Radio-Frequency Interference (RFI) Workshop

13 -14 September 2018

Final report:

Role and importance of microwave space based measurements in weather forecast/predictions and climate monitoring and their socio-economic benefits

ECMWF hosted a workshop in September 2018 on the role and value of microwave observations from space in Numerical Weather Prediction with the specific goal of providing detailed guidance on the potential socio-economic value of microwave bands allocated to the Earth Exploration Satellite Service (EESS). The Workshop was attended by scientists from the world's leading NWP centres (ECMWF (Europe), DWD (Germany), Météo France (France), Met Office (UK), NCEP & NRL (US), CMC (Canada), CMA (China), JMA (Japan), KIAPS (South Korea), BoM (Australia), Met.no (Norway)) and by frequency managers from the ITU, ESA, EUMETSAT, NOAA and the Met Office.

1 Introduction

International and national regulation governs the allocation of microwave spectrum for a range of purposes, including earth system science. Weather prediction and climate monitoring are two important sub disciplines. There are many competing and important application areas. For regulators to make an informed decision about frequency allocations, including maintaining existing allocations, they need up to date and well documented information of the economic and societal value of the remote sensing bands in different application areas.

Operational and research applications in meteorology, climate and hydrology have many measurement areas, and frequency bands used by passive microwave remote sensing instruments are allocated exclusively to this, covered by a specific provision in the ITU Radio Regulations (Footnote RR 5.340), with some more having a shared allocation with other radio-communication services.

Evidence of RFI in lower frequency bands is already considerable, notably on the AMSR-2 instrument, with examples at C, X and K bands being presented by JMA at the workshop, and on the SMOS and SMAP radiometers in L band. It is timely therefore to evaluate the value of existing bands to support the case for strong protection.

Periodically Numerical Weather Prediction (NWP) centres measure the value of all these data types in terms of forecast skill and results of these assessments are shared, for example through the WMO workshops on the Impact of Observations in NWP, organised by the WMO's Inter-Programme Expert Team on Observing System Design and Evolution (IPET-OSDE) and its Coordinators on Scientific Evaluation of Impact Studies (C-SEIS). The overall value of microwave observations in NWP is discussed in Section 3. However the additional steps to estimate individually the impact of specific bands is done less often; this discussion is presented in Section 5. Furthermore the critical step to turn impact on NWP forecast skill into economic and societal impact is rarely presented. This is important information to administration and frequency spectrum regulators and will be presented in Section 6. The vital role of global NWP in contributing to these services is confirmed, and the importance of microwave observations is quantified.

2 Description and principles of microwave remote sensing instruments and frequency bands used and their interrelation with instruments/measurements

Since the 1960s satellites have carried payloads with ever increasing sophistication. For the purposes of NWP, passive microwave sensors have emerged as the most important payload. They are now essential to support services critical to safety of life and property. They are also critical to other application areas such as climate monitoring and prediction, hydrology (e.g. floods) and in general are a key element of disaster management. Consequently, these observations underpin the performance of national warning systems based on NWP systems. A number of bands have emerged as critical to operational systems. They are listed in Table 1. Early instruments used other bands, but the observing system has been rationalised to use the minimum possible number of bands, each one selected playing a unique and indispensable role.

