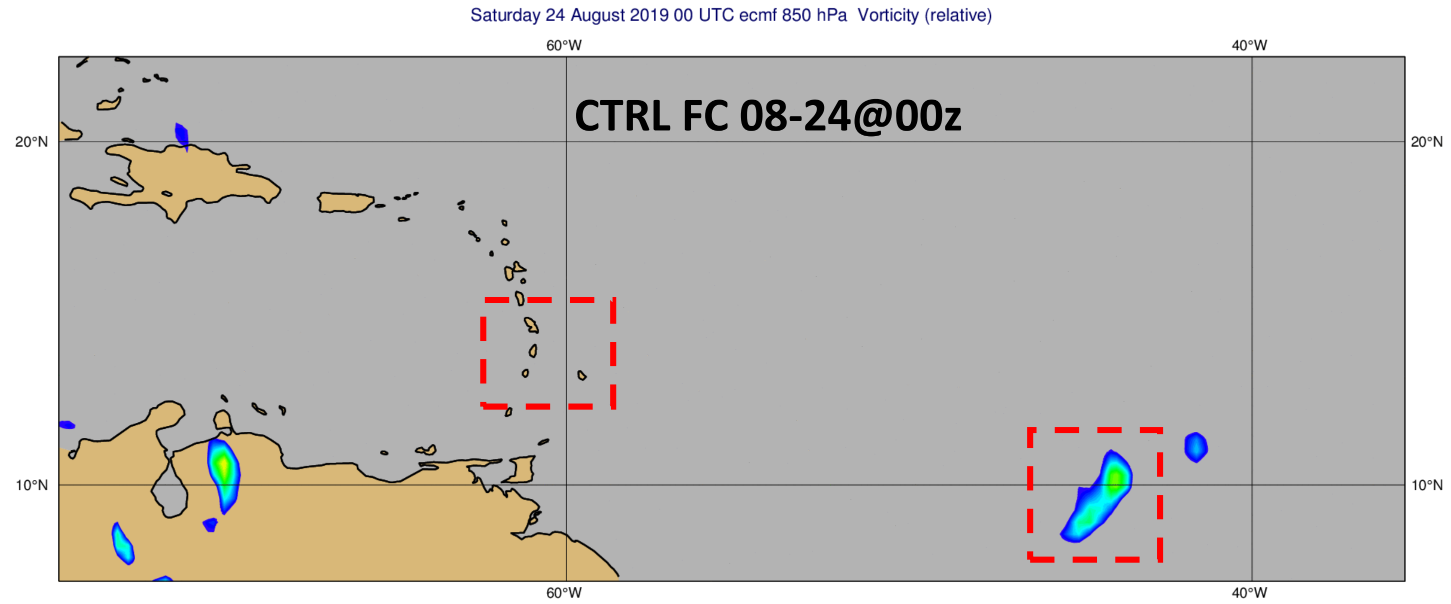
Dorian viewed from the Sentinel-3 satellite



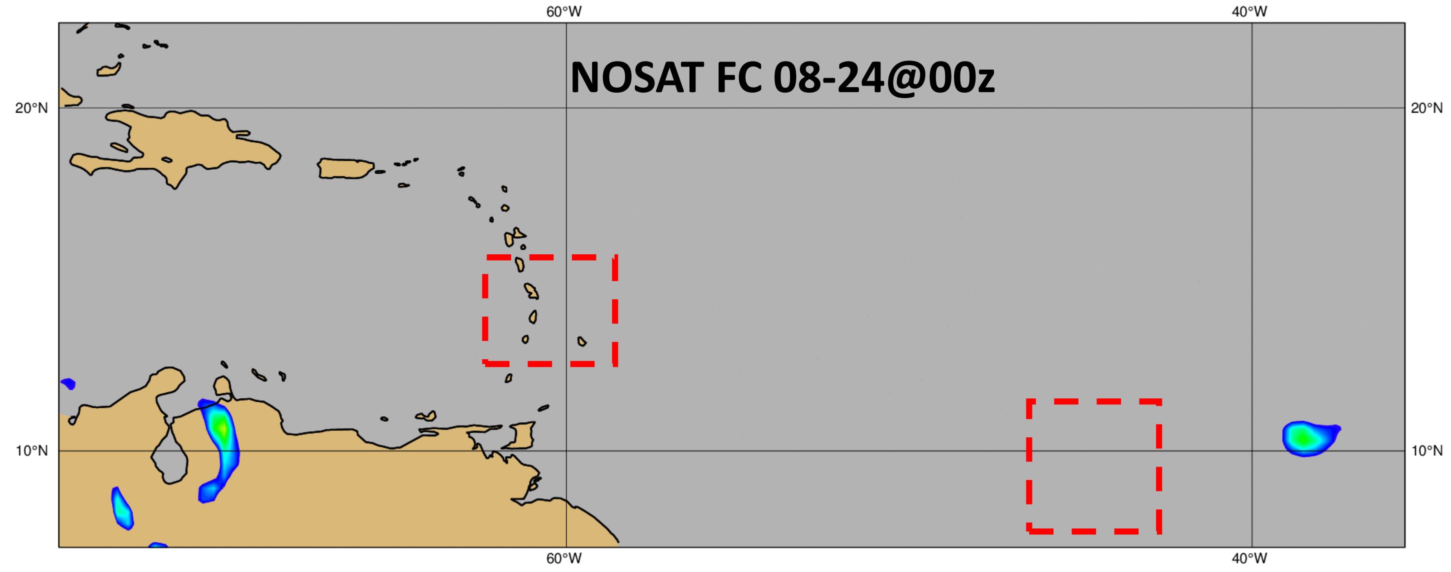
Dorian viewed from the Bahamas

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 **<u>4 days warning</u>** of direct strike on Windward Islands



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

Outline

- Overview of modern NWP DA systems
- Current use and impact of IR systems at ECMWF
- What factors influence this impact ?
- Requirements for future infrared systems ?

