PROCEEDINGS OF SCIENCE

Impact of RFI on Numerical Weather Prediction and Climate Reanalysis

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The use of radio spectrum is well established for meteorological and climate observations. A number of discrete bands (centred on 1.413, 6.9, 10.7, 18.7, 23.8, 31.4, 36.5, 50.2-57.3, 89, 157, 166, 175-192 GHz) already provide unique information on soil moisture, sea and land surface temperature, atmospheric temperature, atmospheric water (in vapour, liquid and ice phases, including precipitation), marine near surface wind vectors, snow on the ground, sea ice and vegetation parameters. These observations are critical both the weather forecasts using Numerical Weather Prediction (NWP) on High Performance Computers, and for climate monitoring. In NWP passive and actively sensed observations using these bands provide over half of forecast error reduction. In the near future a number of bands will also provide more detailed information on ice clouds using bands above 200 GHz. There is a direct link between the availability of RFI-free spectrum in these bands and the major socio-economic benefits of NWP. The data assimilation systems used to initialise NWP weather forecasts are also now used for reanalysis of historical observations over long time periods, in a process known as reanalysis. Reanalysis therefore also depends critically on RFI-free spectrum in these bands and if RFI levels increase in future this may risk introducing spurious trends. RFI is already being detected in bands below 20 GHz, and there is particular concern over the lack of an allocation to Earth observation at C-band for passive ocean monitoring.

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1. Introduction

Weather forecasting beyond a few hours into the future relies on accurate computer simulations known as Numerical Weather Prediction (NWP). NWP in turn relies on millions of accurate observations to create the initial state for these computer projections. In the past these were primarily atmospheric weather observations and satellite measurements sensitive to weather parameters, but NWP now adopts an Earth System approach where observations of the Earth's surface (e.g. land, snow, sea ice, ocean) and atmospheric composition (e.g. ozone, aerosol) are equally important. Many of these observations rely on narrow, discrete spectral radio bands, each with unique properties, from 1.4 GHz to 190 GHz, with in the very near future additional bands up to 670 GHz. Many of these bands are afforded protection under footnote 5.340 of the Radio Regulations. However, as pressure grows on some of these bands, efforts both to demonstrate their value and to monitor the status of RFI are vital. This abstract will describe current approaches and results from NWP centres, and will highlight the need to further develop enhanced bespoke RFI monitoring. This direct link between spectrum management decisions and the direct impact, socially and economically, is shown in Figure 1.

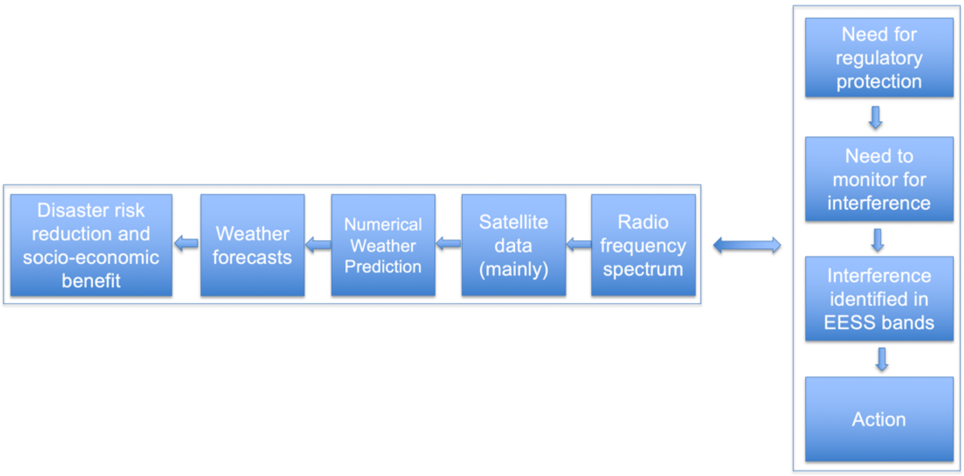

Figure 1: Relationship between spectrum management activities (right hand column) and socio-economic benefits of weather forecasting

2. Current value of bands

Figure 2 shows the latest contributions of different observation types at ECMWF to the skill of short-range weather forecasts through a technique known as Forecast Sensitivity Observation Impact, FSOI (Baker and Langland, 2004). Passive microwave observations account for around 36% of impact (labelled Microwave T and Microwave WV for temperature and water vapour sensitive observations in Figure 2 respectively). Active microwave observations contribute a further 17% of forecast error reduction (labelled GPSRO and scatterometer in Figure 2). So by this metric, at ECMWF in 2023, a total of 53% of the impact of observations on short range forecast skill came from microwave observations. Infrared satellite observations contribute around 18%, surface and aircraft data 13% and 10% respectively and feature tracking in satellite images around 7%. This shows very clearly how important microwave observations are to numerical weather prediction, and thus the high societal and economic benefit of these observations.