Frequency (GHz)	Instruments (Examples)	Application area
1.4-1.427P	SMOS (ESA), SMAP (NASA), Aquarius (NASA), CIMR (ESA) (future)	Soil moisture, salinity, thin sea ice
6.425-7.25s	AMSR-2 (JAXA), CIMR (ESA) (future)	SST
10.6-10.68p 10.68-10.7P	AMSR-2 (JAXA), GMI (NASA), MWRI (CMA), CIMR (ESA) (future)	Heavy Precipitation
18.6-18.8p	AMSR-2 (JAXA), GMI (NASA), AMR (NOAA), MWRI CMA)	Ocean near surface wind,
23.6-24P	AMSU-A (NOAA/EUMETSAT), ATMS (NOAA), SSMIS (DoD), GMI (NASA), AMR (NASA), MTVZA-GY (Roscosmos), MWRI (CMA)	Total column water vapour
31.3-31.5P 31.5-31.8p	AMSU-A (NOAA/EUMETSAT), ATMS (NOAA), GMI (NASA), MTVZA-GY (Roscosmos)	Total column cloud liquid
36-37p	SSMIS (DoD), GMI (NASA), AMSR-2 (JAXA), MWRI (CMA), CIMR (ESA) (future)	Liquid water path and cloud detection on GMI
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)	Temperature profile
86-92P	AMSU-A (NOAA/EUMETSAT), ATMS (NOAA), SSMIS (DoD), MWHS-2 (CMA), MTVZA-GY (Roscosmos), MWRI (CMA)	Precipitation
100-102P 109.5-111.8P 114.25-116P 116-122.25p	MWHS-2 (CMA)	Temperature profile, cloud
148.5-151.5P 155.5-158.5p 164-167P	ATMS (NOAA), GMI (NASA), MHS (EUMETSAT), MWHS-2 (CMA), MTVZA-GY (Roscosmos), SSMIS (DoD)	Precipitation, water vapour
174.8-182.0p 182.0-185.0P 185.0-190.0p 190.0-191.8P	MHS and MWS (EUMETSAT), ATMS (NASA), SSMIS (DOD), MWHS-2 (CMA), GMI (NASA), SAPHIR (CNES-ISRO)	Water vapour
200-209P 226-231.5P	MWS (EUMETSAT) (future)	Ice cloud

Table 1: Critical frequency bands for Numerical Weather Prediction. Protection levels: P = Exclusive passive use; p = Primary protection but shared with active users; s = secondary protection. Note that frequencies above 250 GHz are not considered here. Note that some older instruments use 22-22.4 and 19.2-19.6 GHz instead of 23.6-24 and 18.6-18.8 GHz]. Currently used instruments are also listed. Operational follow-on missions e.g. MWS, MWI are already confirmed It should be noted that in addition to these passive bands a number of active bands are used, notably at 5.3, 13.4, 13.6 13.8, 35.6, 35.8, 94.1 GHz. Note 6.425-7.25 GHz is only recognised in a footnote 5458.

Passive bands are determined based on the fundamental properties of the Earth and its atmosphere. No amount of engineering and funding can change these properties. In general atmospheric opacity is low at low frequency and increases at higher frequencies, due to water vapour absorption and also increased absorption and scattering by clouds and precipitation. Also there are bands where absorption by different gases is much higher, for example oxygen close to 60 GHz and water vapour close to 183 GHz. These frequencies arise from the rotational modes of these molecules and are fixed by the physics of the molecules. For such reason, these bands have always been protected, as they are a unique natural resource.

Below 10 GHz the atmosphere is almost completely transparent, even in the presence of clouds. Therefore, these low frequencies directly sense the planet’s surface. This creates opportunities not possible at higher frequencies, where the atmospheric absorption is non-negligible. At 1.4 GHz observations provide information about salinity and thin sea ice over oceans and soil moisture over land. At 6.8 GHz they provide the only “all weather” sea surface temperature information. At 10 GHz clouds and water vapour remain largely transparent, but heavy rain does attenuate, providing unique information about rainfall (other techniques are indirect). At 18 GHz the properties of sea water are such that emission becomes almost independent of the sea surface temperature, so the surface emission is primarily sensitive to the sea state and small waves, which can be related to near surface wind speed. At 22-24 GHz there is a weak water absorption line and by measuring this line we gain information on total column water vapour. At 31 GHz liquid water attenuates so passive observations provide information on the liquid water content of clouds. It is important to realise that although these are the primary sensitivities, all these channels are weakly sensitive to all the other parameters.

For example, 24 GHz is strongly sensitive to total column water vapour and weakly sensitive to cloud liquid water. 31 GHz is the opposite, strongly sensitive to cloud liquid water and weakly sensitive to water vapour. Only by using these channels together can we interpret physical properties correctly. Although we may refer to 24 GHz as a water vapour channel and 31 GHz as a cloud channel, in reality we should consider all these channels as a set where the loss of any one diminishes the value of the whole set.