What factors influence an observation’s impact ?

Intrinsic to the observation

- Quality and stability
- NRT availability
- Coverage
- Resolution
- Time sampling
- Uniqueness

Non-intrinsic factors

- Orbital deployment
- Skill of DA tuning (Obs error)
- Ability of the DA to use the observation (clouds)
- Coupled nature of the DA (ocean / composition)

Outline

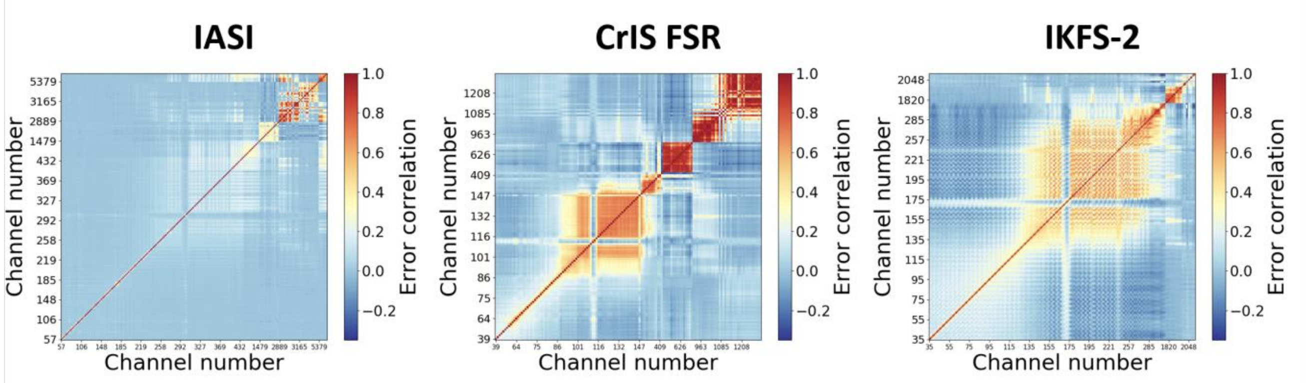
- Overview of modern NWP DA systems
- Current use and impact of IR systems at ECMWF
- What factors influence this impact ?
- Requirements for future infrared systems ?

Noise, spectral resolution and stability

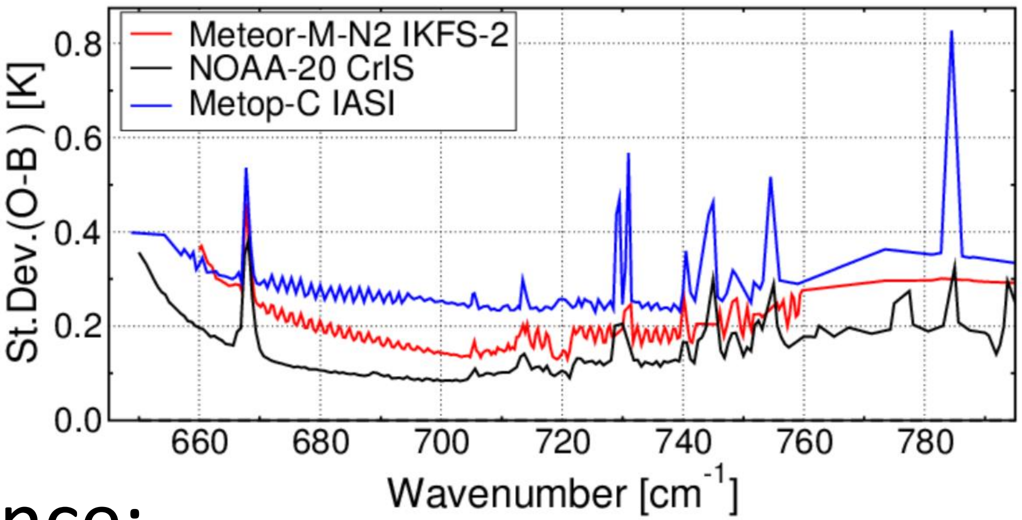
Noise, spectral resolution and stability

Experience (and theory) suggests a good compensation between noise and spectral resolution for NWP (e.g. IASI v CrIS). DA and PCA can also be used to reduce instrument noise.

