The value of passive bands used by microwave instruments in Numerical Weather Prediction

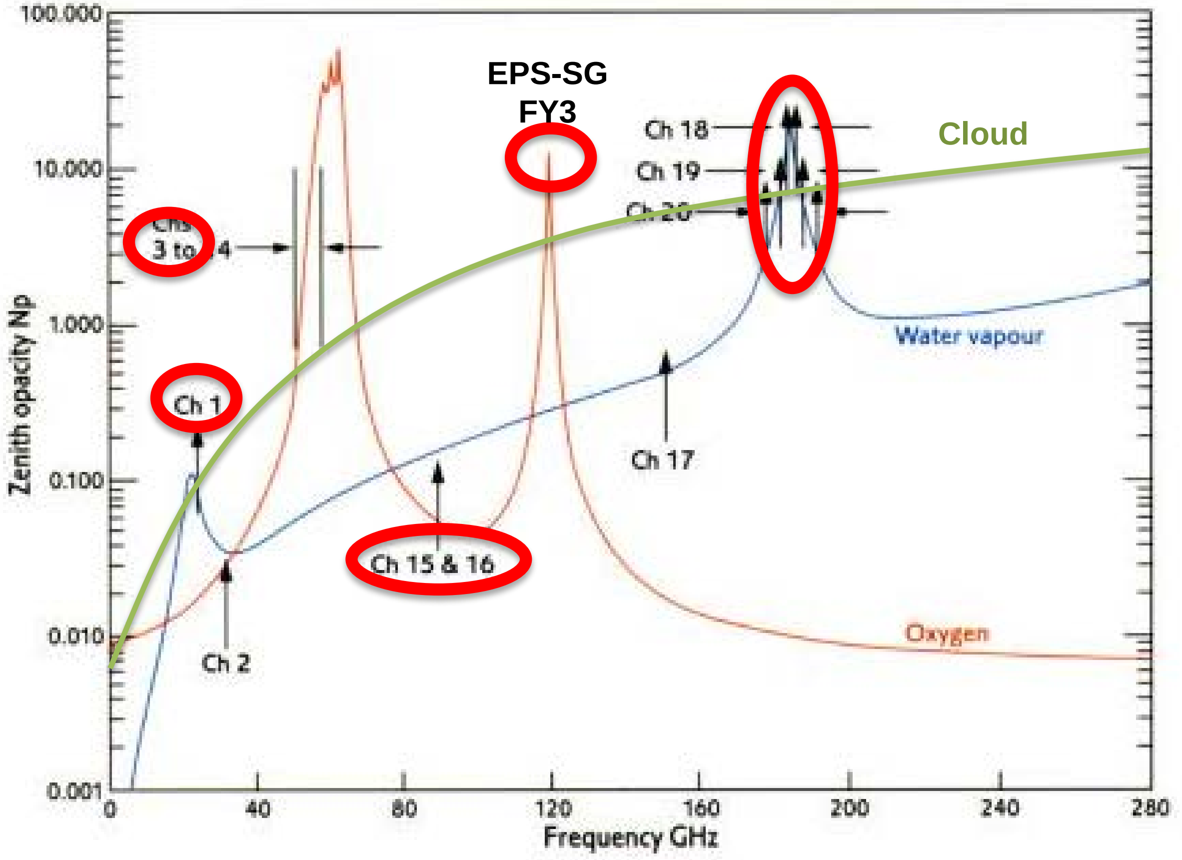
Stephen English

European Centre for Medium Range Weather Forecasts (ECMWF)

stephen.english@ecmwf.int

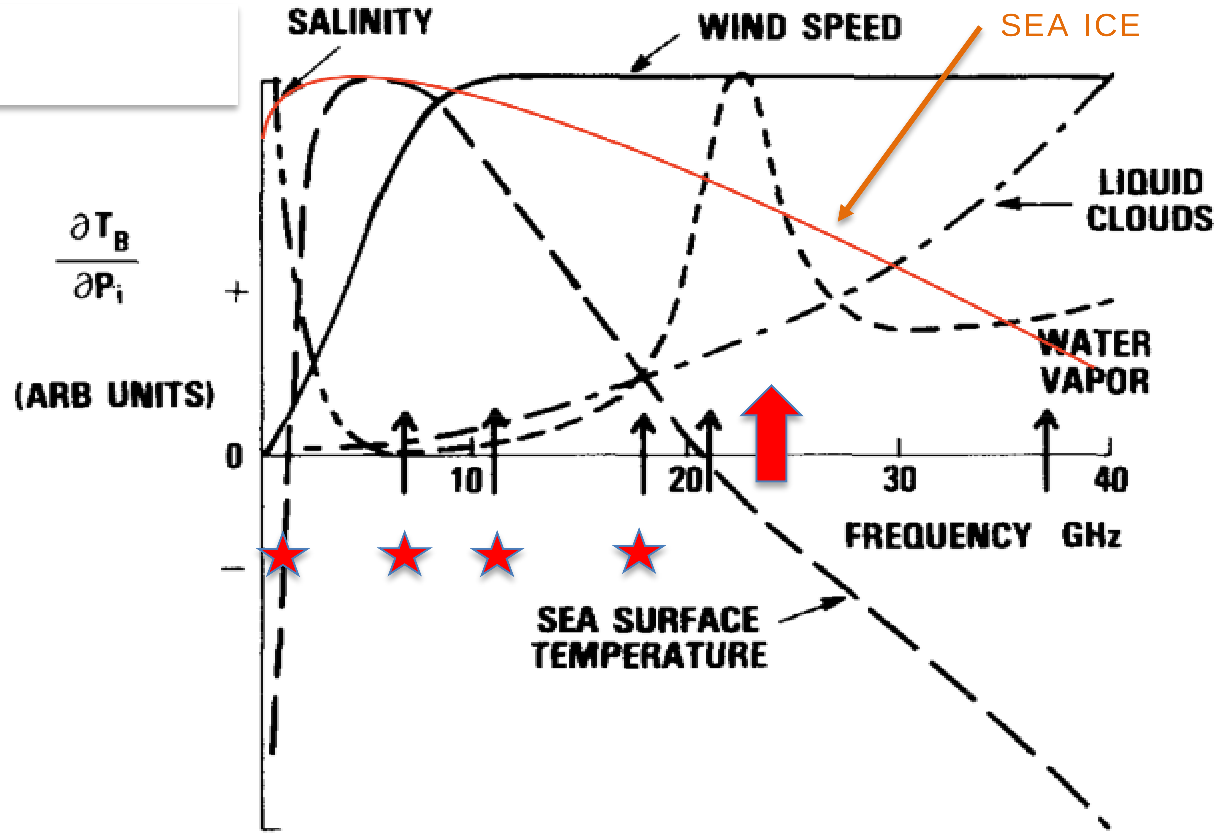
Which bands am I talking about?

AMSU-A, AMSU-B, MHS, ATMS, MWTS-2, MWHS-2, MTVZA-GY, SSMIS, GMI, AMSR-2, SAPHIR, MWS, MWI...



English *et al*, 1994, adapted

AMSR-2, GMI, MWRI, SMAP, SMOS, Aquarius, CIMR, WindSat…

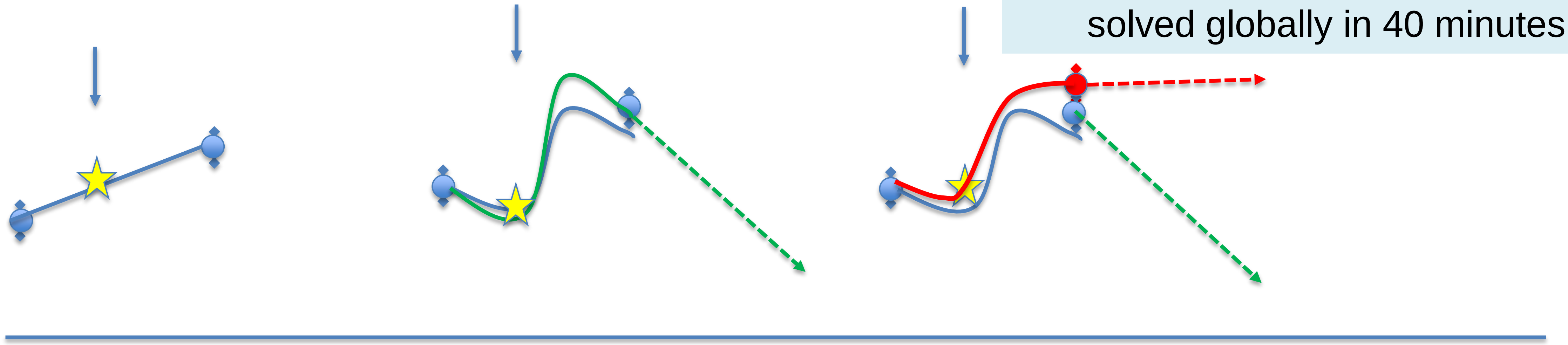


Wilheit, 1979, adapted Kilic 2019, adapted again for this presentation

Bands being actively used or prepared for by NWP centres	
Frequency GHz	*Instruments*
1.4-1.427P	**SMOS (ESA), SMAP (NASA), Aquarius (NASA) , CIMR (ESA)**
6.425-7.25	**AMSR-2 (JAXA) , CIMR (ESA)**
10.6-10.68p 10.68-10.7P	**AMSR-2 (JAXA), GMI (NASA), MWRI (CMA) , CIMR (ESA)**
18.6-18.8p	**AMSR-2 (JAXA), GMI (NASA), AMR (NOAA), MWRI (CMA) , CIMR (ESA) , MWI (EUMETSAT)**
23.6-24P	**AMSU-A (NOAA/EUMETSAT), ATMS (NOAA), SSMIS (DOD), GMI (NASA), AMR (NOAA), MTVZA-GY (Roscosmos), MWRI (CMA), MWS+I (EUMETSAT), AMSR-2 (JAXA)**
31.3-31.5P 31.5-31.8p	**AMSU-A (NOAA/EUMETSAT), ATMS (NOAA), GMI (NASA), MTVZA-GY (Roscosmos), MWS+I (EUMETSAT)**
37	**SSMIS (DOD), GMI (NASA), AMSR-2 (JAXA), MWRI (CMA), CIMR (ESA)**
50.2-50.4P 52.6-54.25P 54.25-59.3p **59.3-59.5 60.40- 61.15 63-63.5**	**AMSU-A (NOAA/EUMETSAT), ATMS (NOAA), SSMIS (DOD), MWTS-2 (CMA), MTVZA-GY (Roscosmos), MWS (EUMETSAT)**
86-92P	**AMSU-A (NOAA/EUMETSAT), ATMS (NOAA), SSMIS (DOD), MWHS-2 (CMA), MTVZA-GY (Roscosmos), MWRI (CMA), MWS (EUMETSAT), AMSR-2 (JAXA)**
100-102P 109.5-111.8P 114.25-116P 116-122.25p	**MWHS-2 (CMA), TROPICS (NASA), MWI (EUMETSAT)**
148.5-151.5P 155.5-158.5p 164-167P	**ATMS (NOAA), GMI (NASA), MHS (EUMETSAT), MWHS-2 (CMA), MTVZA-GY (Roscosmos), SSMIS (DOD) , MWS+I (EUMETSAT)**
174.8-182.0p 182.0-185.0P 185.0-190.0p **190.0- 191.8P**	**AMSU-B (NOAA), MHS (EUMETSAT), ATMS (NOAA), SSMIS (DOD), MWHS-2 (CMA), GMI (NASA), SAPHIR (CNES-ISRO), TROPICS (NASA), MTVZA-GY (Roscosmos), MWS+I (EUMETSAT)**
200-209P 226-231.5P	**TROPICS (NASA), MWS (EUMETSAT)**

A simplified guide to Numerical Weather Prediction

Real systems 10^8 obs and 10^9 model degrees of freedom per 12 hours – solved globally in 40 minutes!