At higher frequency we encounter the strong oxygen absorption band at 50-60 GHz. This is a remarkable spectral feature, enabling us to gain temperature profile information with very little impact from clouds and water vapour. The band extends to 70 GHz but the high frequency side is more affected by cloud and water vapour, so EESS use has always been limited to the low frequency side, between 50 and 62 GHz. Nonetheless the channels where the oxygen absorption is the weakest, between 50 and 54 GHz, do still have some sensitivity to cloud and water vapour, and rely on having the lower frequency channels, in particular 24 and 31 GHz, to account for the weak cloud and water vapour attenuation. Consequently these channels also depend on having the lower frequency channels available to maximise their value. The oxygen absorption between 50 and 60 GHz is composed of many individual oxygen absorption lines. The frequencies needed to provide temperature profile information exploit this to provide information at different heights: lowest where absorption is weakest, highest where absorption is strongest. Therefore a large number of channels is needed across this oxygen absorption spectral line complex to provide vertical profile information.

Above 60 GHz the most important spectral feature of interest is the water vapour line at 183 GHz. Similarly to the 50 GHz channels this spectral line is sampled progressively further from the centre to gain profile information. The effects of cloud are even stronger at 183 GHz than at 50 GHz so additional channels are needed to provide cloud information, in particular at 89 and 150 GHz, and in future also at 229 GHz.

There is also a separate 118 GHz oxygen absorption line. This line cannot provide the same quality of information on temperature as 50-60 GHz, because the spectral absorption line is narrower, which means the channels constructed to give profile information have a smaller bandwidth than at 50 GHz, so the observations have a higher noise level. Also, the effects of clouds are stronger than at 50 GHz. However because of the shorter wavelength, smaller fields of view can be achieved at 118 GHz, so it is of interest for small scale features having large amplitude. For example active and destructive tropical cyclones (hurricanes, typhoons) have a warm core above them, that can be sensed from space and gives important information about the development of these meteorological systems. This feature is small scale, but has a high amplitude, so a higher spatial resolution is useful, even if the measurement noise is also higher.

The bands where all emissions are prohibited under RR 5.340 are up to 275 GHz. New generation instruments are now being developed for launch in the 2020s using frequencies above 275 GHz, both for very detailed information about ice cloud and trace gases. From an NWP perspective, the interest is ice cloud. (e.g. the ICI instrument on the second generation European Polar System, Metop-SG) but capability is not considered here. However in the near future the requirements for bands above 275 GHz need to be more clearly outlined.

3 Importance of MW measurements in NWP

Weather forecasts now rely on NWP for forecast ranges more than a few hours into the future. Early warning systems rely on NWP. In turn NWP relies on accurate observational information when potentially high impact weather systems are in an early stage of development, providing advanced warning and time to take necessary action. Many warnings of weather hazards are now given for systems yet to develop, but which the NWP systems are skilful enough to predict their genesis. To achieve this requires very accurate initial conditions for the NWP model and also a very good knowledge of the associated uncertainty. This can only be achieved by a robust and varied global observing system with a large space-based component (required to give good observational coverage in remote areas). NWP centres use a large variety of observations, including traditional in situ measurements, such as from weather balloons, alongside many types of satellite data. These include microwave and infrared sounding and imaging systems, the latter also including visible light sensors, radio occultation, scatterometer, cloud and precipitation radars, and emerging technologies such as lidars.

Of all of these, microwave observations have the largest impact on the quality of the analyses (initial states) and forecasts, as will be discussed in more detail in Section 4. The reason for this is very simple and relates to the cloud issue discussed in Section 2. The microwave observations are able to provide information on temperature and water vapour in cloudy areas as they are only weakly affected by clouds, whereas the use of infrared sensors in these areas is very limited. It has been shown that areas where high impact weather systems are developing are often cloudy. So only techniques that can provide information in and below clouds can prevent NWP from missing the newly developing systems. Key microwave systems are the passive sounders, discussed in detail in

Section 2, plus L-band radio occultation from GNSS[1] signals provided by GPS, GLONASS, Galileo and BeiDou constellations, cloud and precipitation radar and scatterometers. Radio occultation measures the phase delay of GNSS signals and relates this quantity to density (refractivity) gradients to infer atmospheric information. This has proven very successful, though it is blind to some types of error structure and information at low levels of the atmosphere is relatively limited. However the number of radio occultation soundings remains rather low, around two to three thousand a day in 2018. As a result now and for the foreseeable future passive microwave sounder and imager data remain indispensable for modern NWP systems, and hence modern warning systems of high impact weather events.