Discussions concerning bands generally consider one band at a time. But in practice operational systems need a set of bands to uniquely separate different signals, from changes in temperature, water vapour, liquid water, precipitation, and changes in the earth's surface. The simplest way to consider this is if you have ten unknown quantities, you need ten independent observations. If you lose one, then the problem becomes mathematically ill-posed. This is a simplification but gives a general idea. It is challenging to isolate the value and impact of a single band, as it's loss or degradation will impact the correct interpretation of other bands, making the analysis more dependent on other prior information to solve the ill-posed inversion. However, in the broadest terms the bands between 50 and 58 GHz and between 175 and 192 GHz are the most critical, because they provide three-dimensional temperature and humidity information respectively. However, bands close to 10, 18, 24, 31, 89 and 150 (or 166) GHz are critical to correctly allow for the impact of clouds and rain on the signals. The bands close to 1, 7, 10 and 18 and 31 GHz are also critical for allowing for changes in the earth's surface. The loss of any one band undermines the integrity of the system that delivers the impacts described in the previous paragraph.

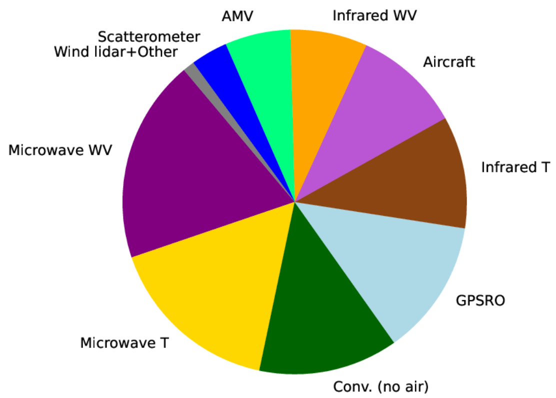

Figure 2. Current impact of main observing systems at ECMWF averaged over 2023.

The DA component of the NWP system is also used to produce a high-quality historical reanalysis datasets e.g. ERA-5 (Hersbach *et al*. 2020). Any impact of RFI on data used by reanalysis makes the assessment of climate trends more difficult especially if the level of RFI is changing with time. At the present time there is no evidence RFI is already impact reanalysis products. However, if there is a future increase in RFI in key bands, this could undermine their interpretation and our ability to accurately monitor climate change. This can occur both through sampling changes due to screening out some data and also the impact of undetected RFI.

3. Monitoring and detection

As shown in Weston and de Rosnay (2021) RFI screening of SMOS L-band data has been significantly improved in recent years but remains sub-optimal and fails to screen all SMOS observations which are affected by RFI (e.g. as shown for ocean observations in Figure 3). ECMWF was part of the ESA RFI4EO project led by Zenithal Blue Technologies aiming at using various statistical and pattern recognition algorithms (ground RFI detection system - GRDS) to improve the RFI screening (Oliva *et al.*, 2021). Results using a month of SMOS data indicated that the GRDS system demonstrates significant improvements.

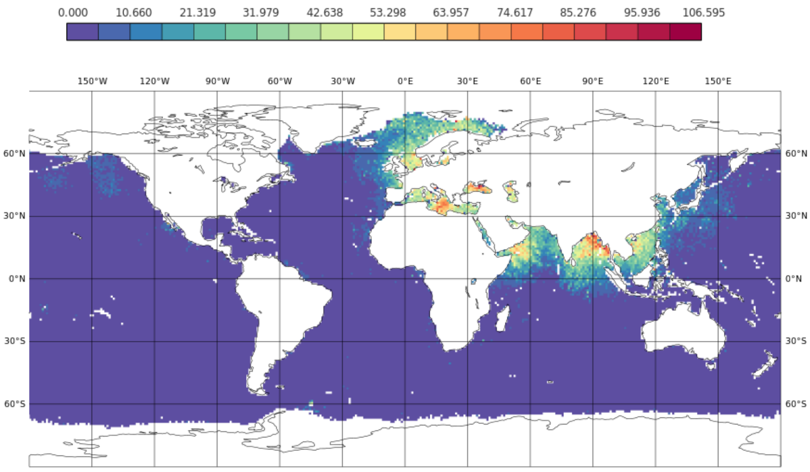

Figure 3. Impact of RFI on L-band (SMOS) 1.400-1.427 GHz in ECMWF NWP system shown as standard deviation of SMOS brightness temperature (in K), at 30 degrees incidence angle, x polarisation), before (left) and after (right) filtering, for land (top) and ocean surfaces (bottom), for April 2024.