Inter-channel error correlations



Magnitude (noise) error



But whatever the instrument performance:

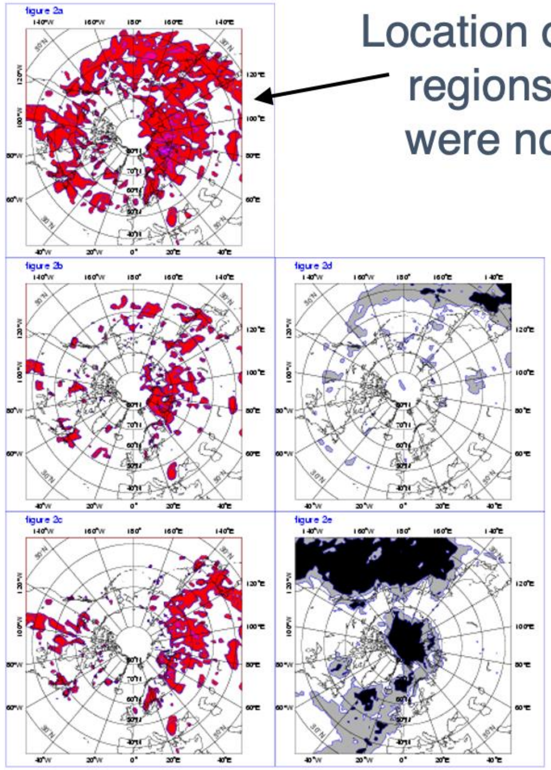
- It must be well understood and traceable
- It must be stable in time

Pixel size and onboard imager for cloud handling

Pixel size and onboard imager for cloud handling

Successful handling of clouds is absolutely critical for infrared exploitation!

Cloudy regions are meteorologically sensitive



Location of sensitive regions (if there were no clouds)