NWP centres and governments worldwide have invested heavily to obtain these observations and to maximise their impact, realising major benefits discussed in more detail in later sections. They can provide information in and below cloud, but as discussed in Section 2 this does not mean they are unaffected by clouds. At ECMWF 20 years of research and development have led to a system known as “all-sky” data assimilation. From an accurate modelling of cloud effects on radiances, and by using all channels an analysis can be created that exploits their information even in the presence of clouds. This is particularly important for water vapour. Clear-sky only assimilation strategies have a tendency to produce analyses that are biased towards dry situations. Furthermore, moist meteorological features such as atmospheric rivers and hurricanes that are responsible for some of the most destructive weather-related events benefit significantly from water vapour observations.

It has been found that the value[2] of microwave humidity observations has increased from just a few percent of the total to over 20% of the total over the last decade, due to better observations and improved all-sky modelling and data assimilation. Independently the microwave temperature sounders also provide around 20% of all observation impact. A further 5-10% of all impact arises from active microwave observations e.g. radio occultation.

In historical terms satellite observations are still very new. Only 20 years ago they had very little impact in NWP systems; almost all impact came from in situ measurements. This has significantly changed over the last 20 years in which satellite observations became the most important element in NWP and this trend is continuing. Furthermore, every new generation of instruments provides more accurate and more complete observations. In Table 1 the large number and variety of these instruments was listed. For example comparing the European Metop satellites first and second generation we can note a huge increase in the accuracy and variety of microwave observations. It takes considerable research effort to fully exploit these observations, and this is on-going. The Metop first generation satellites currently provide the single biggest impact of any one observation source NWP centres have invested heavily in recent years has been to develop new capability that will allow a continued trend to ever fuller exploitation of these datasets and improvements arise every year in their impact. Furthermore the main motivation for the development of modern data assimilation approaches, such as 4D-Var, has been to make better use of satellite observations. This means we see an ever increasing accuracy of Numerical Weather Prediction systems, driven in part by the more complete use of microwave observations.

To summarise, modern state-of-the-art NWP relies heavily on microwave observations and this dependency will only increase in the coming years. In the next section results presented at the workshop are summarised, to gain a snapshot of the current impact of these observations at the NWP centres attending the workshop.

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[1] GNSS: Global Navigation Satellite Systems

[2] As defined by the metric of Langland and Baker (2004)

4 Impact assessment of loss of MW observations

During the workshop held at ECMWF on 13/14 September 2018, global and regional NWP centres assessed the present impact of the loss of passive microwave observations in their systems. All major national and international weather services with global NWP capabilities were represented, as well as some regional NWP centres, as listed in Section 1. The assessments were based on dedicated impact experiments in which the microwave observations were withheld over periods of several months, or on other diagnostics of the forecast influence of observations in the respective operational systems.

The systems from the various centres differ substantially in the choice of assimilation algorithm, in the assimilated data, and in their general sophistication on the use of observations. The wide representation therefore provided a unique overview of the state-of-the-art in the use of microwave observations at operational centres and highlighted the international progress and continuing development in the area. Participants emphasised that their assessments reflect current availability and quality of the microwave observations, as well as their current use of the data in NWP. Recent advances demonstrate that improvements in the use of the data are still being made, and research and development both in instrument technology as well as the data use will further increase the impact of observations in the microwave part of the spectrum in the future.