We define a cost function, which we then solve variationally to find the mathematically optimal analysis

Model background state

Linearised model

Observation operator

$$J(\mathbf{x}_0) = (\mathbf{x}_b - \mathbf{x}_o)^T (\mathbf{P}^b)^{-1} (\mathbf{x}_b - \mathbf{x}_o) + \sum_{t=0}^{T} (\mathbf{y}_t - H_t M_{0\to t}(\mathbf{x}_0))^T \mathbf{R}_t^{-1} (\mathbf{y}_t - H_t M_{0\to t}(\mathbf{x}_0))$$

Model trajectory

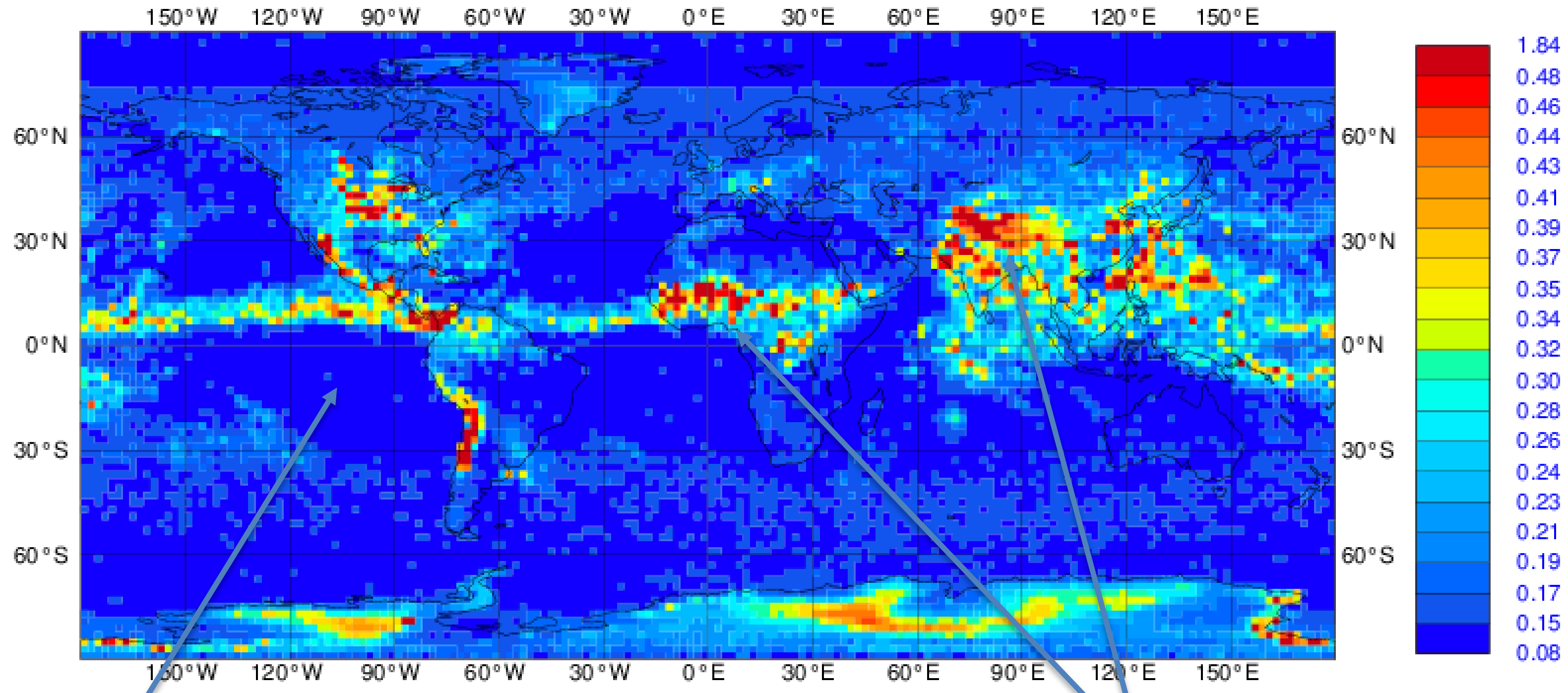
Error on model trajectory

Observations

Error on observations and observation operator

Innovations, and their relevance to RFI

- Every observation contributes to J through $\left(\mathbf{y}_t - H_t M_{0\to t}(\mathbf{x}_0)\right)^T$
- The adjustments are very small e.g. AMSU-A channel 7 (54.74-55.14 GHz)



Many regions St. Dev. of innovations 0.08-0.15 K

Sources of natural interference: clouds, mountains. We use other frequencies e.g. 24 GHz, 31 GHz to work out cloud impact on 55 GHz

If we are used to handling natural “interference” what is the problem?

Instruments used in meteorology and climate use a range of frequencies together

- Combinations of frequencies provide more information than single frequencies
- Therefore we can extract the information on temperature, humidity, wind….only **if we have a complete set of frequencies, allowing us to take account of natural effects e.g. clouds.**

With man-made RFI we have no physical equations to tell us the level of interference

- Our “signal”, **y-MHx**, is very small, so undetected RFI will adjust the trajectory of the model incorrectly and the forecast may go badly wrong.
- Our routine “screening” for clouds etc. will capture some man-made RFI, but not all.
- The probability of RFI is probably unknown in any particular period when the satellite observed (a fraction of a second at a given location), so we can’t allow for this in the Data Assimilation framework in the way we handle clouds and other “contamination” now.

Large RFI is easy to detect and to reject contaminated observations; small RFI comparable with forecast error is not easily detectable and will be misinterpreted.

So how important are these observations using passive microwave bands to operational weather and climate applications?

Radio-Frequency Interference (RFI) Workshop

13 –14 September 2018

<u>Goal</u>

To better quantify value of MW spectrum to Numerical Weather Prediction and to bring NWP experts and frequency managers together

<u>Organisers</u>

NWP: Stephen English (ECMWF)

Frequency Management: Rich Kelley (NOAA)

ECMWF

Participants

<u>Spectrum managers</u>

ITU: Vadim Nozdrin; **NOAA:** Richard Kelley; **EUMETSAT:** Markus Dreis; **ESA:** Elena Daganzo-Eusebio; **Met Office**: Mike Banks

<u>NWP centres by WMO regions</u>

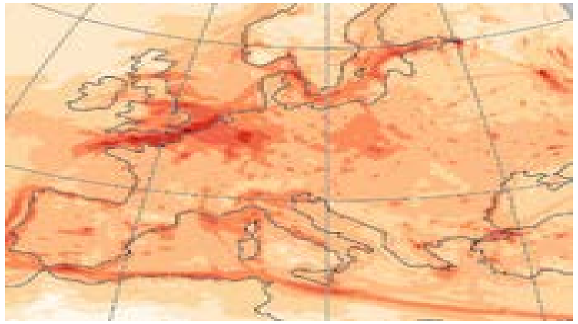
Region (WMO definitions)	Participants
Region I Africa	Nil
Region II Asia	**CMA, China:** Wei Han; **KIAPS, South Korea**: In-Hyuk Kwon; **JMA, Japan**: Masahiro Kazumori.
Region III South America	Nil (but Stephen English **ex-CPTEC**, **Brazil**)
Region IV North America	**NRL, USA:** Ben Ruston and Steve Swadley; **NOAA, USA** Andrew Collard; **ECCC, Canada:** Mark Buehner
Region V South West Pacific	**BoM, Australia:** Chris Tingwell and Fiona Smith
Region VI Europe	**ECMWF**: Niels Bormann, Stephen English; **Met Office, UK:** Chawn Harlow, John Eyre; **Meteo-France** Jean-Francois Mahfouf; **DWD, Germany:** Christina Kopken-Watts; **HIRLAM regional consortium (Met Norway):** Roger Randriamampianina.

Key areas benefiting from EESS bands via NWP application

Public weather advice


Public snow, flood & fire


Hurricane & tornado


Air quality

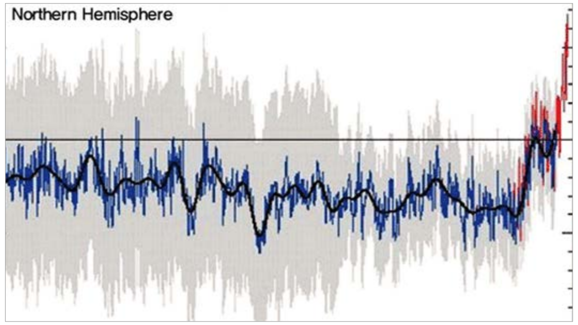
Warnings, public safety, protection of life and property


Transport


Energy


Agriculture


Tourism



Climate change Monitor


Public health and famine


Business and commerce


Defence

Key conclusions of ECMWF workshop in 2018

- Microwave observations are critical to NWP
- NWP is critical to WMO Member State National Warning Systems and many socio-economic sectors (previous slide)
- Passive microwave observations contribute around 40% of the overall improvement of short-range forecast skill, plus a further 10% from active microwave.
  - 50-60 GHz and 176-190 GHz remain the two most critical spectral bands (176-190 much more than 10y ago).
  - 18.7, 23.8, 31.4, 37, 89, 166 essential for direct measurements as well as indispensable in combination with the bands listed above (50-60 GHz and 176-190 GHz)
  - 1.4, 6.8, 10.7, 209, 229 important for emerging applications
- Many countries have detailed financial assessments of the value of their weather and environment services
  - https://www.metoffice.gov.uk/about-us/what/pws/value UK $2.0B per year, USA $11.4B per year
- Harder to quantify benefits in military sector in $

