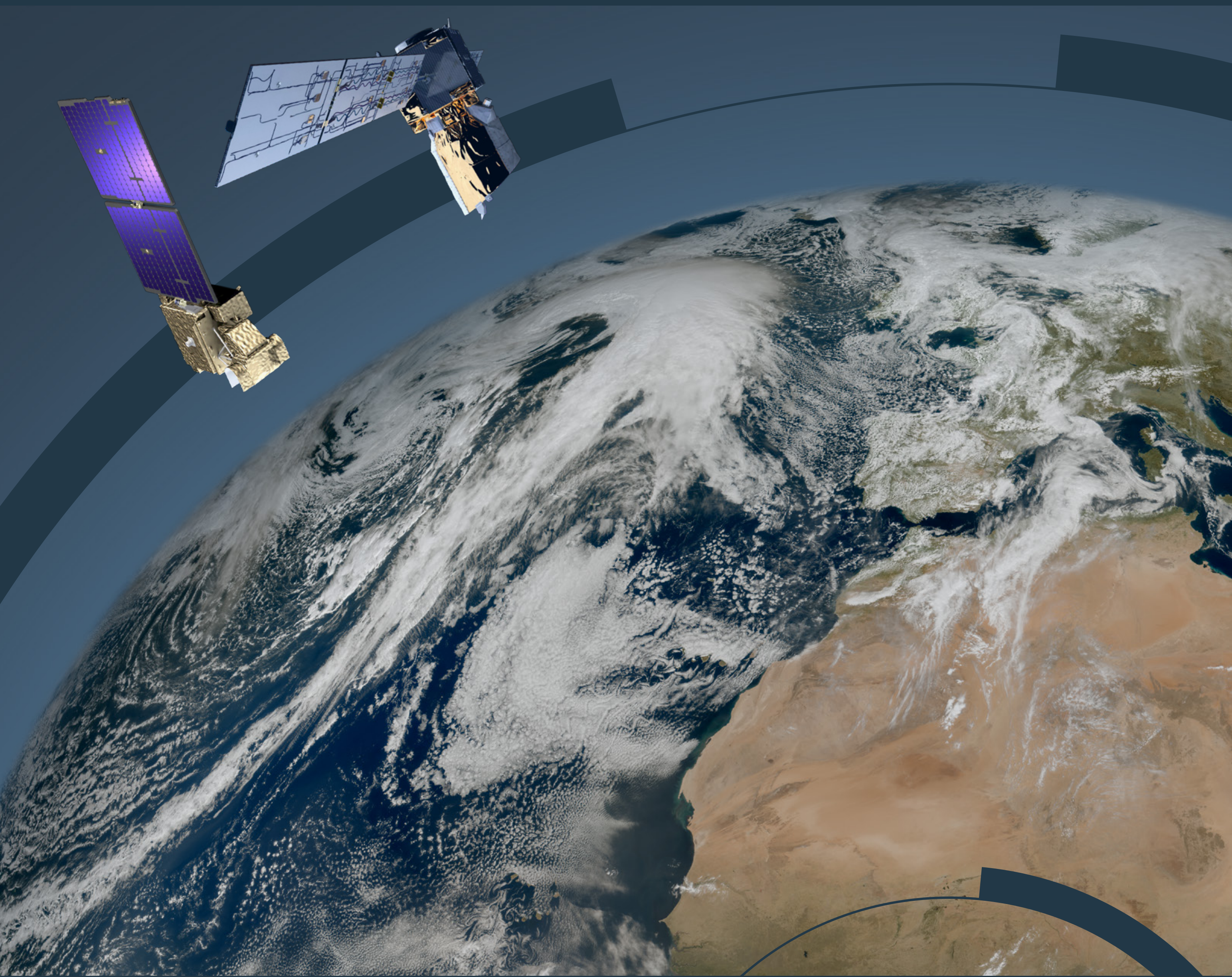
The social and economic benefits of EPS-Aeolus and EPS-Sterna

Full report

Monitoring weather and climate from space



The social and economic benefits of EPS-Aeolus and EPS-Sterna

Full report

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Executive summary

High impact weather and climate events have major economic and social impact on Europe – such events have cost European Economies over 600 billion Euros since 1980 and potentially cost 166,000 lives. Because of this, weather services in Europe contribute at least 53 billion Euros of economic benefits per annum. It is in this context the European Organisation for the Exploitation of Meteorological Satellites – EUMETSAT – is proposing two new additions to its satellite fleet to help Europe further mitigate these enormous impacts, significantly enhance the benefits of weather services and help protect lives. Both missions will provide and extension of its current European Polar Satellite Second Generation system: a Doppler wind LIDAR mission (EPS-Aeolus) and a constellation of microwave sounding micro-satellites (EPS-Sterna). These additions will deliver significant social and economic benefits to Member States through improved decision-making, based on more reliable weather and climate services. The purpose of this document is to provide an estimation of these benefits and to contrast such benefits with the estimated costs of the programmes.

The impacts of weather and climate affect every aspect of human activity. Weather and climate services have been shown to be among the most cost-effective adaptation measures, as global temperatures rise and extreme weather events become more frequent. These services deliver economic, social and environmental benefits across many sectors over a range of timescales – from short-term warnings of imminent danger to life and property, to the longer term projections of climate change essential for adaptation.

A growing library of studies has quantified substantial socio-economic benefits from weather and climate services. The benefits escalate as forecast accuracy and reliability improve, since better services lead to a greater reliance on those services by decision makers, across a wider range of applications.

This report has identified quantifiable benefits to EUMETSAT Member States of **52.8 billion Euros** annually (at 2024 e.c.). Benefits accrue from the use of weather services by governments, businesses and citizens to protect property and infrastructure and to improve decision making across a range of applications, including transport, energy, agriculture and water management. Whilst no quantitative assessment has been made of the wider social and economic benefits of saved lives and enhanced wellbeing, it is clear that forecast and warning information enables the saving of many hundreds of lives annually across EUMETSAT Member States.

Numerical weather prediction (NWP) systems provide the data upon which most weather forecasts are based. Advanced numerical methods are now available to evaluate in an objective and quantitative manner the level of impact of satellite data on the performance of NWP. It is thereby possible to estimate the socio-economic impact of specific satellite-based observations used by NWP systems.