There was broad consensus that microwave observations overall are presently the leading satellite observing system for global NWP. While there were differences in the experiments or diagnostics provided and hence the magnitudes and details of some of the results, the findings for all centres were consistent in several main points:

- Passive microwave observations contribute around 30-40 % of the overall improvement of short-range forecast skill using the same metric discussed in the previous section2, and provide around 15-30 % of the total number observations assimilated.
- Withholding microwave observations results in the largest degradation of forecast skill, among a number of satellite observing systems considered, including hyperspectral infrared, GNSS-RO and satellite cloud drift wind observations. In the DWD system microwave data and cloud drift winds are tied for the largest impact.
- Over the Southern Hemisphere, microwave observations provide a larger impact than all conventional observations. In the Northern Hemisphere the benefit from microwave observations can be about as large as all conventional observations together in the summer, though conventional observations are most important in winter.

The degradation in the forecasts without microwave observations means a loss of average forecast skill of around 3-6 hours for most centres, for a 72 hour forecast. In other words, without microwave observations, the same level of forecast guidance could only be given 3-6 hours later than it is today. This means a significant loss of time to issue warnings, for instance in the case of severe weather events.

The impact of the loss of microwave data can also be assessed in terms of the years of progress lost in NWP. Forecast errors have been reduced steadily over the last decades, and in the ECMWF system the degradation from the loss of microwave observations would be equivalent to losing 2-4 years of this improvement. In other words, without microwave observations the quality of weather forecasts from ECMWF would only be as good as it was 2-4 years ago, with the largest degradations in areas of the globe where it is not practical to have dense networks of in situ observations, and consequently satellite data is most important. A study by ECMWF also illustrated the loss of resilience of the observing system that would result from the loss of microwave data. Indeed, when microwave observations are not present, the degradation from the loss of hyperspectral infrared observations is several times larger than when microwave observations are present. This shows that more generally observation outages, for instance due to interference or other reasons (e.g. communication problems or instrument anomalies), could have a much more detrimental effect, and hence forecast quality would be more variable. A consistent and reliable forecast quality is however the basis of reliable weather warnings and services.

The overall impact found for the global NWP systems was also reflected in the regional systems. Here, some NWP systems are run over specific limited areas to provide higher spatial resolution and detail for short-range weather forecasts. At the lateral boundaries of the limited area domain, these systems use forecasts from a global system to account for meteorological system developments in the wider area. A study by met.no has shown significant forecast degradation when microwave data is lost for the regional model as well as the global system that provides the lateral boundary conditions.

The above impact results only assess the impact of losing the microwave data for assimilation. Several centres pointed out that further benefits are achieved through feedback on development of forecast models. For instance, microwave observations have been used to identify and correct deficiencies in cloud parameterisations or the handling of stratospheric warming events. This results in additional benefits for forecast skill through improved forecast models, but these benefits are harder to quantify.

It needs to be stressed that this workshop was concerned with the requirements of operational weather forecasting. Climate monitoring and prediction have other requirements, and these are equally sensitive to errors introduced by RFI or can be, on occasion, even more sensitive to variations in the mean values. In broad terms the requirements of climate and other applications such as nowcasting, flood monitoring and prediction and air quality are similar to NWP, as the frequencies needed are dictated by the physics.

5 Impact assessment for individual channels

All spectral bands listed in Table 1 contribute to the overall forecast impact achieved with passive microwave satellite data (except for the channels beyond 200 GHz that are presently not available, but planned for future instruments). They do so through the varied and complementary information they provide on the Earth System, as outlined in section 2. The assessment of the impact of individual channels is difficult to do for the following reasons:

- The impact of a given channel is often reliant on the presence of other channels, and therefore the attribution of the impact to a single channel of a multi-channel instrument would be inappropriate;
- It is not practical to conduct experiments in which single channels or spectral bands are withheld for all the bands used, due to the huge computational cost;
- The different information on the Earth System provided by these observations mean that an inter-comparison of their impact on a particular aspect is not meaningful. This is because the different bands affect different, often complementary, aspects of the Earth System, involving different time-scales and with different relevance for a given application.