sensitivity surviving high cloud cover

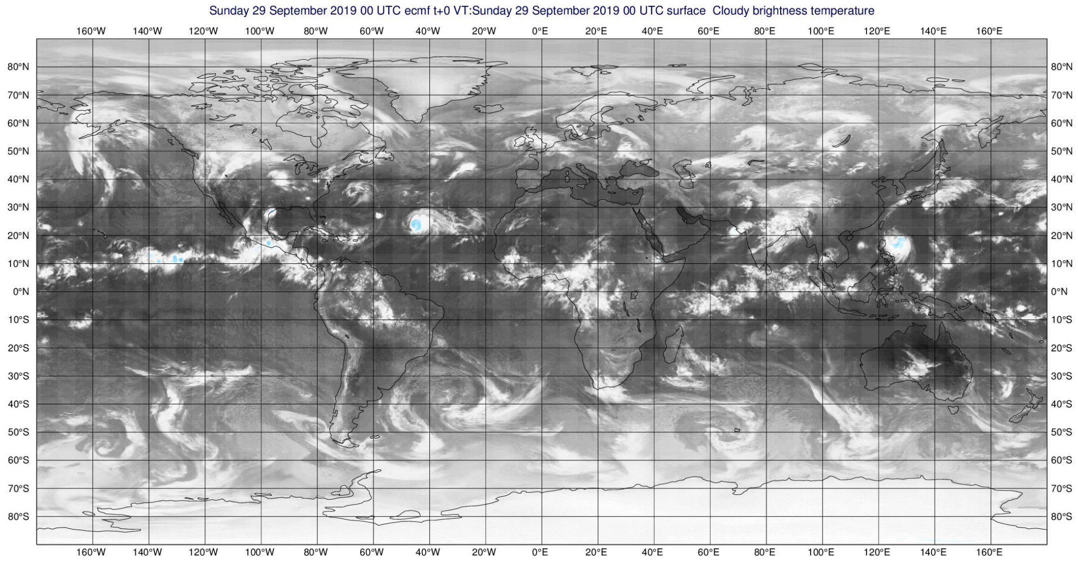
monthly mean high cloud cover

sensitivity surviving low cloud cover

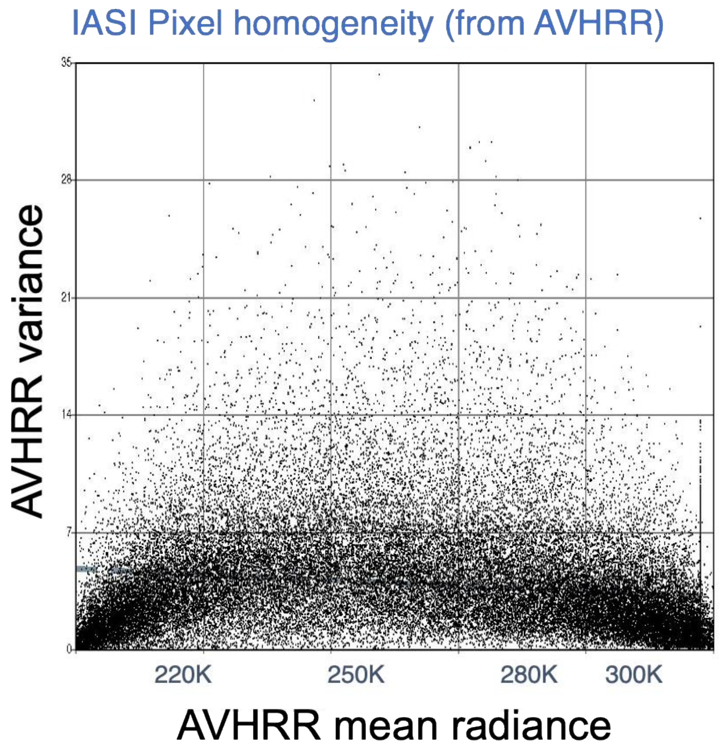
monthly mean low cloud cover

From *McNally (2002) QJRMS 128*

Clouds are everywhere

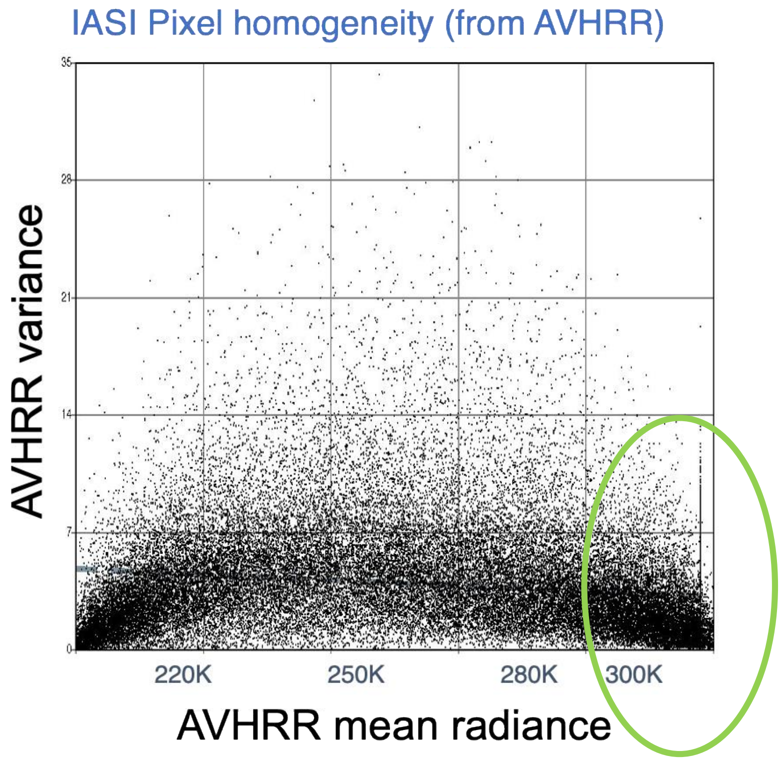


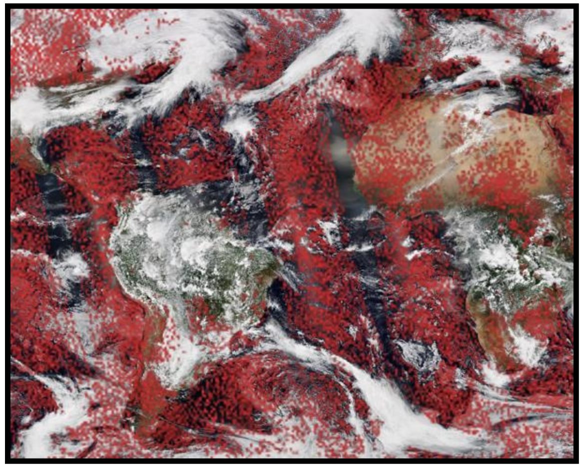
Pixel size and onboard imager for cloud handling

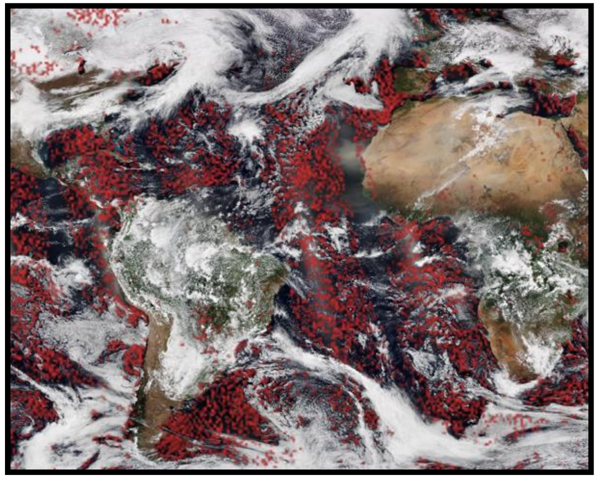


Pixel size and onboard imager for cloud handling

We can assimilate homogeneous clear pixels / channels

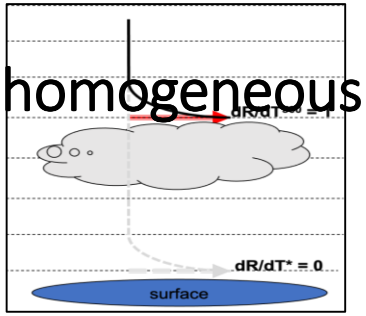


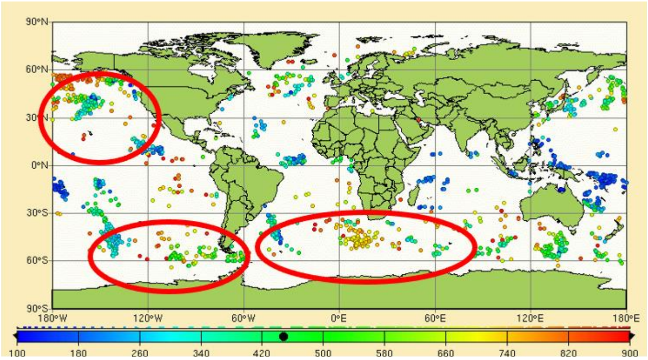




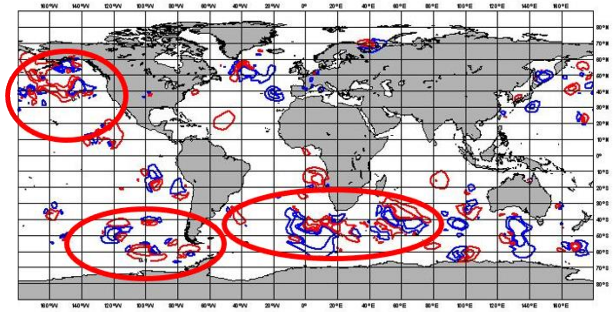
Pixel size and onboard imager for cloud handling