The EPS-Aeolus Doppler LIDAR instrument will provide wind measurements globally, through the depth of the atmosphere from the surface up to at least 30 km. This is a unique capability not currently met by any other observing system. A less capable prototype has already been shown to improve forecast skill out to eight days ahead: it was the third most impactful space instrument and the most impactful source of wind observations over the ocean. Comprehensive impact studies by the European Centre for Medium-range Weather Forecasts (ECMWF) and Météo France have assessed that the enhanced capabilities of EPS-Aeolus will, on average, **reduce NWP forecast errors by 3%** across the Northern Hemisphere.

The EPS-Sterna microsatellite constellation will substantially increase the quantity and frequency of microwave sounding data available for both NWP and very-short-range ‘nowcasting’ applications. Impact studies have indicated that EPS-Sterna will **reduce NWP forecast error by 6%** on average over the territory of EUMETSAT Member States, and by 9% over the Arctic region. It will improve forecast skill for all basic weather variables, and enhance situational awareness of rapidly developing weather systems. The proposed constellation of three pairs of satellites on three equidistant orbital planes has been shown as the optimum configuration, outperforming a three-satellite constellation by 52%. The beneficial impacts delivered by EPS-Aeolus and EPS-Sterna will be largely independent and additive.

The reductions in forecast error will improve forecast accuracy, leading to more timely and effective decision making. More skilful forecasts will open up new applications for weather services, further increasing the benefits. The lifetime costs and quantifiable socio-economic benefits are summarised in the table below. Combined lifetime net present benefits amount to **44.2 billion Euros**, with a **benefit-to-cost ratio of 33**.

Executive summary

There are uncertainties implicit in this evaluation, and the methodology excludes some key benefit areas that are not amenable to quantitative analysis. Sensitivity analysis shows that even when applying the most cautious assumptions the benefits of the two systems still outweigh the costs 17 times.

EPS-Aeolus and EPS-Sterna will support cost effective adaptation measures to climate change, and deliver wider social and economic benefits through saved lives and enhanced wellbeing. Benefits are expected to increase over their operational lifetimes due to advances in NWP, the increasing frequency of high-impact weather events and growth in the weather and climate services market. Investing in these programmes will further promote Europe's leadership in earth observations from space, pioneering new approaches that will inspire other nations to follow.

	EPS-Aeolus	EPS-Sterna	EPS-Aeolus and EPS-Sterna
Operational lifetime	2032-2042	2029-2042	
Lifetime net present costs	688	641	1,329
Lifetime net present benefits	13,600	32,700	44,200
Benefit to cost ratio	20	51	33

Summary of lifetime net present costs, net present benefits (million Euros at 2024 e.c.) and benefit-to-cost ratios for EPS-Aeolus and EPS-Sterna.

Acknowledgements

The assistance of many contributors to the source material referenced in this report is gratefully acknowledged.

Section 2 draws on socio-economic benefit studies commissioned by the National Meteorological Services of member States, including Croatia, Finland, Switzerland and the United Kingdom. Economic and fatality statistics have been extracted from the EM-DAT International Disaster Database from the Centre for Research on the Epidemiology of Disasters; and the European Environment Agency's analysis of economic losses and fatalities from weather and climate-related events in Europe, which uses the RiskLayer's CATDAT and Munich Re's NatCatSERVICE databases.

We especially thank Alain Ratier, who led the writing of NWP skill impact assessments presented in Sections 3 and 5. This synthesis builds on the results of simulations and studies conducted by the German Weather Service (DWD), ECMWF, the Royal Dutch Meteorological Institute (KNMI), Météo-France, the Norwegian Meteorological Institute, the Met Office in the United Kingdom, the United States' National Oceanographic and Atmospheric Administration (NOAA), the Swedish Meteorological and Hydrological Institute (SMHI) and others, as well as presentations and discussions at two workshops co-organised by the European Space Agency (ESA) and EUMETSAT in 2022 and 2023. The ECMWF data used to assess the impacts of microwave soundings in June-November 2019 were provided by Michael Rennie.

Iterative discussions with Christophe Accadia (EUMETSAT), Philippe Chambon (Météo-France), Katie Lean (ECMWF), Gert-Jan Marseille (KNMI), Michael Rennie (ECMWF) and Bengt Rydberg (SMHI) were essential to compare study results and produce relevant figures.

Feedback from Member States following a presentation of preliminary results in September 2023 has also been most helpful in finalising the report.

1. Introduction

EUMETSAT proposes two additions to the EPS-SG[a] system: a Doppler wind LIDAR mission (EPS-Aeolus) and a constellation of microwave sounding microsatellites (EPS-Sterna). These additions will deliver significant social and economic benefits to Member States through improved decision making based on more skilful weather and climate services. This report presents an assessment of these benefits.

The impacts of weather and climate affect every aspect of human activity. Extreme weather events and their associated natural hazards and disasters are projected to become more frequent as global temperatures rise. The 2015 Paris Agreement of UNFCCC[b] recognised the urgent requirement for every government to invest in climate adaptation as a key component of the long-term global response to climate change, to protect people, livelihoods and ecosystems. Reliable weather and climate services are essential for informing effective climate adaptation.

Observations from meteorological satellites are crucial inputs for the generation of weather and climate services by the National Meteorological and Hydrological Services (NMHSs) of EUMETSAT Member States, supported by ECMWF and the World Meteorological Organisation (WMO). Sustained investment in satellite observations, drawing on the latest advances in space-based science and technology, is essential for NMHSs to strengthen resilience as weather and climate risks increase.

The social and economic benefits (SEBs) of weather and climate services derive from the impact of decisions that protect citizens, reduce loss and damage, improve organisational efficiency and safeguard wellbeing. Benefits accrue across a wide variety of sectors: from public safety and weather-sensitive operations such as aviation, surface transport, energy, agriculture, construction, retail and tourism; to strategic infrastructure planning for long-term climate resilience.