Nevertheless, the NWP centres represented at the workshop also gave an indication of the impact of individual bands or groups of channels on general tropospheric and stratospheric forecast skill. The assessment was based on experiments withholding selected instruments or on diagnostics estimating overall forecast error reduction. The following general points emerged from the individual studies:

- The 50-60 GHz temperature-sounding band provides the largest impact on tropospheric and stratospheric forecast skill for all centres. Successful use of the data relies on the availability of measurement data from channels around 23.8 and 31.4 GHz to identify contributions from clouds. Thus, the impact on the channels around 23.8 and 31.4 GHz is equally important and indispensable to exploit the 50-60 GHz temperature-sounding bands.

- Similarly large impact is obtained in the ECMWF system from the humidity-sounding observations around 183 GHz. This impact is larger in the ECMWF system than in any system from the other participating centres. This is because it is the only centre that uses these observations under all-sky conditions, rather than only in cloud-free or non-precipitating cloud situations. This gives very significant additional impact, including on wind through implicit tracing of humidity and cloud structures during the assimilation. Other centres also show clear benefit from the 183 GHz channels, albeit less than they gain from the 50-60 GHz channels. This is an example of recent advances in the use of satellite observations that have not yet been achieved at all centres. Successful use of the data relies on the presence of channels around 89 and 150 GHz to further characterise the contributions from clouds and the surface.

- Several centres achieve benefits from the channels around 18.6, 22/23, 31/37, 89, and 150 GHz through their sensitivity to clouds, total column water vapour, and ocean surface winds. Again the impact is largest for centres that use the data in all-sky conditions and allow feedbacks on cloud and dynamic variables in their systems (such as at ECMWF or NCEP). The full exploitation of these observations in NWP, including the wealth of surface information contained, is still in development.

In these experiments only the value through direct assimilation of these observations into the atmospheric analysis has been considered. A clear recommendation of the workshop is also to capture the impacts also on surface fields, in particular sea ice and sea surface temperature. Therefore further experiments which measure this effect are urgently required. In this context surface sensing channels, including 23.6-24 GHz will have an even larger impact than they do on the atmosphere. It is equally important to recognise that these observations, which are sometimes called interface observations because they are sensitive both to the Earth's surface and atmosphere, are of growing importance as atmospheric and surface data assimilation and prediction are until recently not coupled (i.e. are analysed independently). A major trend now is to couple these systems, and in this coupled environment so called "interface observations" will increase substantially in value. A good example is observations providing low level atmospheric wind information that can directly improve the analysis of the sea surface temperature, as the mixing in the top layers of the ocean is more accurately represented.

6 Socio-Economic benefit assessments (on different economic, public sectors)

As discussed above, satellite measurements in the microwave bands play the key backbone role for the high quality of weather forecasts achieved in current systems. A loss or degradation in the quality of microwave measurements will be directly harmful to the quality of the forecasts which are necessary for a wide range of economic activities as well as the safety of modern societies. The areas affected by a loss or degradation of microwave observations include:

- Daily weather forecast
- Flood and storm damage warning and mitigation, public safety
- Severe storm forecasts (including tornados, hurricane), public safety
- Transport and logistics by road and rail, shipping and particularly aviation

- Energy, including the large and increasing renewable energy contribution
- Agriculture
- Tourism
- Public health, including air quality monitoring and forecasts
- Climate change monitoring
- Diverse business applications (including e.g. building industry)
- Defense services and military operations, training and planning
- Providing early warning signs for famine over large scales
- Private households

The socio-economic benefits of weather services through the use of its forecasts in all these areas, although difficult to quantify, have been covered in several recent studies in many different countries worldwide ranging from Europe to the USA and also to developing countries, with efforts lead by the WMO on the development of objective techniques to quantify their true value. In this section figures for the financial benefits arising from Numerical Weather Forecasts in various countries will be presented where these are publicly available[3].

Services to the public sector include household access to forecasts and warnings to assist planning of events, trips and other activities and to minimize weather effects on property and health. Forecasts of weather help the public enjoy their environment when the weather is likely to be good and stay safe and comfortable when it is likely to be unfavourable. In extreme cases of flooding, heat waves, tornadoes, hurricanes, etc., weather warnings save lives as the public can only take action to avoid the hazard if they have been notified of its potential for occurrence. Extreme events such as flood and severe wind and snow storms lead to damage much of which can be mitigated with prior warning. Emergency and disaster response teams also benefit enormously from timely prior knowledge of a potential event. Storms, tornadoes, hurricanes and also snow storms, in particular, also lead to disruption of the land transport system leading to accidents, loss of services and reduction in trade. Much of this disruption can be mitigated against with the aid of good forecasts, e.g. through the provision and positioning materials such as grit-salt and road-clearing equipment.