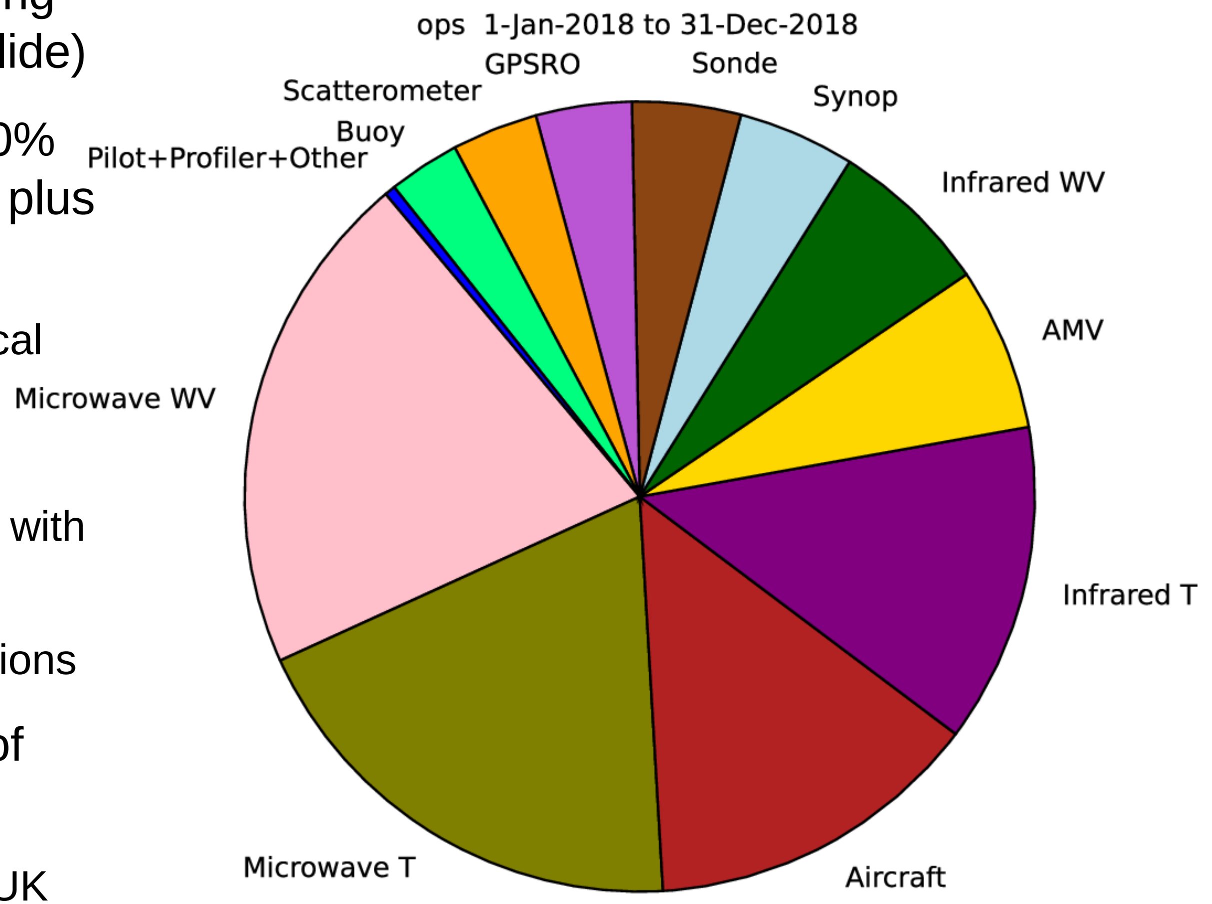
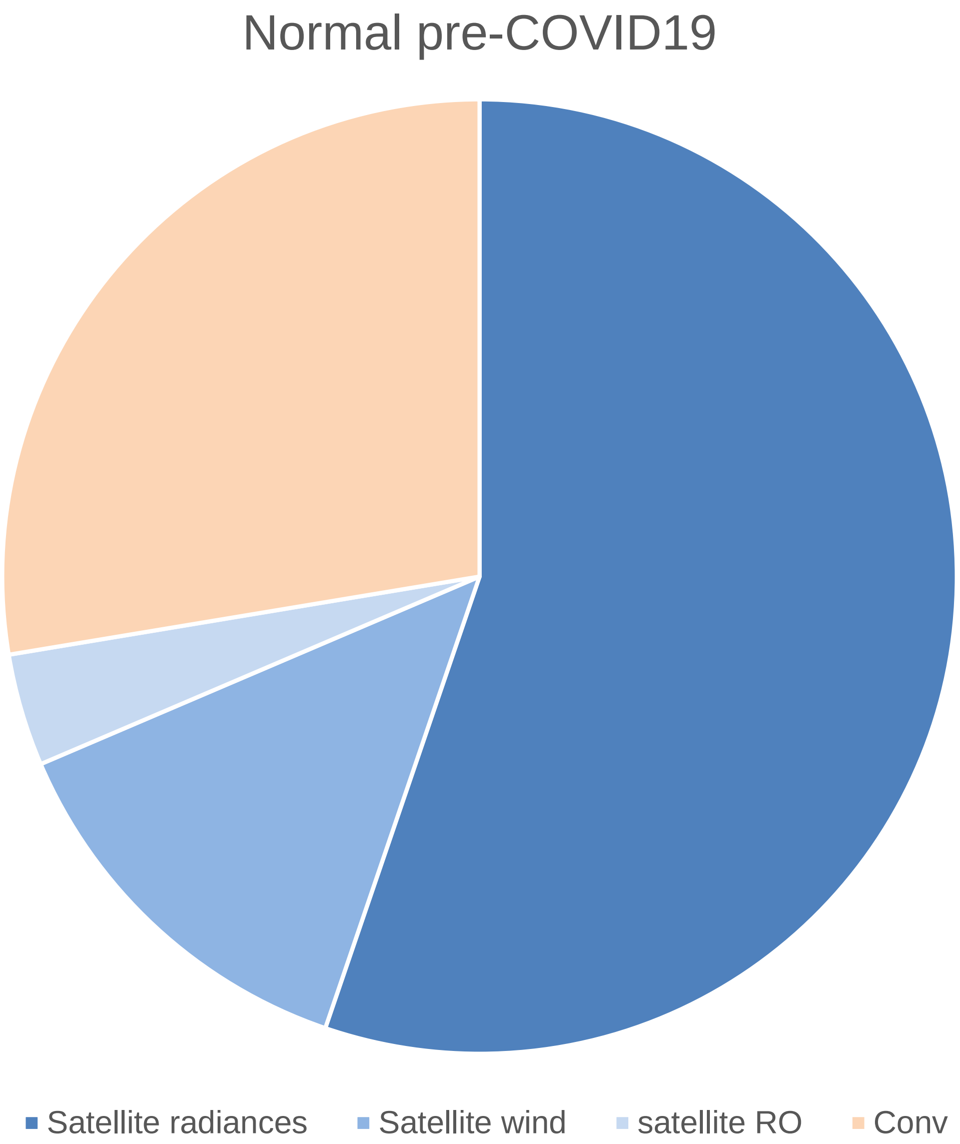
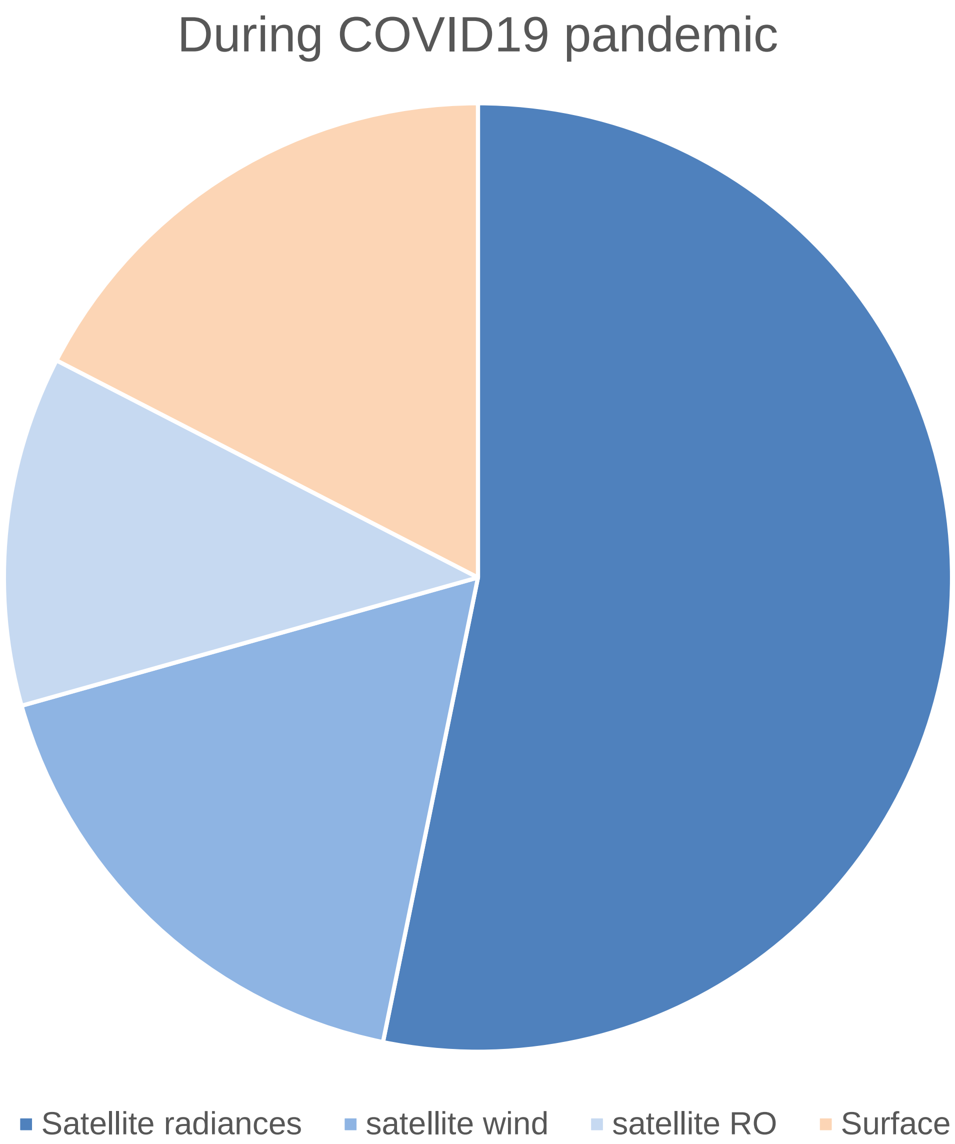