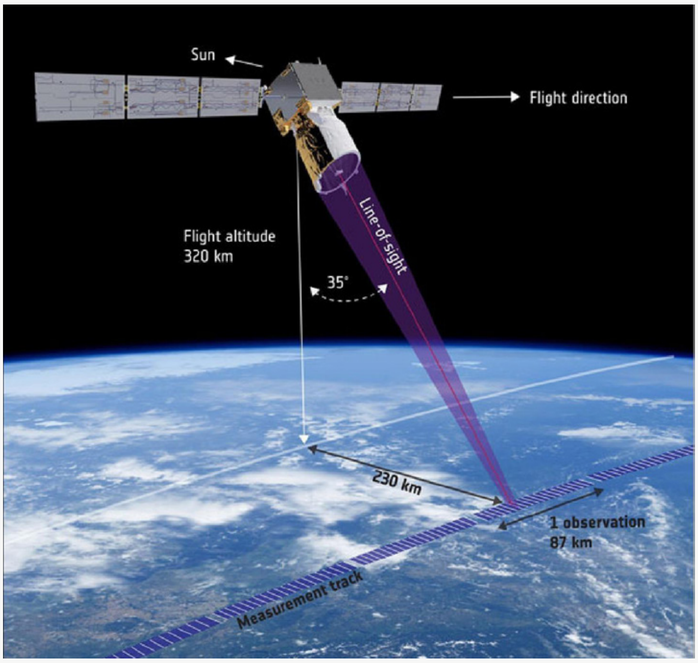


Figure 1.1. *Artist's impression of the Aeolus precursor mission. (Source: ESA)*

Whilst these benefits are difficult to assess in precise, quantitative terms, a growing library of studies has demonstrated that they are substantial, indicating benefit-to-cost ratios ranging from 2:1 to more than 36:1[1]. Furthermore, the value of SEBs escalates as accuracy and reliability improve: better services lead to a greater reliance by decision makers on those services across a wider range of applications[2].

[a] EUMETSAT Polar System – Second Generation

[b] United Nations Framework Convention on Climate Change

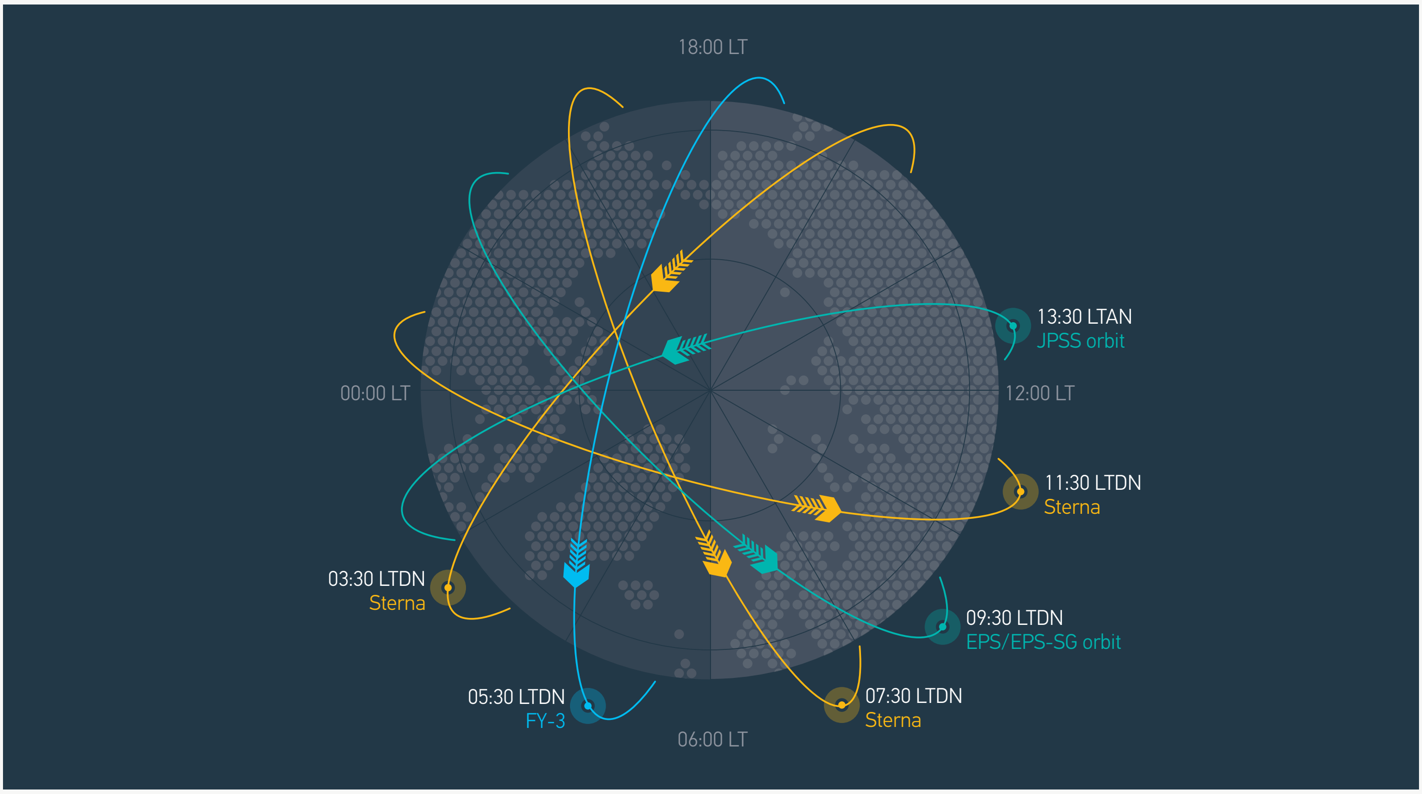


Figure 1.2. *Planned orbits for the EPS-Sterna constellation (in red). [LTDN: Local Time of Descending Node; LTAN: Local Time of Ascending Node]. (Source: EUMETSAT)*

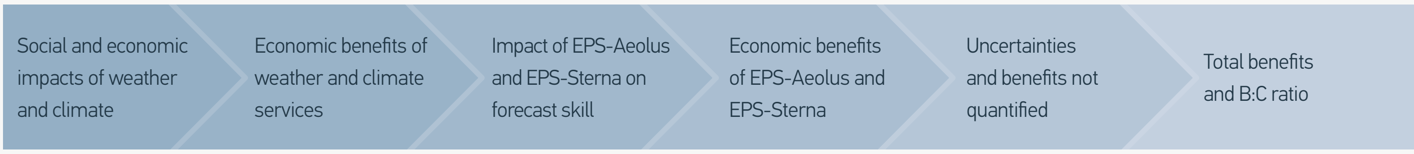


Figure 1.3. *Approach to the socio-economic benefit case.*

The incremental benefit from the addition of a specific satellite system may be quantified by assessing its impact on the accuracy and reliability of meteorological data, and then estimating the additional value that accrues from enhanced decision making. Global Numerical Weather Prediction (NWP) centres have developed methodologies for assessing the relative contributions to forecast skill from existing and proposed satellite data sources[3]. As a result, estimates of their respective contributions to the SEBs of weather services can be extracted.