It has been estimated through studies in the UK that public flood warnings saved £64m per year. One of the key inputs to the flood warning system is Met Office precipitation forecasts. Likewise, warnings of severe wind storm damage has been estimated to save £80m while savings arising from snow storm warnings is estimated at £100m. The total value of benefits to the UK economy alone from public service warnings is estimated to be £1.5bn per annum. The value of all US daily weather forecasts is about 109 USD/annum per household and 11.4 billion USD in total, while NOAA's

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[3] Unless specified otherwise source information taken from:

https://www.metoffice.gov.uk/binaries/content/assets/mohippo/pdf/c/a/pws_value_for_money_review_-_march_20151.pdf

https://public.wmo.int/en/media/news/socio-economic-benefits-of-weather-and-climate-services

https://www.metoffice.gov.uk/binaries/content/assets/mohippo/pdf/1/n/met_office_general_review_economic_summary.pdf

https://www.metoffice.gov.uk/about-us/what/pws/value forecasts, warnings and associated emergency responses during a typical hurricane season result in 3 billion USD benefit (Weiher, 2018).

Services to the defence sector come in the form of weather forecasts, weather warnings and tactical decision aids. The value of weather forecasts and general climate knowledge to military operations has also been well established since the pre-industrial era, but this value has grown dramatically since then with new factors necessary e.g. the ability to estimate fuel consumption and costs. Today the weather forecast is as important as ever particularly with airborne and naval operations. Tactical decision aids have been developed that link weather to infra-red visibility and radar ducting allowing the prediction of weather effects on sensors that allow operations in low-visibility conditions, if the weather is right. Defence customers are also interested in weather phenomena that are specific to the areas where they operate. For example, the potential for a haboob is much greater in an arid region than in the UK, so specialised advice is necessary when operating in Afghanistan, Syria or arid regions elsewhere.

The aviation sector shares some of the needs that the defence sector has with regards to forecasting weather. For take-off and landing, knowledge of wind speeds and their components along the runway are particularly important. The height of the cloud-base and sub-cloud visibility for is vitally important for landings without the assistance of flight instrumentation. Fog and snow accumulation are major issues for the operation of airports. Icing due to flying through super-cooled liquid water is a key hazard to aircraft that can be mitigated through up-to-date forecasting of the occurrence of such cloud types. The aviation sector is also very interested in flying at high altitude over and in cirrus anvils of storms and needs specific information about the height to which clouds penetrate into the atmosphere as well as the potential for engine icing while flying in such clouds. The total net direct benefits to the UK economy of national services to aviation have been found to be £400m per year in 2015 and may generally add 2% of economic value to this sector.

Likewise the transport sectors on land (road and rail) as well as on sea are reliant on forecasts both for safeguarding against extreme weather events as on an everyday basis for the time and energy efficient planning of shipping routes. A study in the relatively small country of Switzerland (Bade et al., 2011) arrived at an estimate of minimally 93-113M SFR/year benefit resulting from transport (traffic, aviation) applications due both to avoiding public expenses and through direct benefit to businesses.