We can assimilate homogeneous overcast pixels

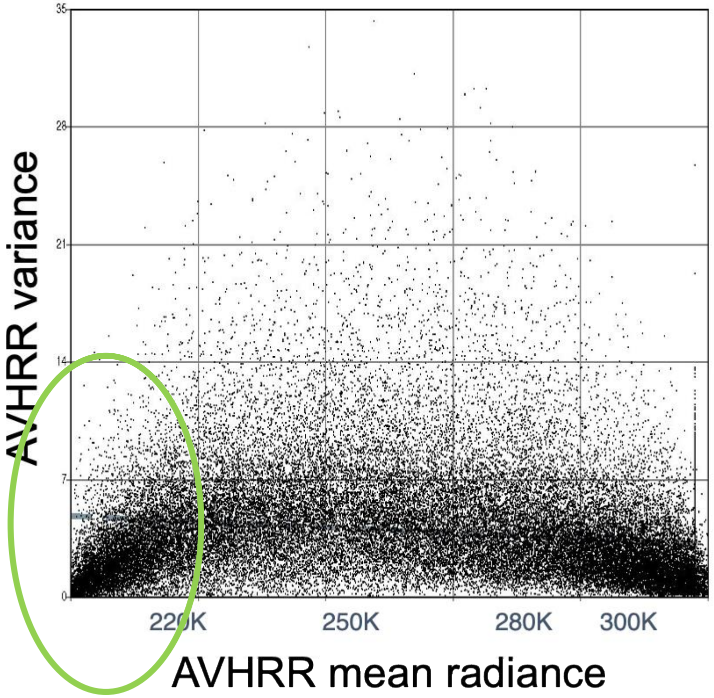




Temperature increments above low clouds

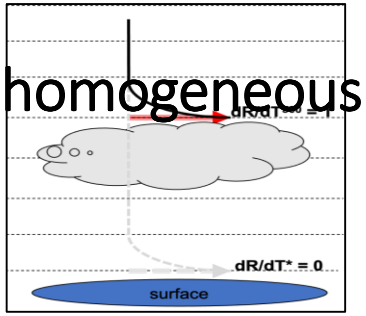


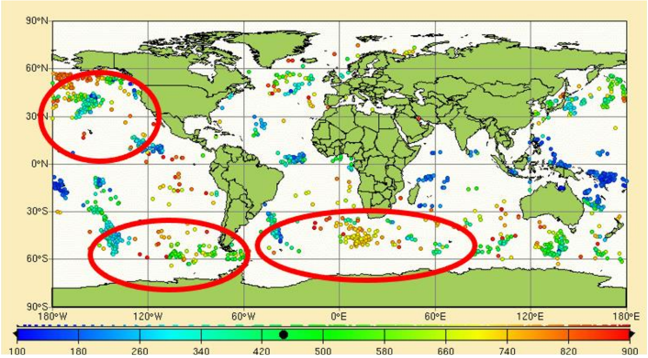
IASI Pixel homogeneity (from AVHRR)



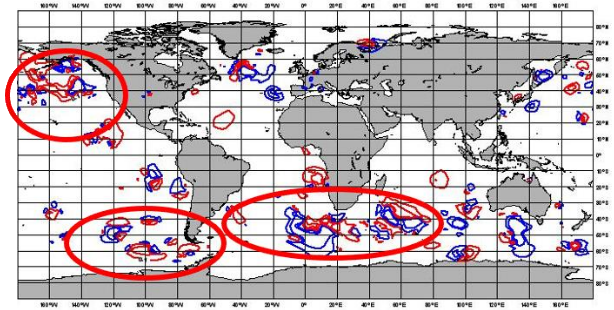
Pixel size and onboard imager for cloud handling