Global meteorological satellite coverage is achieved through the co-operative contributions of many nations to the Integrated Global Observing System co-ordinated by WMO. In response to WMO's Vision for Observations Provision in 2040[4], EUMETSAT's strategy, Destination 2030[5], aims to consolidate its contribution to the realisation of this vision by exploring further contributions to the Global Observing System.

Two additions to the EPS-SG system are currently being assessed: a Doppler wind LIDAR[c] mission (EPS-Aeolus) that will improve NWP skill by adding a missing wind profiling capability to the EPS-SG system (Figure 1.1), and a constellation of microsatellites (EPS-Sterna) expanding the EPS-SG microwave sounding capacity, that will both increase NWP skill and provide more frequent soundings for nowcasting (Figure 1.2).

This report presents the benefit case for investment in these proposed additions (Figure 1.3), drawing on specially commissioned NWP impact studies and utilising established SEB assessment methodologies.

- Section 2 assesses the SEBs of weather services to Member States for key benefit areas where a quantitative estimation is, in general, feasible;
- Section 3 provides analyses of the projected contributions of EPS-Aeolus and EPS-Sterna to forecast skill;
- Section 4 overlays the analyses in Sections 2 and 3 to quantify the SEBs expected from each of the proposed additions;
- Section 5 considers the uncertainties implicit in the SEB valuation methodology, together with contributions to benefit areas that are not amenable to quantitative analysis; and
- Section 6 summarises the case for EPS-Aeolus and EPS-Sterna based on both quantitative and qualitative benefit assessments.

c *Laser imaging, detection, and ranging*

2. Social and economic benefits of weather and climate services

The benefits of weather and climate services have been assessed using established methodologies. The economic added value for EUMETSAT Member States is presented along with wider benefits of saved lives and enhanced wellbeing.

Weather and climate services deliver societal, economic, environmental and social benefits across many sectors over a range of timescales – from short-term warnings regarding imminent danger to life and property, to longer term projections of climate change that are essential for adaptation activities.

Economic benefits[6] can include:

- productivity and efficiency savings from the application of weather services to operational decision making;
- exceptional cost avoidance through weather and climate services supporting actions that would not be possible without such services;
- better policy decisions and regulation enabled by weather and climate services; and
- risk mitigation and wider benefits from the use of weather and climate services.

Further improvements in prediction capabilities generally deliver commensurate and measurable increases in the associated SEBs[7].

In order to provide an insight into these benefits, the usage and impact of weather and climate services are evaluated across a range of sectors, drawing on SEB assessments from published literature.

Full realisation of the potential benefits will only be achieved if improvements in prediction are translated into improved actions. Service users, whether public, private, individual, institutional and/or commercial, need to be enabled and encouraged to access and use weather forecasts for decision making to the fullest possible degree. To the extent that this is not yet fully achieved, this analysis may over-estimate benefits. However, this is likely more than offset by a financial approach that focuses primarily on short-term forecasting benefits, and does not seek to quantify wider wellbeing benefits or to assign an economic value to the significant number of lives saved. The overall value presented should, therefore, be taken as conservative – likely under-estimating the overall SEBs from improved weather and climate services.

For clarity, all monetary valuations quoted have been converted to Euros at 2024 economic conditions.

2.1. Safety of life and protection of property

Climate change is increasing the frequency and severity of extreme meteorological and hydrological events. Weather and climate services help to save lives and avoid costs by informing resilient design, and then by prompting timely actions before, during and in the aftermath of extreme events.

Short- to medium-range forecasts (up to two weeks ahead) enable preparations to be made for extreme events such as thunderstorms, windstorms, floods, forest fires, cold spells and heat waves. These forecasts then feed early warning systems which, when embedded within efficient civil protection policies and used by public and private operators, enable life and property to be protected in many ways.

On longer timescales, sub-seasonal to seasonal forecasts (up to six months ahead), based on probabilistic, coupled atmosphere-ocean prediction systems, can give early indications of increased likelihood of unusually wet, dry, warm or cold seasons. These enable contingency planners working within national and local governments and businesses to make risk-based decisions for the season ahead, ensuring that early preparations are in place in case of unseasonable conditions.

On multi-decadal timescales, climate services support long-term adaptation planning and infrastructure design that builds resilience to the increasing risks of the changing climate.

2.1.1. Safety of life

2023 is almost certain to be the warmest year on record globally, more than 1.4°C above the pre-industrial average temperature. During the year extreme heatwaves and droughts, exacerbated by climate change, caused thousands of additional deaths, with many more people losing their livelihoods and being displaced[8]. Such impacts will inevitably increase as temperatures continue to rise.

In Europe between 1970 and 2021, according to a recent WMO report, there were 1,784 disasters attributed to weather, climate and water extremes resulting in 166,492 deaths[9] (see Figure 2.1), with fatalities across EUMETSAT member States averaging 2,800 a year.