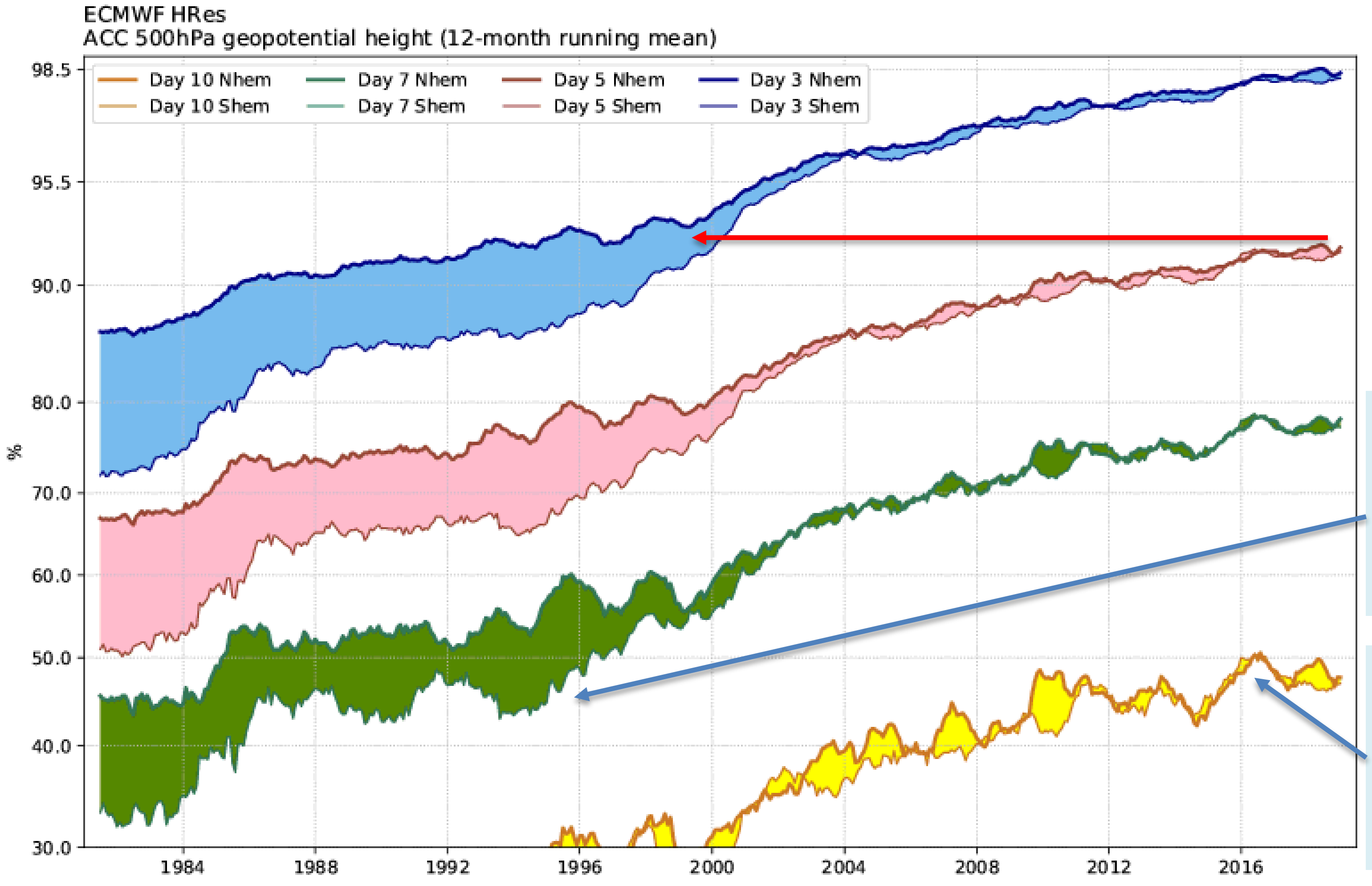
Figure from Alan Geer, ECMWF

Satellite data dominates **global** NWP skill, but surface networks are important





Long term improvement in NWP skill

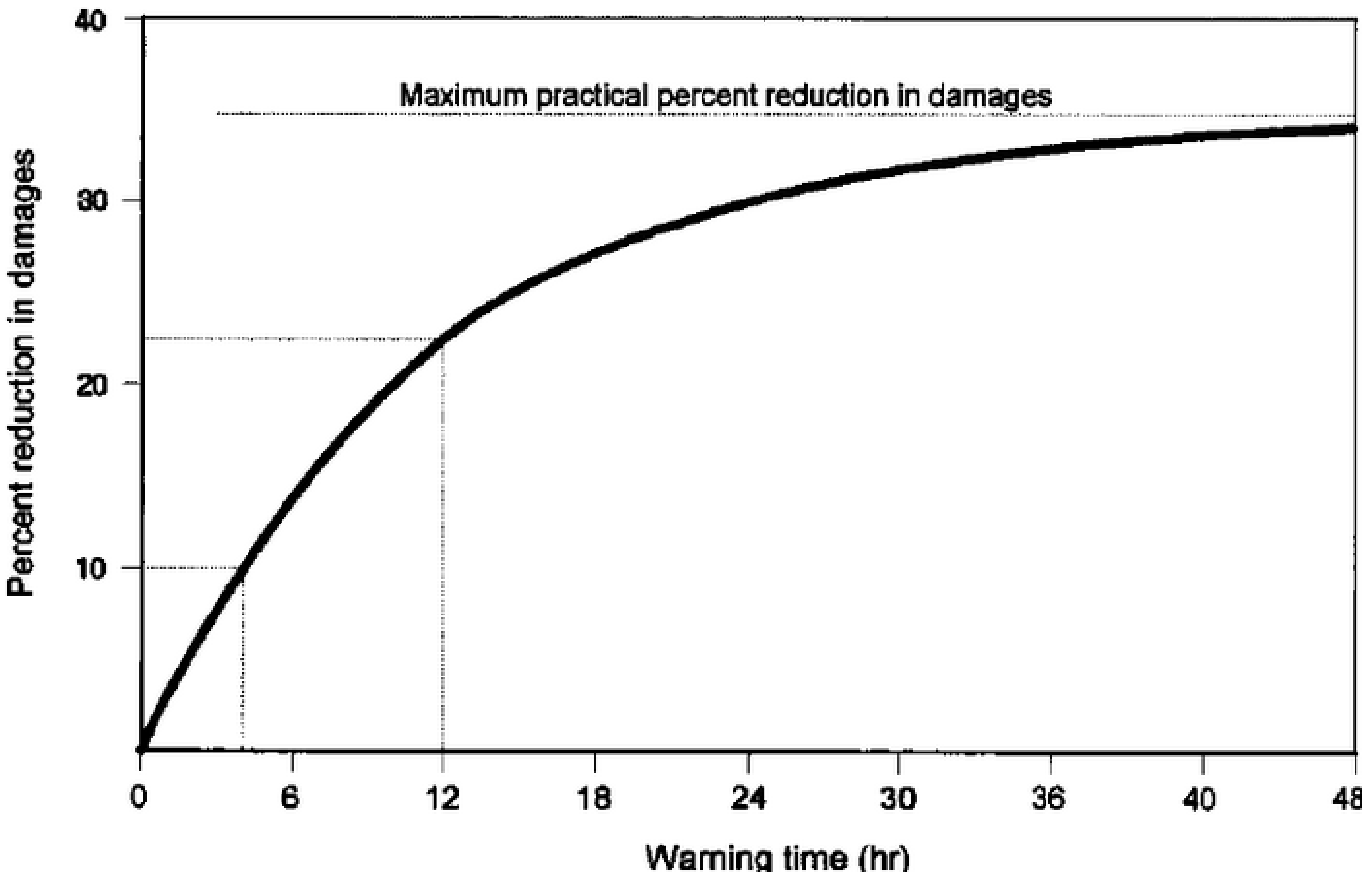


1 day per decade skill improvement

Before satellite era: southern hemisphere skill 1-2 decades behind northern hemisphere

Satellite era: southern hemisphere as good as “well observed” northern hemisphere

Day’s curve helps us understand impact of early warnings…..



Day's curve for damage mitigation as a function of the forecast lead times. Source: Day et al., 1970.

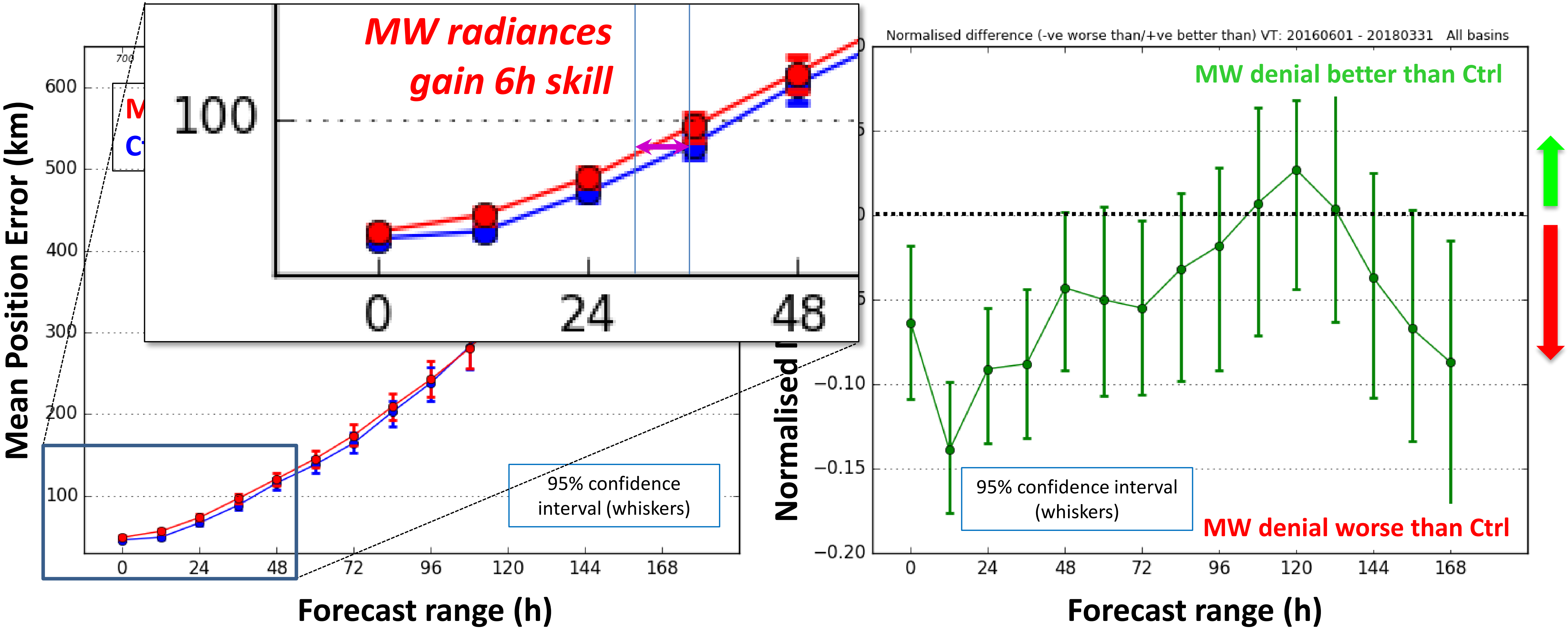
Day’s curve: A 6-h warning time can reduce damage by 12% whereas a 12-h warning time can lead to a 24% reduction.