3. Climate monitoring

Long term climate data records enable us to monitor and understand changes in the earth's climate. At a time of climate change the importance of this is clear. What may be less clear is the reliance on these data records on the same EESS bands that are needed by Numerical Weather Prediction. In addition to climate data records from individual observation types, climate monitoring is also achieved by combining different observations into a single long-term analysis using the same data assimilation systems now used for NWP. This is known as re-analysis and by using current data assimilation technology, this can extract more information from older observations than was possible at the time they were originally measured (Hersbach *et al.* 2020). Many parameters in this re-analysis are driven by Earth observations that rely on EESS bands. For example, sea ice relies on the availability of bands at 10.7, 18.7, 23.8 and 31.4 GHz. Sea surface temperature relies on the band at 6.9 GHz. Knowledge of total atmospheric content of water vapour and liquid water relies on the bands at 23.8 and 31.4 GHz. Atmospheric temperature relies in the bands between 50.2 and 57.3 GHz. Water vapour profile information relies on bands between 175 and 191 GHz. Knowledge of the total atmospheric content of water in ice clouds relies on EESS frequencies at 166 GHz, 175-191 GHz and above 200 GHz. These dependencies are described in the report generated by the ESSEO team at ESA (Soldo *et al.* 2023, English 2024).

If significant RFI occurs in any of these bands long term climate data records could be compromised. However, even the possibility that they might be means when a change is observed, the question has to be asked: is this climate change, or is this RFI?. If we examine recent trends in different parameters in the ERA-5 reanalysis we can see the expected climate change signals. For example in Figure 3a we see declining sea ice concentration, in Figure 3b we see rising SSTs and in Figure 3c we see rising global total water content. These long-term trends are clear. And as the bands that are needed for these parameters are currently mostly RFI-free, these trends can be trusted. However, as we move forward, these bands are at risk of RFI, and if RFI may be occuring comtinued trends may be questioned. For example, would we trust observations of the recent faster increase in global average SSTs (that is real and associated with the El Nino phenomena)?

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When SMOS, which observes at 1.4 GHz, was first launched, significant RFI was found. With time many of these sources were shut down (Oliva *et al*. 2016). Thus, in the raw data, there is an apparent trend, but when RFI impacted data is excluded, this trend disappears. This shows (in reverse) what could happen if undetected RFI begins to occur in other bands. In these other bands detection and removal of RFI impact observations may be more challenging than at L-band. So spurious trends may be misidentified as real trends. This is a particular concern already at 6.9 GHz, Figure 5, where comparisons of observed and modelled observations over both land and sea show a non-gaussian distribution with an excess of scenes where the observation is warmer than the model. It is very likely this is due to RFI. It is of high importance, to climate science as well as NWP, to ensure the long-term ability to monitor SST in cloudy areas.