Heat waves led to the greatest loss of life – the 2003 heatwave alone accounting for between 50% and 75% of all fatalities from weather- and climate-related events in the last four decades[10]. In recent

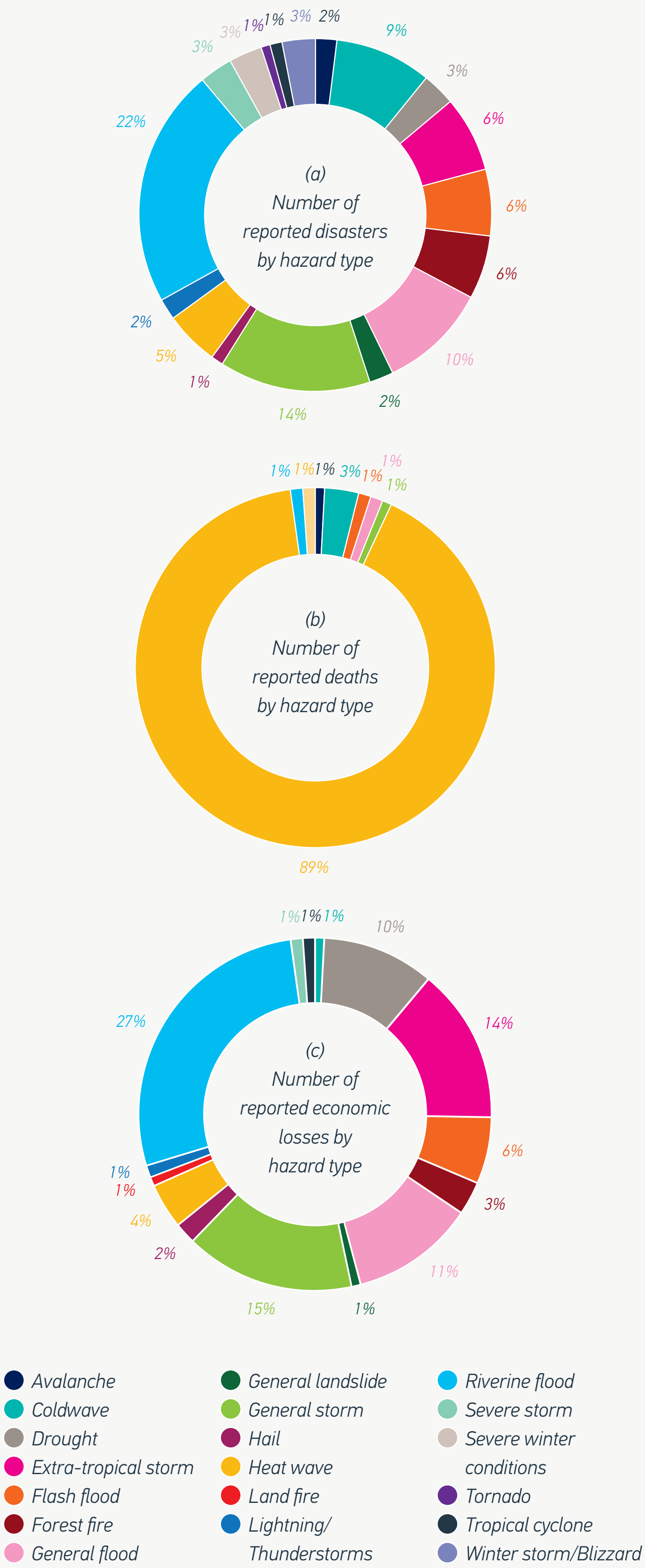


Figure 2.1. *Distribution of (a) number of disasters, (b) number of deaths and (c) economic losses by hazard in Europe (1970–2019). (Source: WMO Atlas of Mortality and Economic Losses from Weather, Climate and Water Extremes (2021))*

decades, the frequency and intensity of heat waves have increased across Europe due to climate change, representing a significant and growing risk to the health and wellbeing of populations. Other notable heatwaves occurred across France in 2006 and 2015, and in Western and Central Europe in 2022. In France alone, nearly 33,000 heat-related deaths were recorded between 2014 and 2022[11]. And whilst extreme cold weather is becoming less frequent, severe cold spells still present a significant risk to life – such as those in Northern and Eastern Europe in late winter 2012, and in Italy, Croatia and Turkey in January 2017. Exceptionally cold weather across much of Central and Western Europe in February and March 2018 led to dozens of fatalities, of which at least 27 were in Poland[12] and ten in the United Kingdom (UK)[13].

As global temperatures and sea levels rise, floods are increasing in frequency and severity. Between 1980 and 2013 the frequency of flood events in Germany and Central Europe increased by a factor of two[14]. Severe flooding occurred across Central Europe, including parts of Germany, Czechia, Austria, Switzerland, Slovakia, Poland and Hungary in June 2013; in the UK in the winter of 2013–14; in Calabria and Sardinia in Italy, Mallorca in Spain and parts of Southern France in October 2018; in the Black Sea region of Turkey in August 2021; and most recently in May 2023 in Italy, Croatia, Austria and Bosnia and Herzegovina leading to 15 fatalities[15]. In July 2021, exceptionally severe flooding in Germany and neighbouring countries resulted in over 200 people losing their lives[16]. Under a 2°C warming scenario, such an event as this would be up to 1.4 times more likely[17].

Severe winter storms often lead to fatalities. In February 2010 Storm Xynthia devastated coastal regions of Spain, Portugal and France. Strong gusts, huge waves and storm surges battered many coastal towns, spreading floods inland and destroying buildings. At least 50 people were reported to have lost their lives[18]. In October 2013 Storm Christian (the St Jude's Day Storm) swept across northern Europe causing at least 15 fatalities in France, UK, Netherlands, Germany and Denmark[19]. Storm Friederike led to the deaths of at least eight in Germany in January 2018. Storm Eunice resulted in 16 deaths in February 2022 in Netherlands, Poland, England, Germany, Belgium and Ireland;[20] and most recently Storm Ciarán led to at least 15 deaths in autumn 2023 in France, Germany, Netherlands, Belgium, Spain, Portugal and Italy[21].

In the Mediterranean region, rapidly rotating storm systems similar to hurricanes known as Medicanes occasionally occur, mostly in autumn and winter with a maximum in September. These are characterised by gale force winds, severe precipitation, thunderstorms and occasionally tornadoes, risking casualties and damage to property and infrastructure[22]. In November 2017 Cyclone Numa brought catastrophic flooding to Greece resulting in at least 15 deaths[23], and in October 2021 Cyclone Apollo struck Southern Italy, causing widespread flood damage and at least ten fatalities[24].

Tornadoes, waterspouts and lightning storms also present serious hazards, especially in Central and Southern Europe. Over 4,000 tornadoes were observed in EUMETSAT Member States between 1950 and 2015, most numerous in Italy, Turkey, Netherlands and Germany, resulting in at least 206 fatalities and 750 million Euros in damage[25]. Historical studies in Greece alone have documented at least 343 fatalities from lightning since 1895[26] and 29 fatalities from 612 tornadic events since 1709[27].