Impact of MW radiances on tropical cyclone forecasts

(Fernando Prates)

Mean position error

T_{Co} 399 experiments, period: 1 June – 30 Sept 2016, 1 Dec 2017 – 31 March 2018
All basins, homogeneous samples



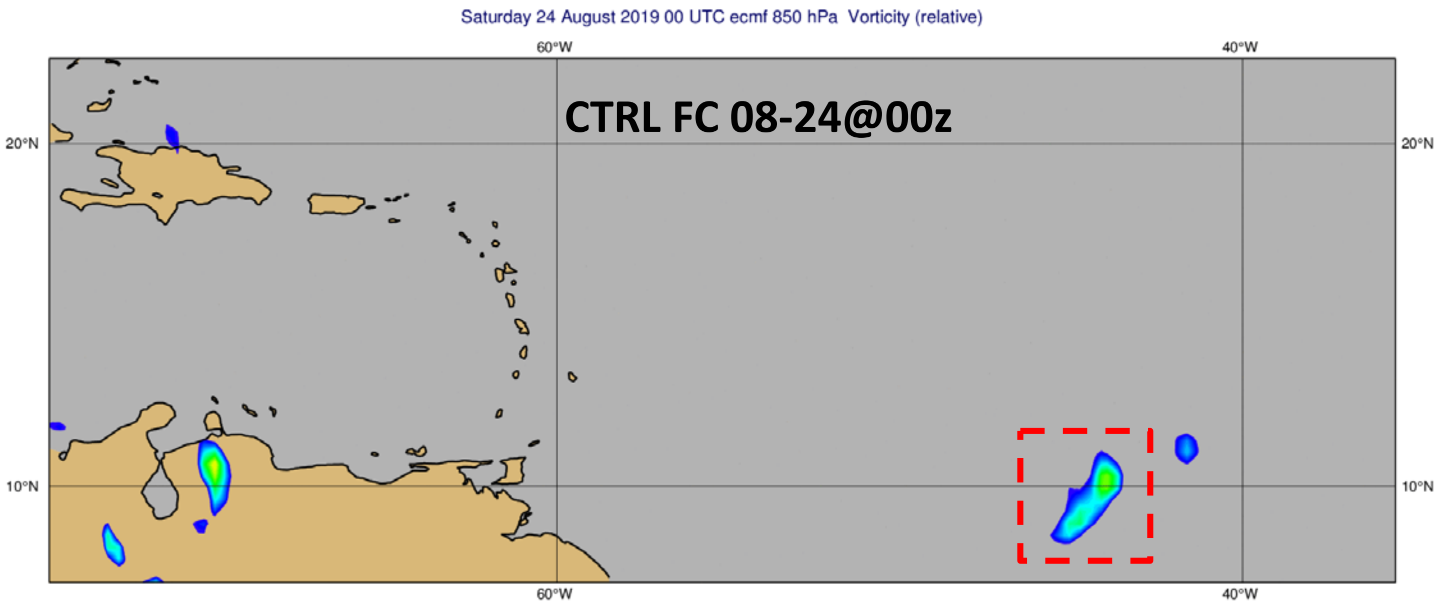
So what?

It is therefore defensible to say…

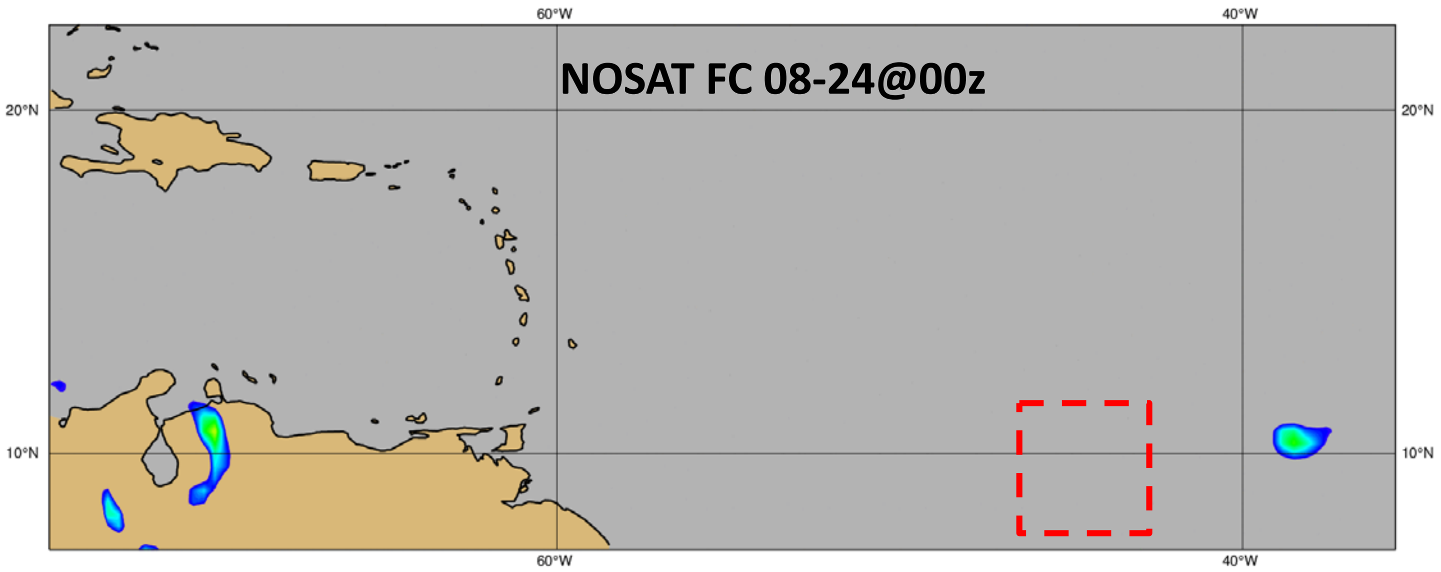
Microwave satellite observations double disaster reduction even when other observations are available.

And nothing else comes close to this…..

Dorian genesis…to first strike on Windward Islands

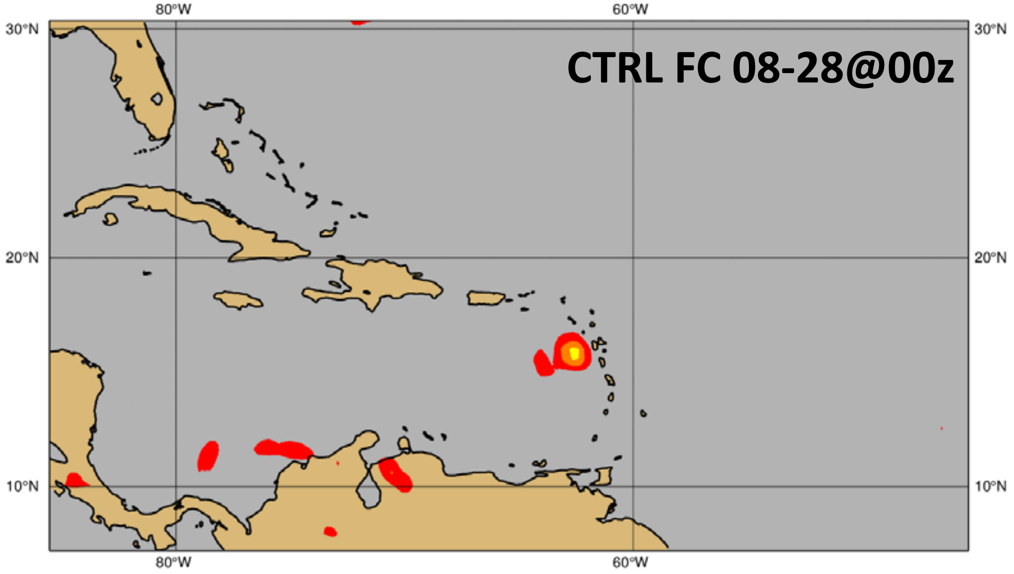


Control system with satellites identifies storm genesis on 24th August and provides 4 days warning of direct strike on Windward Islands

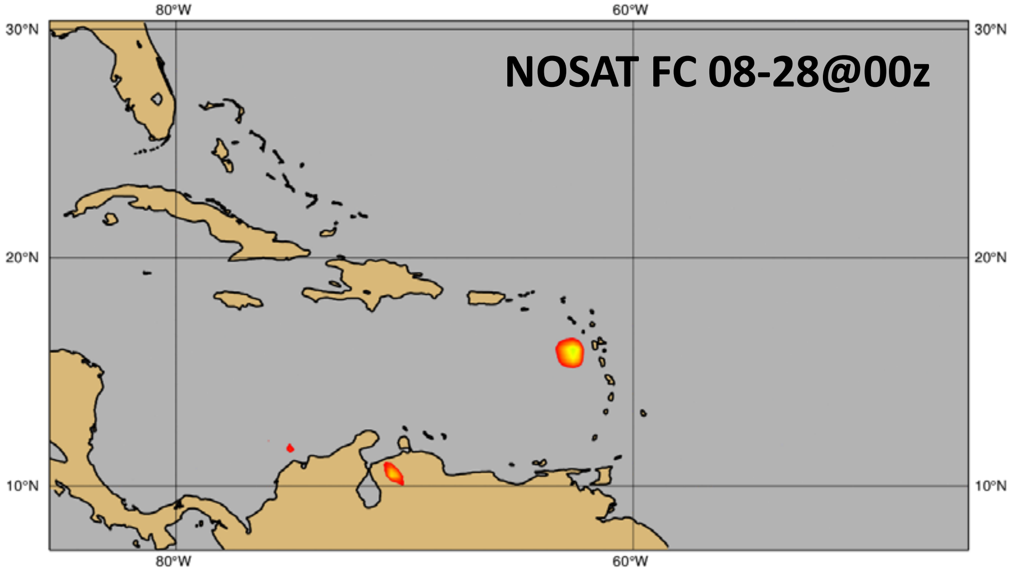


System with satellites denied (for 36hrs prior to forecast) misses the storm genesis and provides no warning of strike on Windward Islands

Transition from Windward Islands …to Bahamas…

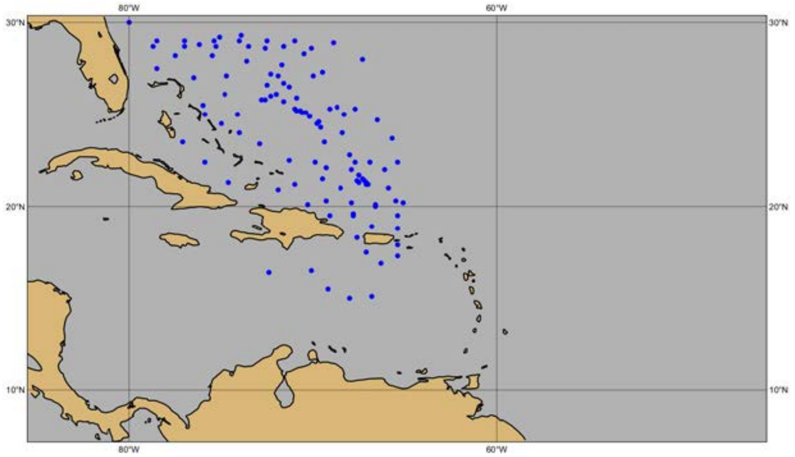


Wednesday 28 August 2019 00 UTC ecmf 850 hPa Vorticity (relative)