We can assimilate homogeneous <u>overcast</u> pixels



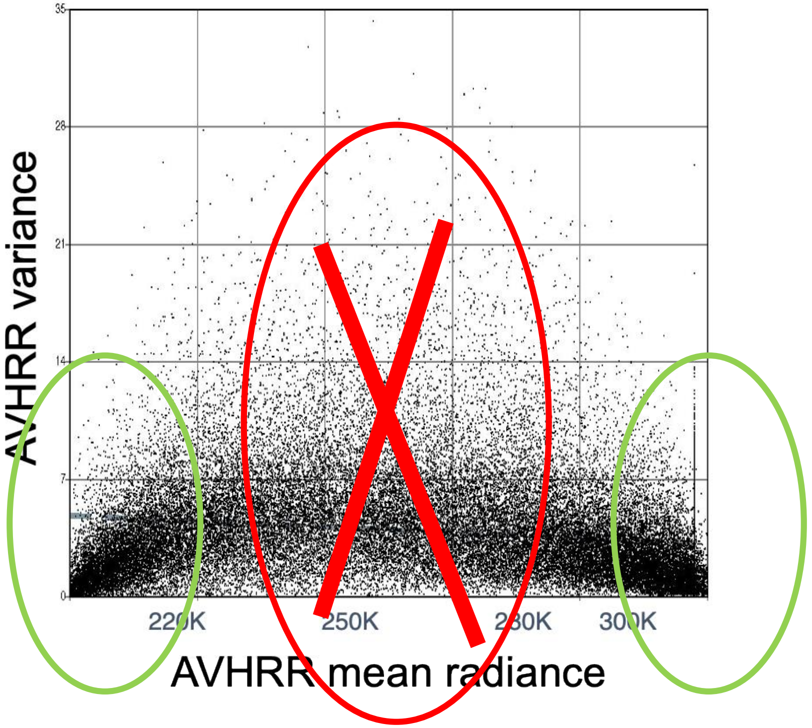


Temperature increments above <u>low</u> clouds

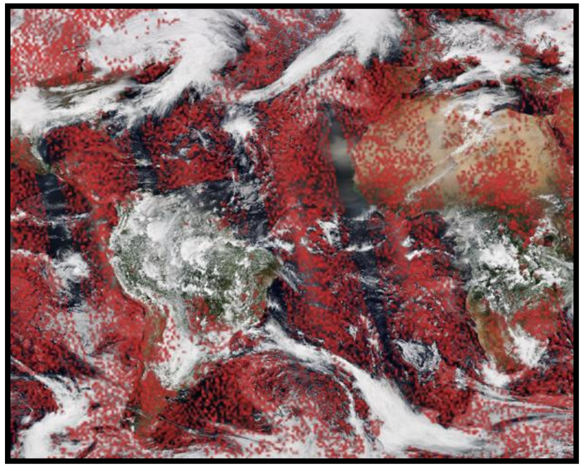


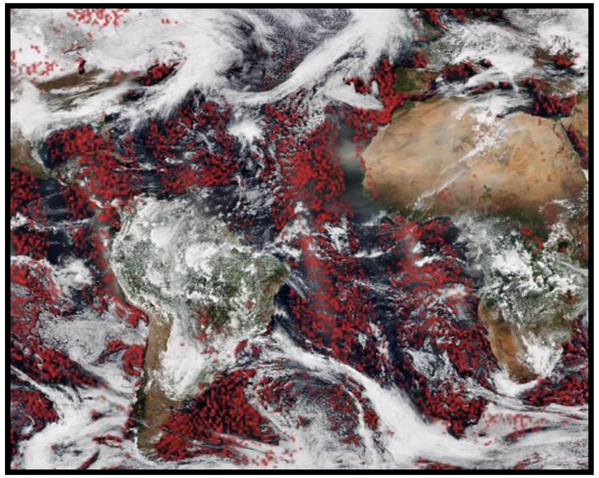
We can not assimilate heterogeneous pixels!

IASI Pixel homogeneity (from AVHRR)