Avalanches caused over 1,000 deaths in EUMETSAT Member States in the ten years from 2012 to 2021, of which 268 were in France and 251 in Italy[28]. The Rigopiano avalanche in Italy in 2017 resulted in 29 fatalities[29], and at least 41 people were killed in two avalanches in Van Province in Turkey, in February 2020[30].

Forest fires, due to the combination of dry vegetation and wind, have also been devastating, mainly in southern Europe. Notable outbreaks occurred in Greece in 2018 and 2021, in Portugal in 2016 and 2017, in Turkey in 2020 and 2021 and in Greece in 2023. In June 2017, 64 people died in the deadliest fire in Portugal's history, as fires raged for five days in the Leiria region[31].

Due to severe heat waves in July 2018, wildfires spread through Greece, Latvia, and Sweden; in Greece, forest fires in the Attica area killed at least 92 people[32], making it Greece's worst natural disaster in over a decade, and further devastating wildfires hit Greece in July and August 2023, killing at least 29[33].

Whilst it is difficult to assess how many lives are saved by early warning systems each year across all EUMETSAT Member States, a World Bank study in 2012 estimated that hydro-meteorological information and early warning systems save several hundred lives per year across Europe, and that if such systems in all low- and middle-income countries globally were modernised to the level of Europe an additional 23,000 lives could be saved per year[34]. In the case of floods, the implementation of early warning systems globally between 2000 and 2017 contributed to a 45% reduction in mortality rate – from 6,025 deaths per year in 2000 to 3,331 deaths in 2017[35]. When warnings are issued, civil protection agencies, organisations and businesses enact safety measures including, in extreme cases, evacuation; and individuals implement their own mitigation actions, such as avoiding travel, erecting flood barriers and laying sandbags.

A review of the UK's Public Weather Service in 2015 suggested that modern forecast accuracy, dissemination of warnings and the resulting mitigating action save many tens of lives each year from direct impacts of the weather. In addition, for extreme events such as North Sea coastal flooding, hundreds of lives are potentially being saved, while excess deaths from heatwaves may be reduced by about 40 per event due to warnings[36].

As heatwave frequency increases, heat health alerts based on NMHS advice are gaining becoming an essential tool to protect citizens and minimise the impact of extreme heat. For example, during 2023 both the French[37] and UK[38] governments strengthened their prevention actions in advance of heatwaves through revised heat health alerting systems, with a greater emphasis on raising public awareness in advance.

In recent years the development of impact-based, people-centred, multi-hazard early warning systems[39] has further increased the impact of weather forecasts and warnings on public safety. This transformation in the way people receive, understand and act on information has led to an enormous escalation in the numbers of people evacuating in response to early warnings, saving many thousands of lives globally[40]. A key element of this transformation has been the building of close partnerships between NMHSs and civil resilience responders through integrated decision support services[41]. For example, in August 2017 the United States' National Weather Service's engagement with emergency managers as Hurricane Harvey approached the Texas Coast was credited with saving 'hundreds, if not thousands of lives'[42] in Galveston County alone.

A further key enabler has been the revolution in mobile communications over the past 20 years, enabling targeted warning messages to reach many more people, even in remote areas, so that there is a much greater awareness of the approach of weather-related hazards[43].

It is also important to stress that the benefits from weather and climate services depend largely, and non-linearly, on their accuracy, and that threshold effects are important. For example, the decision to evacuate due to a potential severe event cannot be made if the probability of false alarm is too high (or if the warning area is too large) as, after a few unnecessary evacuations, trust in the warning system will be lost, rendering it ineffective. Research on the response to tornado warnings in the United States of America (USA) – amongst the most deadly of extreme weather phenomena – confirms that the credibility people assign to information provided, based on their previous experience, directly impacts their decisions about how to respond when warnings are issued[44]. When forecast accuracy improves such that the chance of false alarms becomes low enough, significant prevention measures can be taken before disasters. Thus a limited improvement in forecast accuracy can lead to a disproportionately large increase in SEBs.

As well as warning of extremes, weather services also play an essential and growing role in ensuring safe operations in many sectors: most notably for transport on land, at sea and by air[45]. To observe appropriate levels of safety, these operations need detailed weather information and, in the absence of such information, it is unlikely that passenger travel would be safe enough to be commercially viable in its current form.