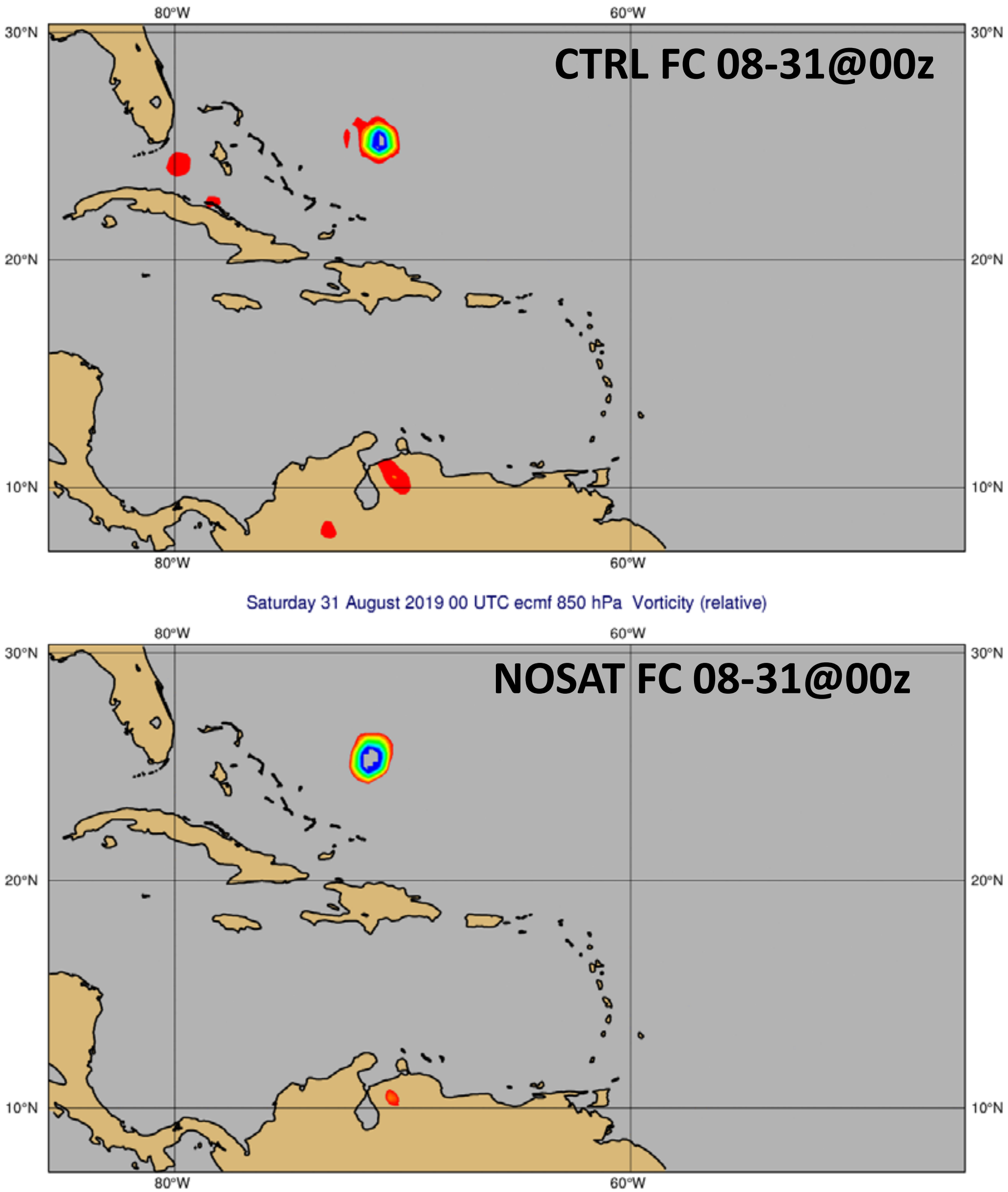


Control system with satellites correctly predicts the storm's transition to hit on the Bahamas 4 days later

System with satellites denied wrongly predicts a near miss for the Bahamas, despite the availability of extensive US drop-sonde activity.



Stall over Bahamas …no Florida land-fall



Control system with satellites correctly predicts the storm's stall over the Bahamas and no land-fall on Florida

System with satellites denied fails to predict the stall and wrongly forecasts a direct hit on Florida (like many earlier CTRL forecasts!)

Current issues

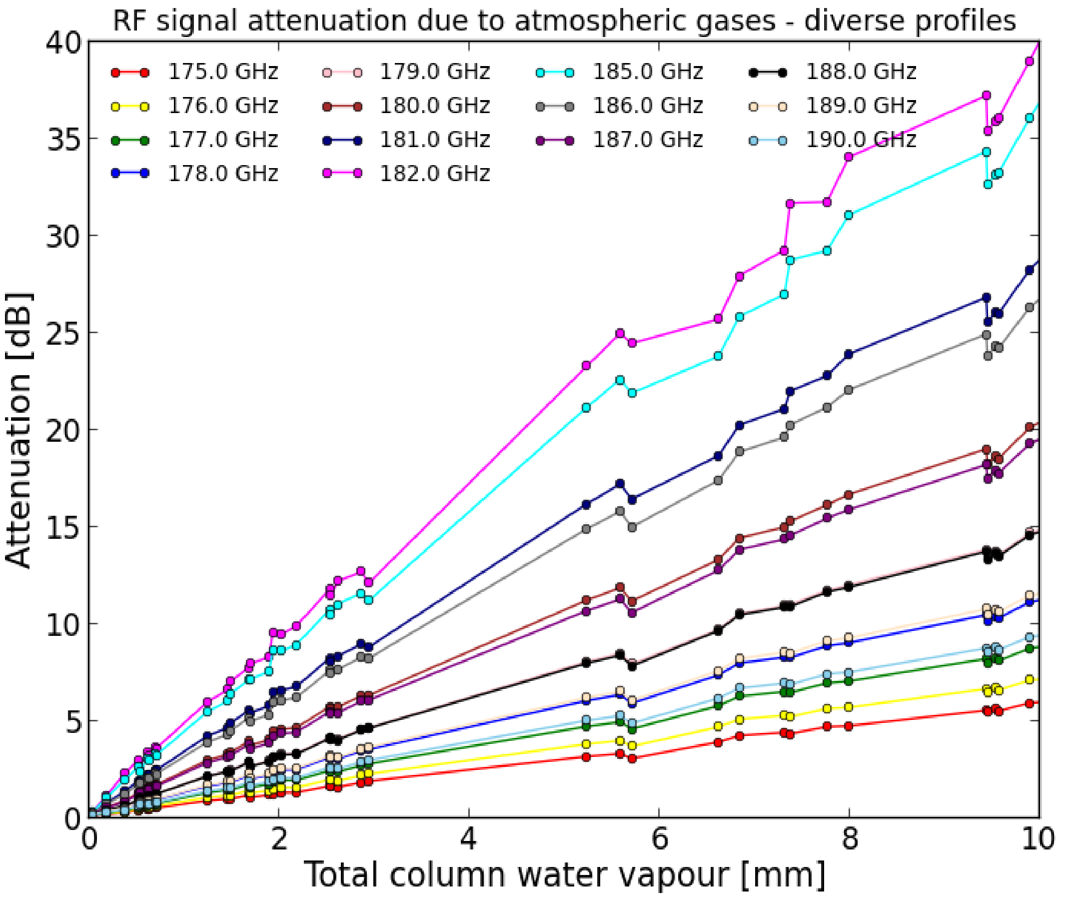
- Aftermath of 24 GHz decision at WRC-19: Threat to a critically important frequency
  - Value of operational weather services was not sufficiently taken into account
  - Public statement of Secretary General of World Meteorological Organisation

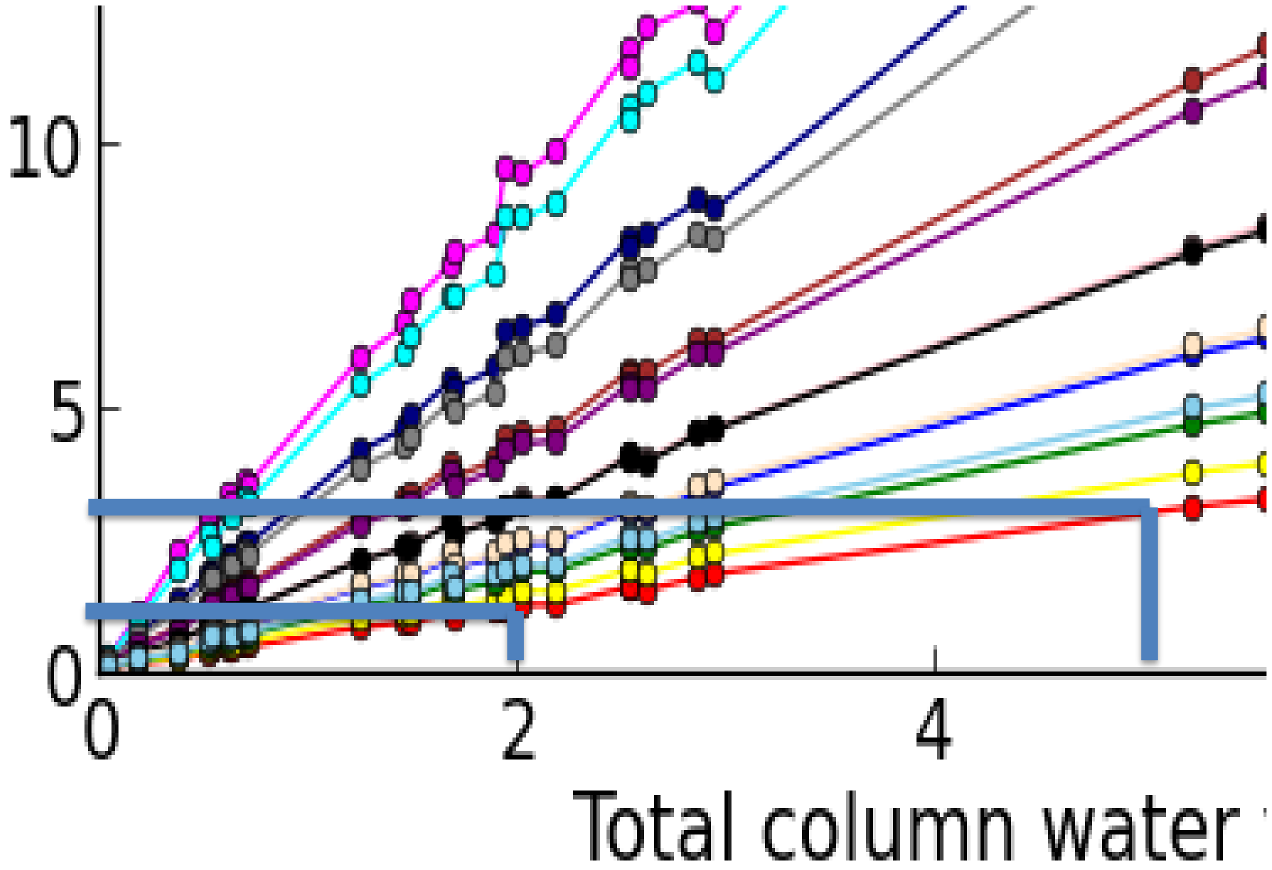
- We can’t allow repetition, but now ……

- 89 GHz
- 118 GHz
- 183 GHz

We need coordinated studies to demonstrate the impact and the value of these bands

How much does the atmosphere attenuate at 183 GHz?