We can assimilate homogeneous <u>clear</u> pixels / channels



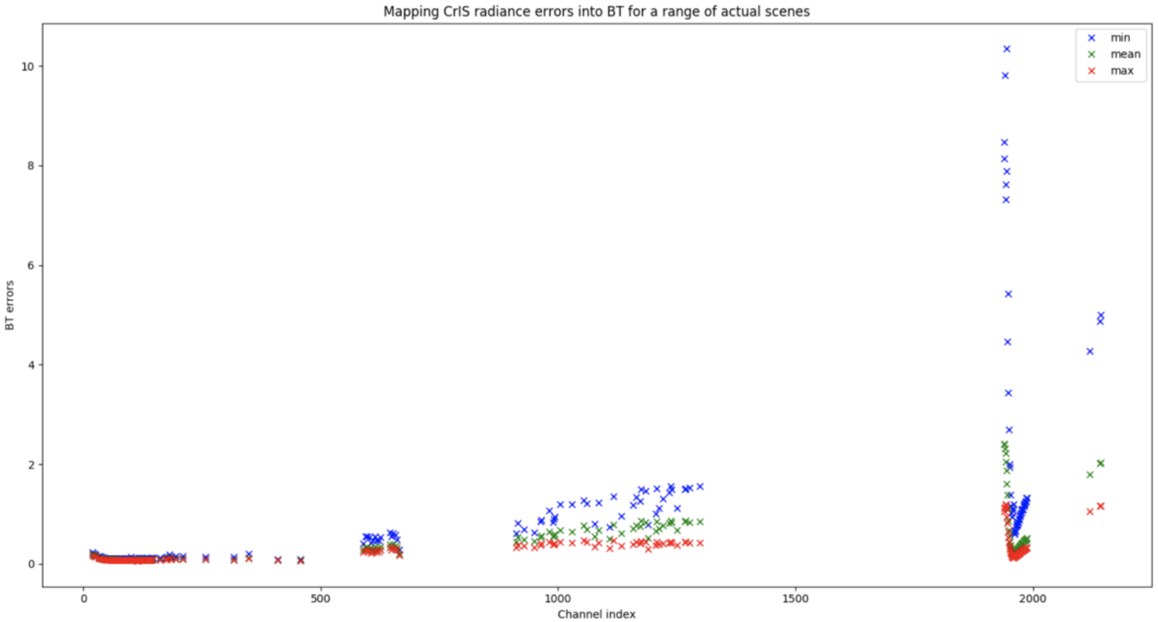


Spectral band coverage

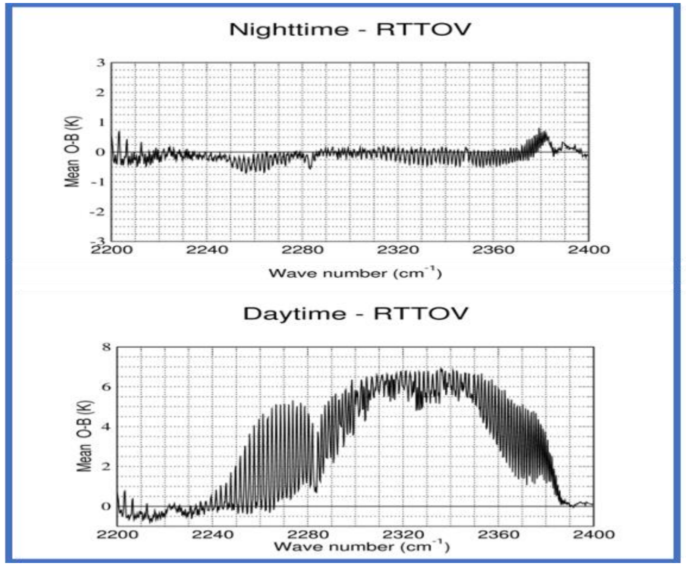
Spectral band coverage

In theory DA systems can exploit similar (or in some respects enhanced) information content from SW+MW and LW+MW. But in practice there are currently some challenges associated with SW radiance assimilation.

Scene dependence of the noise is extreme in the SW causing some numerical problems in covariance estimation



Non-LTE in radiative transfer for stratospheric channels and direct solar effects in window channels



DA studies are in progress at ECMWF to demonstrate SW+MW assimilation

Main messages

- Modern NWP systems are extremely accurate and high spatial / temporal resolution – even at the global scale. They are evolving towards **coupled Earth System simulators**.

- ECMWF typically benefits from the **real-time assimilation of 70+ different satellite sensors**. Much of the data assimilation is adaptive and autonomous, but new sensors require significant human resources (problematic sensors will simply be ignored).

- Hyper-spectral **infrared radiance data currently have a significant impact** on forecast accuracy both directly (e.g. temperature / humidity information) but also on the ocean and atmospheric composition (including wind tracing)

Future infrared sensor discussion…

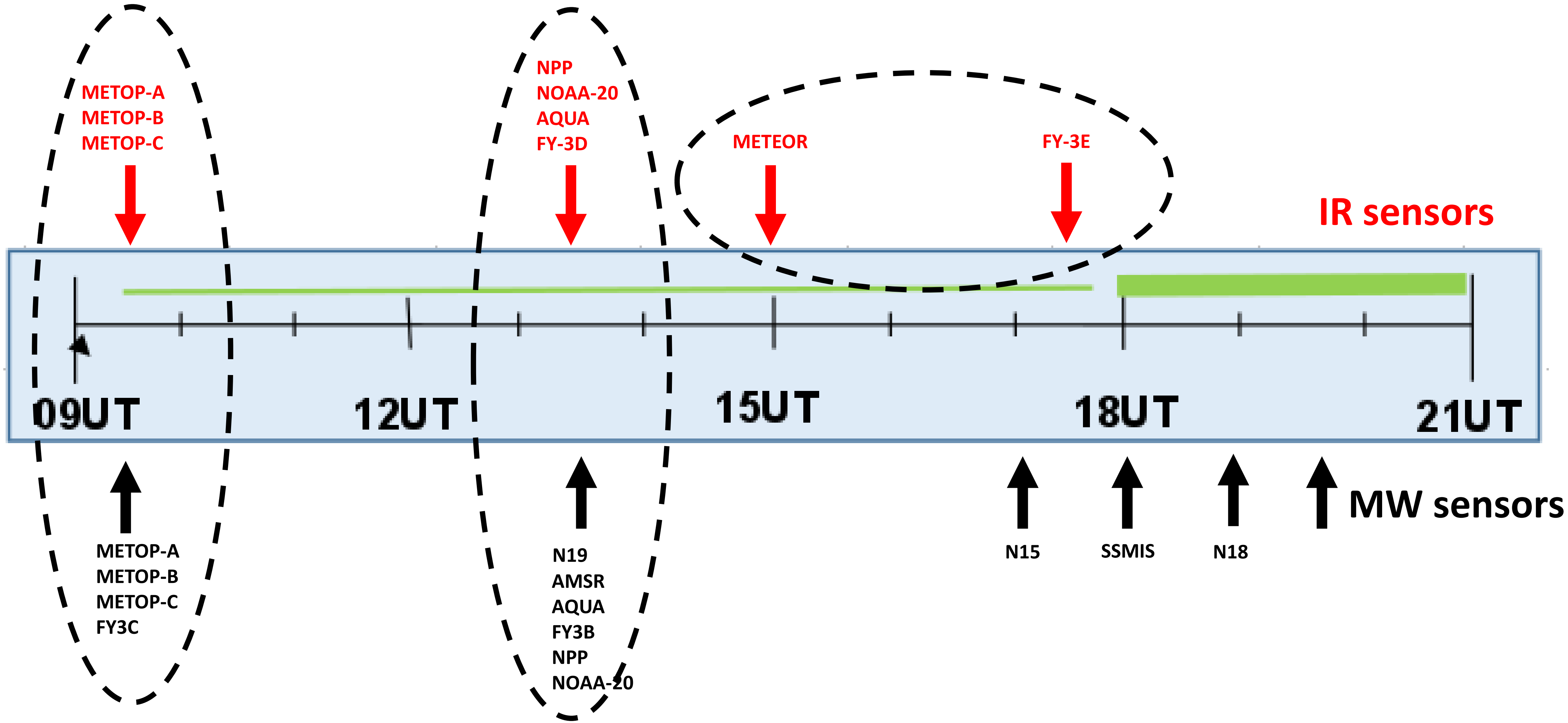
1. We have evidence that in NWP-DA systems, higher instrument noise can be compensated for if there is sufficient spectral resolution. We should not have our *microwave brain* on and insist of low instrument **noise at the expense of all else**.