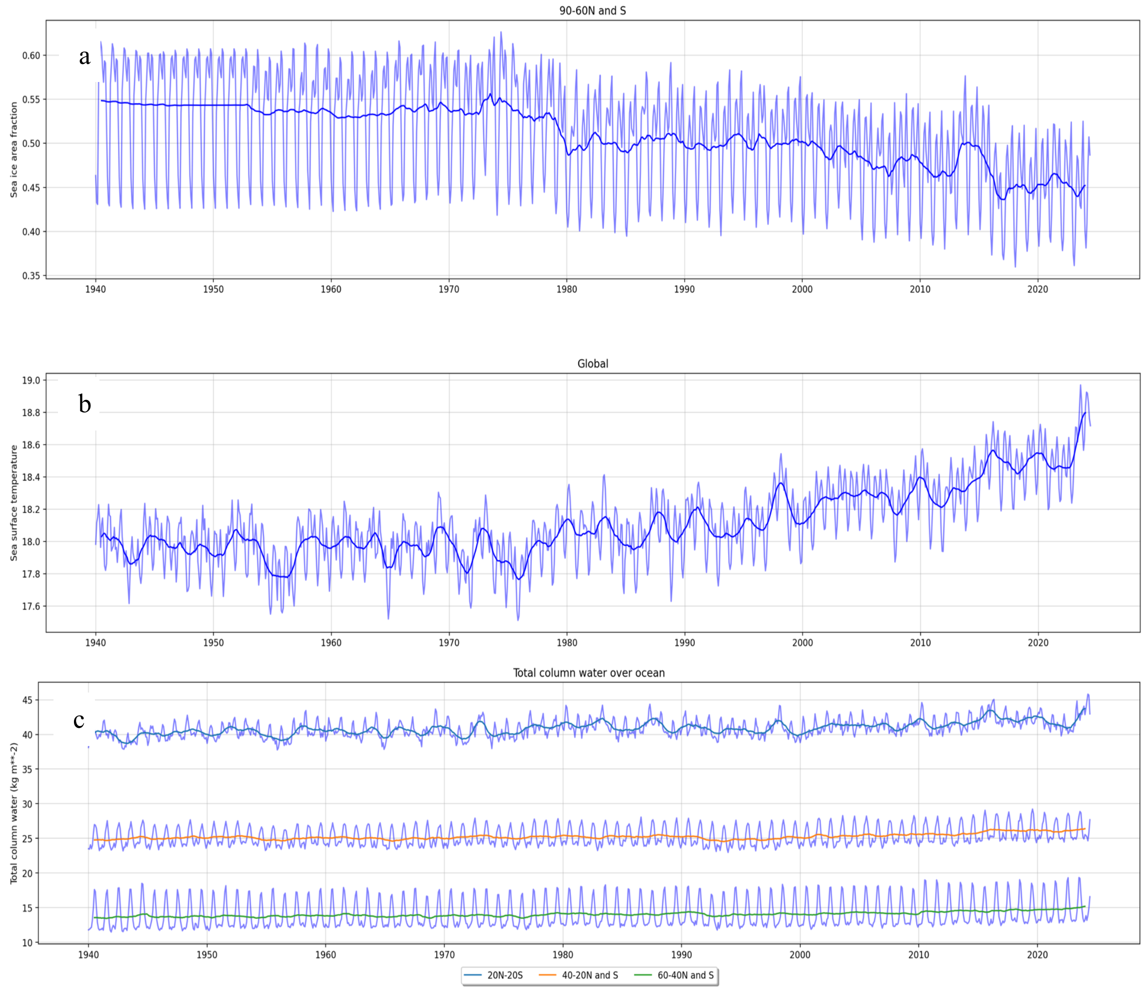

Figure 4: ERA-5 trends (1940-2024) in tropical, middle latitude and polar latitude bands for a) sea ice, b) SST and c) total column water vapour

4. Summary

Clean spectrum in critical bands underpins the performance of modern NWP systems, which in turn underpins the reliability and accuracy of warnings, resulting in saving of life and property, in addition to day-to-day socioeconomic benefits. This clean spectrum cannot be taken for granted

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and enhanced monitoring of interference is being developed. This is showing increased occurrence of RFI in bands below 20 GHz. Enhanced monitoring and on-flight filtering needs to be backed up by strong and effective regulation based on international agreement, at the World Radiocommunication Conferences.

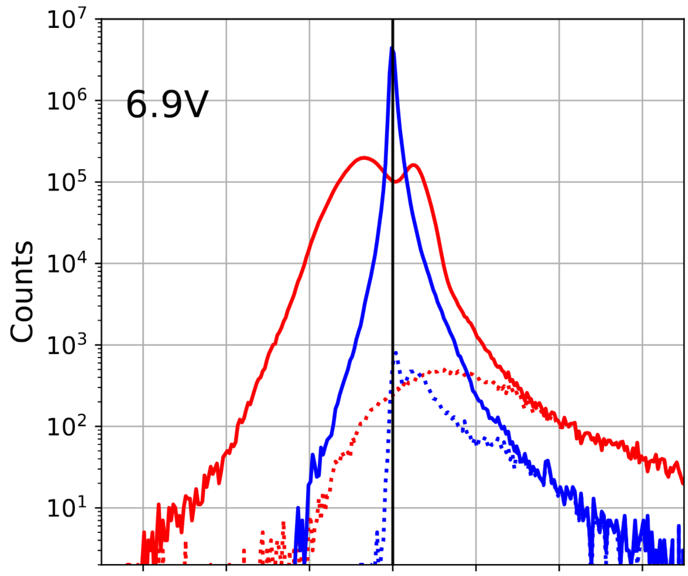

Figure 5: Difference between observed and modelled data at 6.9 GHz From Duncan and Bormann (2024).

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