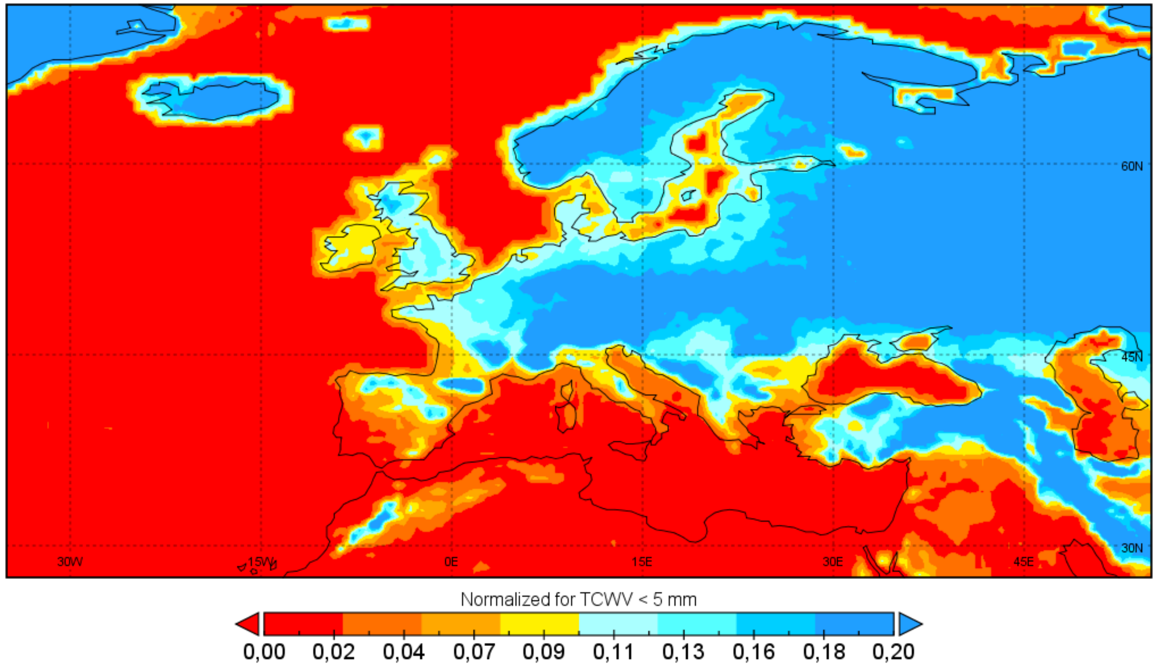


1 dB @ 2 mm
3 dB @ 5 mm

DMSP + MERIS CDR shows TCWV < 5mm is common and less than 2 mm is not uncommon, especially in northern half of N. America and Asia. ERA-5 also confirms these results.

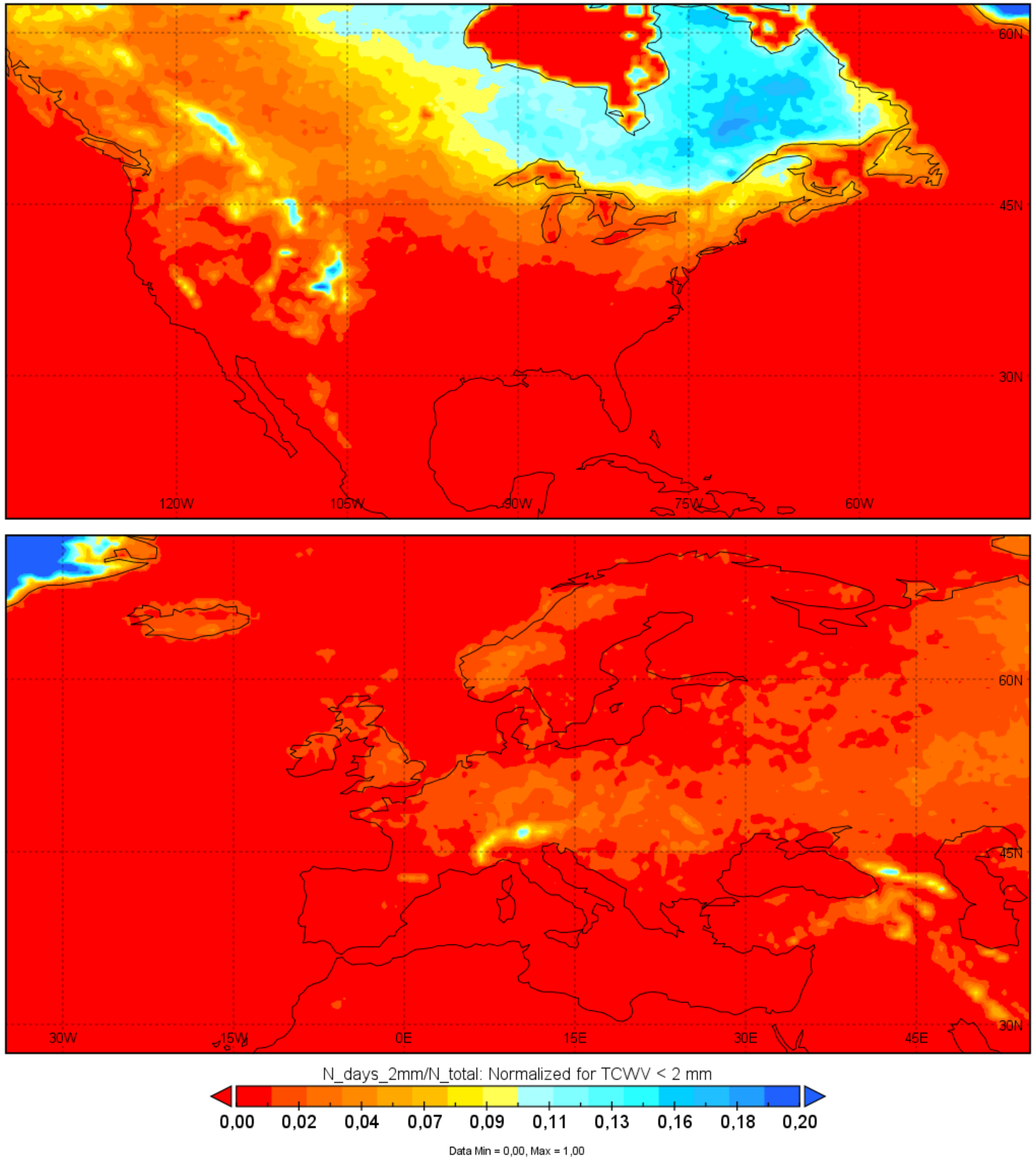
Normalized TCWV < 5 mm

N_days_5mm / N_days_total (MERIS+SSMI 2003-2008 Daily)



Normalized TCWV < 2mm

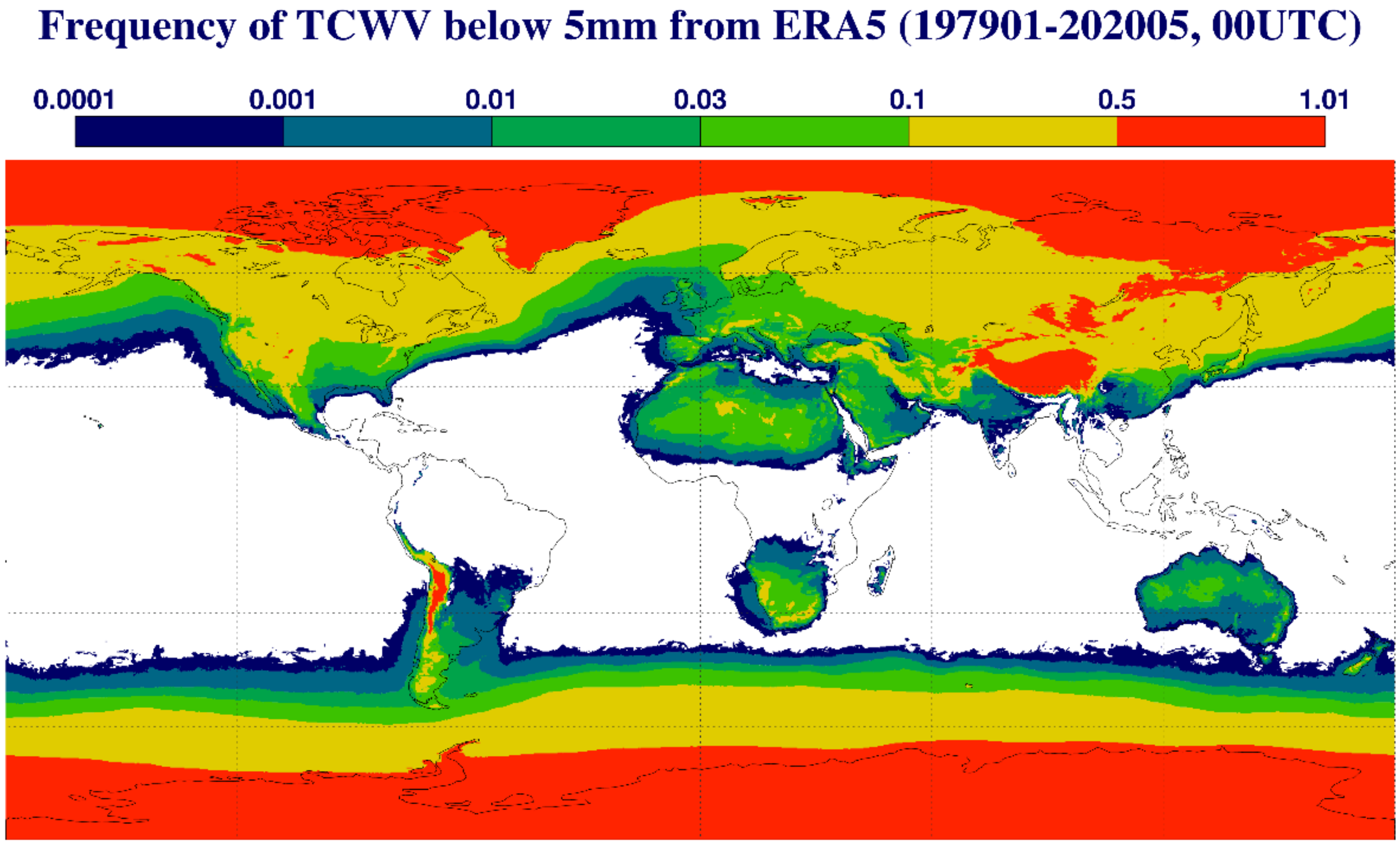
N_days_2mm/N_days_total



GlobVapour project (Lindstrot et al. 2014)