2. The handling of clouds is a critical issue for IR exploitation. We can successfully assimilate fully clear pixels and fully overcast pixels – but highly heterogeneous pixels are very challenging. Thus, a sounder with a **small pixel size is highly desirable**.

3. The operational use of the **SW band is yet to be demonstrated** – but if the SW instruments offer significant potential benefits (e.g. small SAT constellations) we should resource and accelerate efforts to solve the existing problems.

Spare slides

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



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

Anthony P. McNally

European Centre for Medium-Range Weather Forecasts, Reading, UK

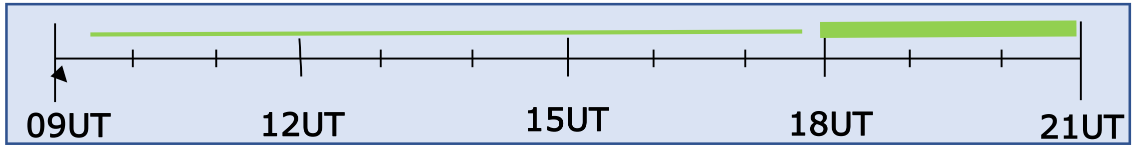
Correspondence
Anthony P. McNally, ECMWF, Shinfield Park, Reading RG2 9AX, UK.
Email: anthony.mcnally@ecmwf.int

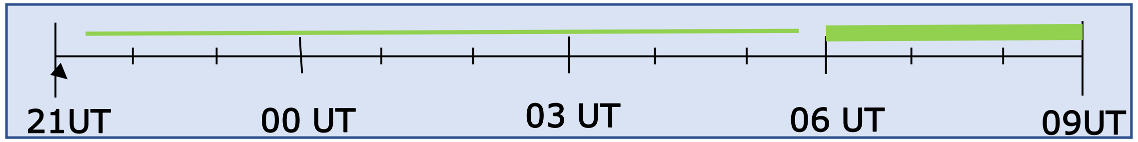
Funding information
EUMETSAT project
EUM/RSP/SOW/15/814210

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

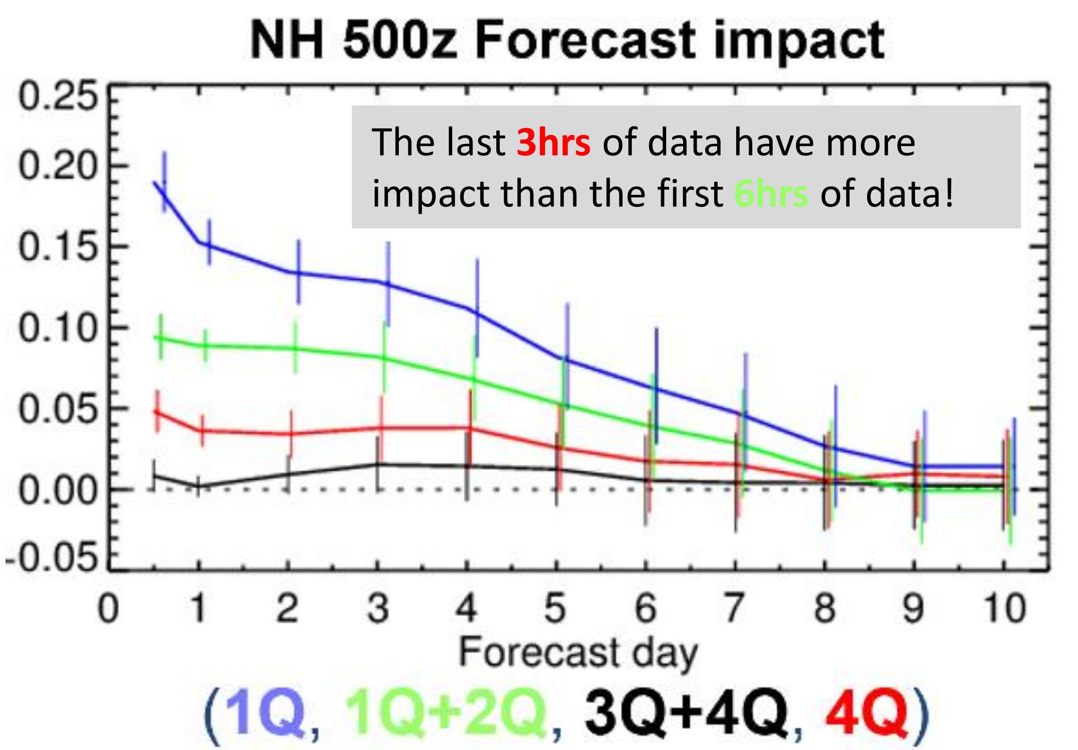




Observations located near the **end of the 12 hour window are significantly more influential** than observations located at the start of the window for two reasons:

- 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 sensitivity gives rise to the idea of ***influential orbits***