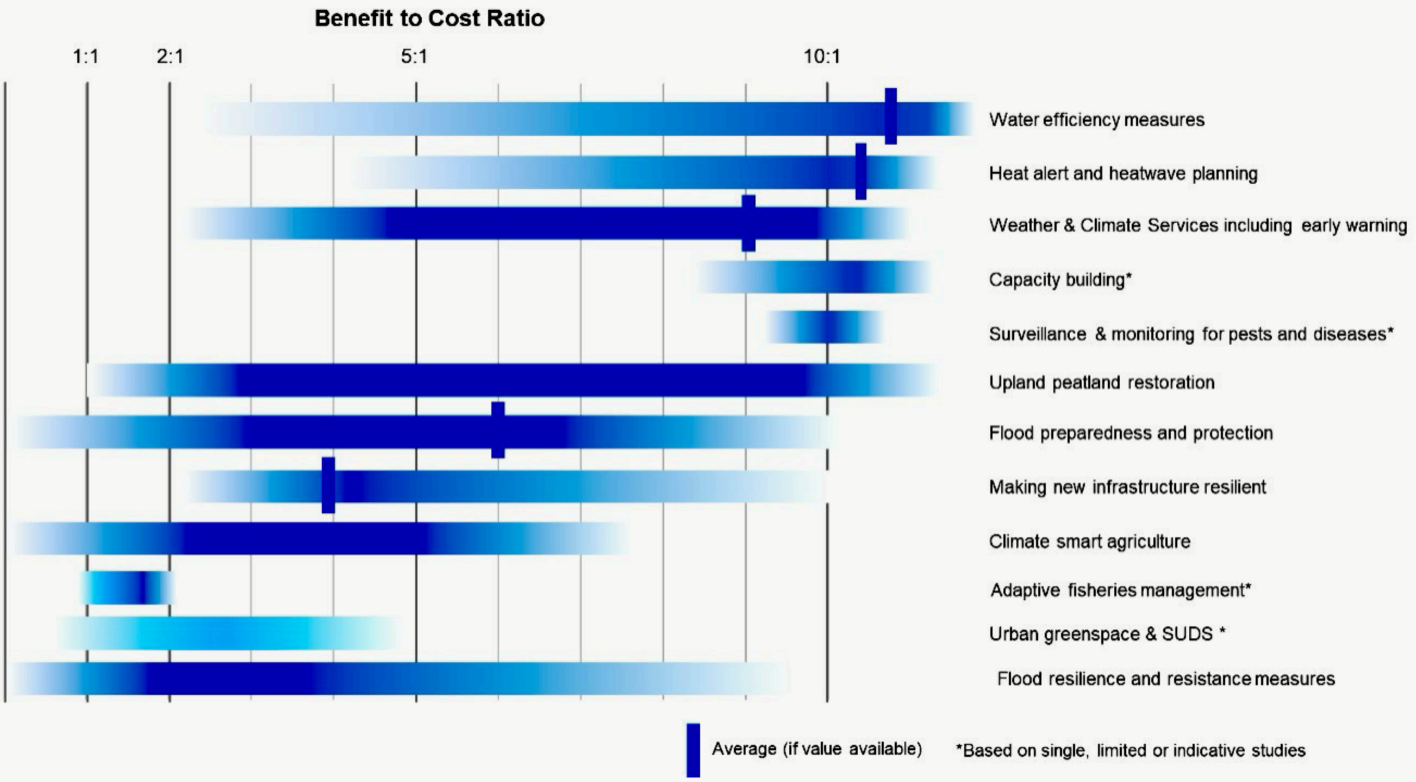


Figure 2.2. *Benefit-to-cost ratios for adaptation for selected UK climate change risk assessment risks. Among the most cost effective adaptation measures are (i) heat alert and heatwave planning and (ii) weather and climate services including early warnings. (Source: Watkiss et al. (2021))*

Other hazards also need to be considered, such as technological catastrophes (e.g. accidents in a chemical or nuclear plant), wind-borne pathogens and volcanic eruptions. In these cases, the capacity to forecast the wind, and thus the dispersion trajectory of the contaminant, can save hundreds of lives. Even in everyday life forecast information plays a large safety role for the public exposed to specific weather-related risks, such as those related to leisure activities in the sea (e.g. sailing, diving), in the mountains (e.g. hiking, skiing) or in the air (e.g. paragliding).

Although no comprehensive quantitative assessment is offered for the benefits associated with safety of life, it can be conservatively assumed, based on the figures available, that on a European scale, many hundreds of lives are saved annually by forecast and warning information. Although this study does not attribute an economic value to lives saved, this clearly represents a profound benefit for EUMETSAT Member States.

In addition to the saving of lives, access to reliable weather forecasts and warnings have been shown to bring substantial benefit to wider societal wellbeing, considering longer-term socio-economic factors such as poverty, health, education and livelihood productivity. The World Bank found that by providing universal access to improved weather forecasting and early warning, more than 27 billion Euros in additional benefits could be produced on average per year globally[46].

2.1.2. Protection of property and infrastructure

Between 1980 and 2020, total economic losses from weather- and climate-related events in the 30 EUMETSAT Member States amounted to 600–660 billion Euros. Between only one quarter and one third of these losses were insured[47]. The July 2021 flood disaster in Germany and Belgium caused some 44 billion Euros in economic loss – the costliest natural disaster for the region since 1970 and the world's second-highest in that period, after the 2011 Thailand flood. The previous month severe convective storms with thunderstorms, hail and tornadoes caused widespread damage to property throughout much of Europe. The resulting insured losses were estimated at 4.9 billion Euros.[48]

In 2022, natural disasters resulted in global economic losses in excess of 300 billion Euros, of which around 140 billion Euros were insured – well above the 10-year average of 89 billion Euros[49]. While the most costly event was Hurricane Ian, floods, hailstorms and similar perils caused over 55 billion Euros of insured losses[50]. In Europe, insured losses due to weather included 4.6 billion Euros from Storm Eunice in February and 20 billion Euros due to the drought between June and September[51]. The cost of natural disasters in France alone reached 11 billion Euros in 2022, a level not seen since 1999, the increase linked to 'the intensification of extreme climatic phenomena' and an 'increase in their frequency', according to France Assureurs[52]. Severe hailstorms in France in May and June 2022 resulted in insured losses of more than 5 billion Euros, exceeding the previous record set in 2014 by three to four times[53]. Similar losses were incurred in 2023 due to a series of prolific summer hail events across Italy, Germany, France and Croatia[54].

The rising cost of extremes is driving a marked increase in the price of insurance, as global reinsurers respond to the growth in claim payouts[55,56]. Swiss Re predicts that property losses from natural disasters due to climate change could increase more than 60% by 2040[57].

Weather and climate services help to limit such losses as far as possible. Early warnings save lives and provide substantial economic benefits. Just 24 hours' notice of an impending hazardous event can cut the ensuing damage by 30%[58]. A recent study by the Global Commission on Adaptation[59] concluded that early warning systems save assets worth at least ten times their cost. A 2015 study found that the Met Office's Public Weather Service in the UK saves over 200 million Euros in damage annually[60], contributing to an overall benefit-to-cost ratio of 14 for all Met Office services[61]; and a more recent report for the UK's Climate Change Committee ranked weather and climate services amongst the most cost effective adaptation measures against climate change risks, with benefit-to-cost ratios of around ten (Figure 2.2)[62].

Timely flood warnings enable a range of pre-emptive actions to reduce losses. A EU report found that that the operation of flexible flood defences in response to flood warnings reduces damage by 30%[63]. A study on the Elbe and Danube floods[64] showed that 31% of the population in flooded areas implemented preventative measures aimed at protecting property. These measures included moving goods to the second floor of buildings (implemented by more than 50% of the inhabitants who carried out prevention measures), moving vehicles outside the flood zone (more than 40%), protecting important documents and valuables (more than 30%), disconnecting electricity and gas supplies and unplugging electric appliances (more than 25%) and installation of water pumps (between 2% and 10%). Among the inhabitants who did not implement any mitigation measures, 65% said that they had been informed too late, and about 20% said that they were not at home and therefore could not do anything. For this part of the population, it would seem that an earlier warning would have allowed better preparation and therefore lower subsequent damage. This observation is supported by Day[65], who provides an explicit relationship between the ability to protect property and the warning lead-time.