ECMWF

ERA-5 frequency of TCWV < 5mm 1979-2020

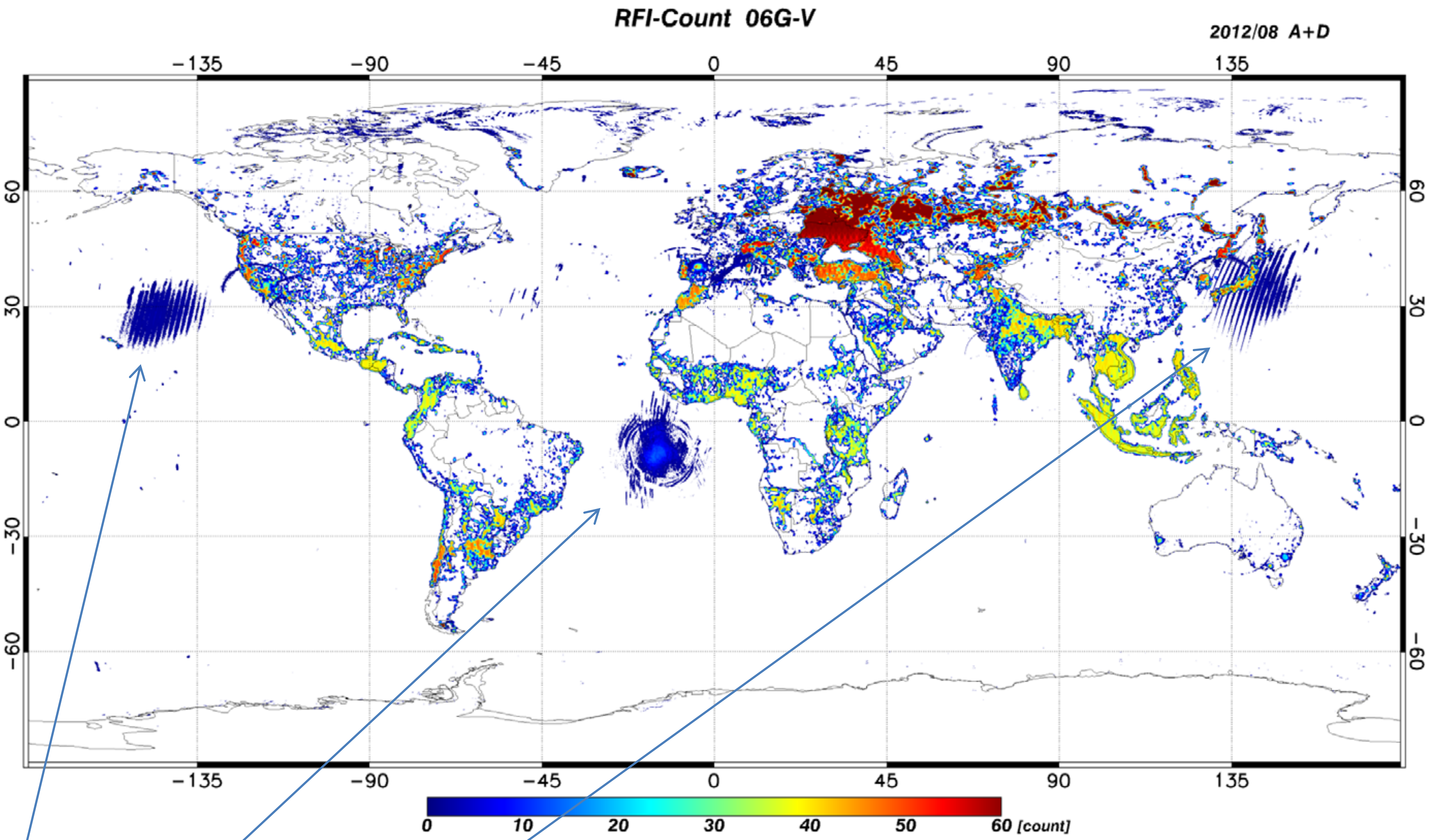


Examples of RFI

- **L-, C-, X-, K- bands all showing significant RFI now**

- **Too early for 24 GHz (5G rollout has not begun at 24 GHz in most places)**

Example of current RFI shown by JMA (Japan) in C band (unprotected)

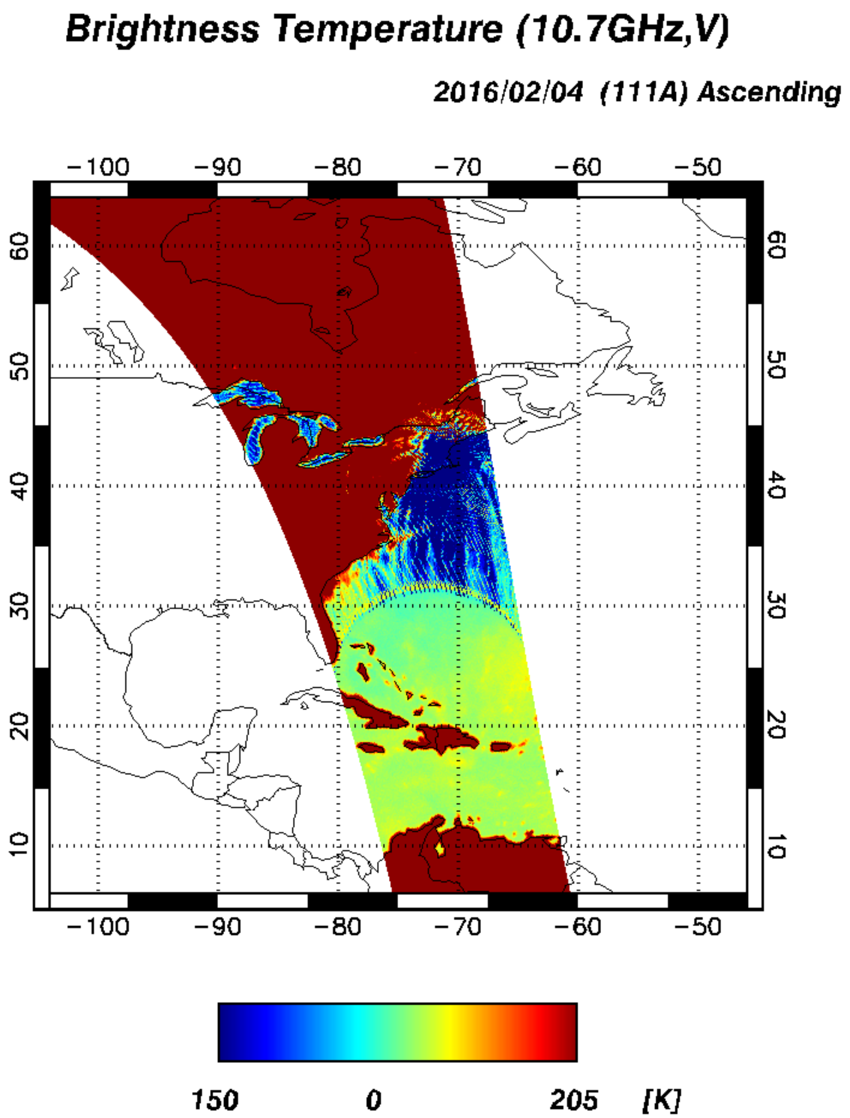


RFI sources:

1. Globalstar (satellite phone)
2. Ascension island(Ground-Satellite communication)
3. Japan, South-east Asia (ground-ground communication)

M. Seki, presented by M Kazumori at RFI workshop

Examples of current RFI shown by JMA (Japan) in C, X and K band



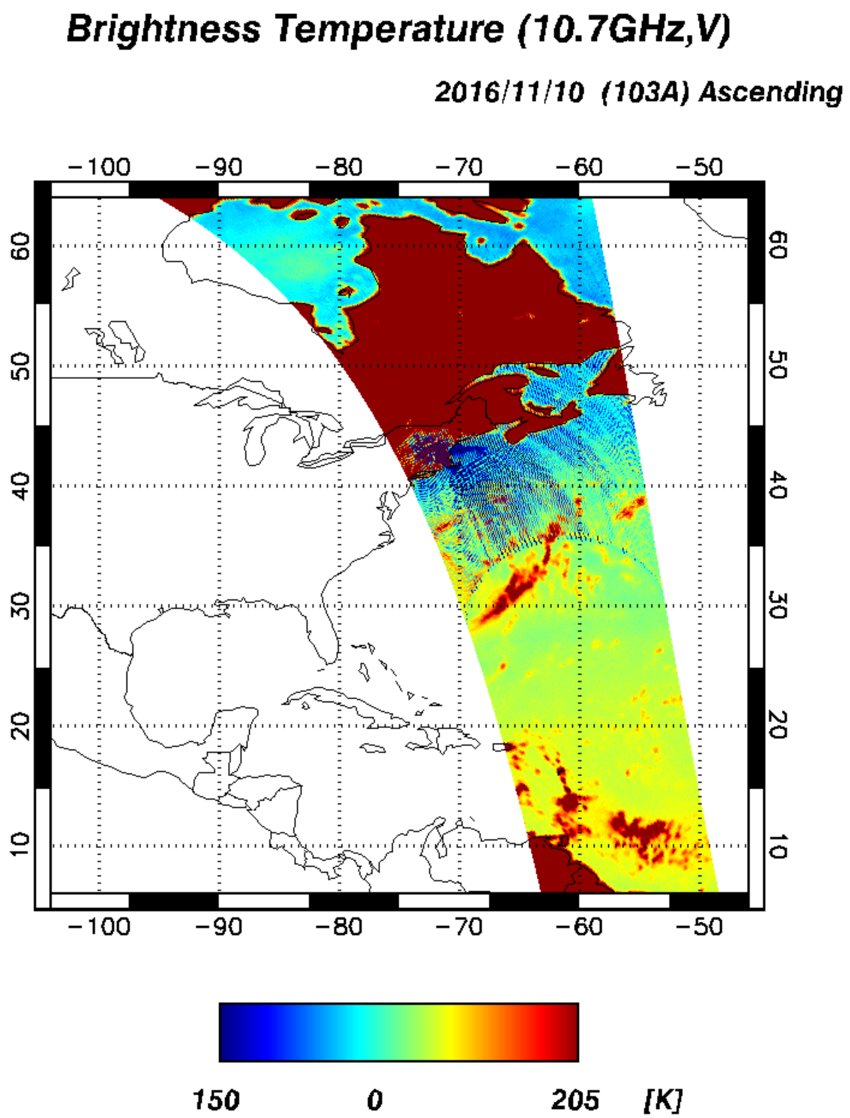


Figure from A. Shibata, JAXA

Conclusions

- All NWP centres report that passive and active microwave observations are the most important type of observation for weather prediction, providing **~40-50% of all forecast skill from observations**.
- This has been temporarily raised higher during the COVID-19 pandemic due to loss of aircraft observations – the space observing system remains robust.
- Exploitation is becoming more sophisticated: e.g. more use over land and sea ice.
- The loss of microwave alone would seriously degrade forecast capability, and the loss of multiple types would have a catastrophic impact.
- The socio-economic cost of degraded NWP capability is many billions per country per annum, loss of life and property, degraded military operations and also our quality of life.

The benefit of NWP can only be achieved with the continued and improved use of current spectrum allocation and the protection of these frequency resources from interference.