Weather forecasts and warnings further add value to the economy due to their guidance to businesses in retail, agriculture, tourism, construction and energy sectors. Business in retail use forecasts to predict the demand of products from swimsuits and barbeques in summer to umbrellas and cold weather clothing in winter. The agriculture sector needs to know when soils are likely to be dry enough to justify the expense of irrigation and when the ideal times are to sow seeds, harvest crops and apply pesticides and fertilization. Construction firms need the weather forecast to assist with timing of roof and window repairs to avoid inclement conditions as well as to assist in planning for digging and other operations that are more difficult when soil is water-logged or frozen. The energy sector with its conversion towards renewable energies increasingly relies on precise forecasts, especially of winds and cloud, to manage and ensure the stability of networks and electrical energy supplies. A broad analysis of benefits of meteorological services done in Croatia (Leviäkangas et al. 2007) estimates that each year the benefit is around 27-39 M€ resulting from transport, building sector, energy production, and agricultural production. A Swiss study (Frei, 2010) resulted in a benefit of several hundreds of millions of Swiss Francs resulting from the sectors public households (54-362M SRF/annum), agriculture (around 42M SFR/annum) and water power energy (about 98M SFR/annum). The value of meteorological information services in Finland was estimated in 2009 (Leviäkangas und Hautula 2009) to around 262-285 M€/annum resulting from the sectors traffic (road, shipping, aviation), logistics, energy, agriculture, and building. Additionally, the study recognizes that this benefit can be increased substantially through provision of improved meteorological information.

A study in the USA (Weiher, 2018) estimates that US electricity providers save about 166 M$/annum through using 24-hour range forecasts. As the energy supply is the basis of all economic activities in modern societies and as this supply will to a very large proportion and increasingly rely on renewable energies, i.e. solar, water and wind, the importance of very accurate weather forecasts will be growing even more and become indispensable over the next decades.

The socio-economic benefits of weather and climate forecasts issued by Météo-France have been evaluated in 2018 by an independent firm («France stratégie») chosen by the Ministry of Ecology from the French government. Global figures reveal that socio-economic benefits range between 1 B€ and 2.5 B€ per year. The benefits take into account those coming from climate change adaptation that represent between 20% and 30% of the total figures. They have considered impacts on the most relevant sectors such as aviation (crash avoided, reduction in fuel consumption, reduction in delays for companies and passengers – global benefit around 95 M€ per year), agriculture (added value on yields – global benefit around 160 M€), general public (tourism and publicity – global benefit around 94 M€ per year), security of people and goods (heat waves, reduction in damages and losses from floods and cyclones – global benefit around 600 M€ per year), public transport (accident reduction during snow and black ice events, reduction in time delays during snow events – global benefit around 180 M€), military defence (optimisation of outdoor activities – global benefit 150 M€), energy (adequacy between production and demand – global benefit around 60 M€ per year), and research and development (improved knowledge on meteorology and climate – global benefit around 45 M€ per year). All the benefits are located over the French territories that encompass the national one in Europe and oversea territories in tropical regions (French Guyana, French Caribbean, La Réunion island, New Caledonia, French Polynesia).

From Day's Curve (Day 1970, used in many policy studies e.g. Hallgatte 2012), it is possible to assess the damage mitigation as a function of forecast lead time (to justify early warning systems). A 6-h warning time can reduce damage by 12% whereas a 12-h warning time can lead to a 24% reduction. A degradation in the quality of the NWP forecasts, preventing reliable early warnings can therefore be evaluated in terms of corresponding financial losses.

7 Conclusions

The workshop presentations showed consistently across all the main NWP centres that microwave observations are the most important, providing 30-40% of all forecast skill from observations. Further it was shown that the exploitation is becoming more sophisticated, being assimilated in all-weather conditions over both land and ocean surfaces. The loss of even one type of observation, in particular from passive microwave sensing instruments, has a significant impact on the forecast skills, and the loss of multiple types could have a catastrophic impact. In order to assess the socio-economic impact of degraded NWP capability, a number of studies were summarized. These employ different techniques and look at very different countries and economies, but all these studies conclude that there are huge weather forecast benefits to societies both in terms of public safety and also direct monetary economic benefits. As the quality of satellite data as well as the forecast systems themselves improve, this benefit will further increase. Likewise as societies grow, becoming increasingly information reliant, forecast information is gaining further importance in many sectors, especially as it is crucial for the safety of energy provision both now and in the future. It has been described how a loss in forecast skill caused by a degradation of the available observational data sets, in particular the satellite observations in the microwave bands, will have a large direct negative economic impact for countries worldwide affecting a vast range of sectors and businesses.

These various benefits of NWP to societies can only be achieved with the continued and improved use of current spectral allocation and the protection of these frequency resources from interference.

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