There is also a large potential for businesses to take mitigation measures. The International Commission for the Protection of the Rhine has estimated that 50–75% of flood losses could be avoided with emergency preparation measures, such as moving machines and equipment to avoid damage and moving toxic materials to safe storage areas to prevent local pollution.[66]

According to Carsell[67], a warning issued 48 hours before a flood enables the overall damage to be reduced by more than 50%. Using European Environment Agency (EEA) data (1980–2020) the average annual cost of flood losses across all EUMETSAT Member States is 6.2 billion Euros per year[68]. If it is assumed that only half of these floods are correctly forecast 48 hours ahead, and that in these cases warnings are reducing losses by 50%, it can be shown that the theoretical losses in the absence of warnings services would be 8.3 billion Euros per year, and that the benefits from early warnings amount to 2.1 billion Euros per year. This is consistent with a European Commission Joint Research Centre study which concluded that flood early warning systems in Europe have the potential to reduce the costs of flood damages by an estimated 38 billion Euros over 20 years[69].

Using the same EEA dataset, the average annual cost (1980-2020) of storm damage across all EUMETSAT Member States (having the benefit of warning services) is 5.6 billion Euros and for other severe phenomena (forest fires, snow, heat waves, cold spells, etc.) is 3.5 billion Euros. If warnings are enabling losses from these hazards to be reduced by around one third through preventative actions similar to those taken for floods, the corresponding savings are 4.5 billion Euros per year.

This assessment is based on historical impact data, while weather-, climate- and water-related risks are increasing. Therefore the above total of **6.6 billion Euros per year** is considered to be a conservative valuation of the economic benefits to EUMETSAT Member States from the use of forecasts to protect property and infrastructure.

2.2. Added value to the economy

Weather and climate services are widely used by businesses to optimise their activities. This section seeks to quantify the benefits to EUMETSAT Member States of short-term weather services, for which EPS-Aeolus and EPS-Sterna are expected to have the greatest impact. In addition, there is a growing application of longer term weather outlooks, seasonal predictions and climate services across all industry sectors, for which the benefits have not been assessed.

In the transport sector forecast information is used to assist in air traffic management, maritime route planning, and rail and road network management. These are considered in more detail in Section 2.2.1.

Energy sector organisations use both historical and projected climatological data for strategic infrastructure planning. Forecast information is used to anticipate supply and demand as a function of weather conditions, as well as to adjust available production capacity and, if needed, purchase additional capacity at the most affordable price. Tailored warnings of adverse conditions assure the protection of weather sensitive operations. Energy industry benefits are considered in more detail in Section 2.2.2.

Farmers, foresters and the fishing industry make use of weather and climate services to make decisions on all timescales: they inform farming decisions on planting and harvesting dates, use of fertilisers and other inputs, irrigation, and on preventative measures in case

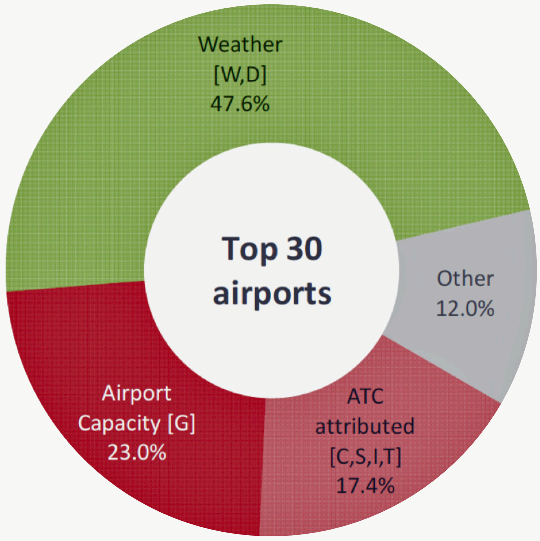


Figure 2.3. *Distribution of airport arrival air traffic flight management delay by attributed delay cause, 2019. (Source: EUROCONTROL (2020))*

of floods, frost or heavy precipitation. Agri-businesses also rely on meteorological information to forecast yield and production, and anticipate market conditions. Agricultural, forestry and fishing sector benefits are considered in more detail in Section 2.2.3.

Other sectors which benefit from weather and climate services include water management, the construction industry, retail, and leisure and tourism. In these and many other sectors, weather and climate services increase productivity. Their use is growing worldwide with many new specialised downstream businesses being created to assist in the tailored exploitation of weather information. Section 2.2.4 considers these broader benefits in more detail.

2.2.1. Transport sector

Aviation

In 2015 the European Commission's Aviation Strategy[70] valued the direct economic contribution of aviation to European Union (EU) Gross Domestic Product (GDP) at 140 billion Euros with an overall impact, including tourism, of 630 billion Euros. Jet fuel price increased by around 75% in 2022 and the International Air Transport Association (IATA) estimates that the 2023 global airline fuel bill will be close to 220 billion Euros, accounting for around 28% of operating expenses[71].

EUROCONTROL assessed the total economic cost of delays and cancellations due to 'all-causes' in 2017 at 17 billion Euros. This rose to 22 billion Euros in 2018, with approximately 350 million passenger flights impacted through delays or cancellations[72]. An analysis of delays in 2019[73] (the most recent year for reliable data pre-pandemic) attributes 21% of en-route delays and 48% of arrival air traffic delays to weather (Figures 2.3 and 2.4).

Accurate meteorological information is essential for efficient and safe operation of aviation, including airport operations, route planning, in-flight aircraft performance and air traffic management. Adverse weather poses risks to flight safety and is one of the main causes of flight delay and schedule disruption, while fuel-efficient route optimisation substantially reduces fuel usage. The civil aviation sector is therefore a major user of weather services, deriving a wide range of benefits to operational safety, efficiency and environmental impact: it is unlikely that the sector could exist in its current form without meteorological support.

Several studies have evaluated the economic benefits of meteorological services for aviation. The World Bank estimated that 11 billion Euros in aircraft fuel savings per annum can be attributed to weather forecasting globally[74]. The Met Office operates one of two World Area Forecast Centres for the International Civil Aviation Organisation, as well as providing local meteorological services for the UK and regional services over Europe. The annual economic benefit of these services to the UK was evaluated at nearly 1.4 billion Euros in 2015[75].

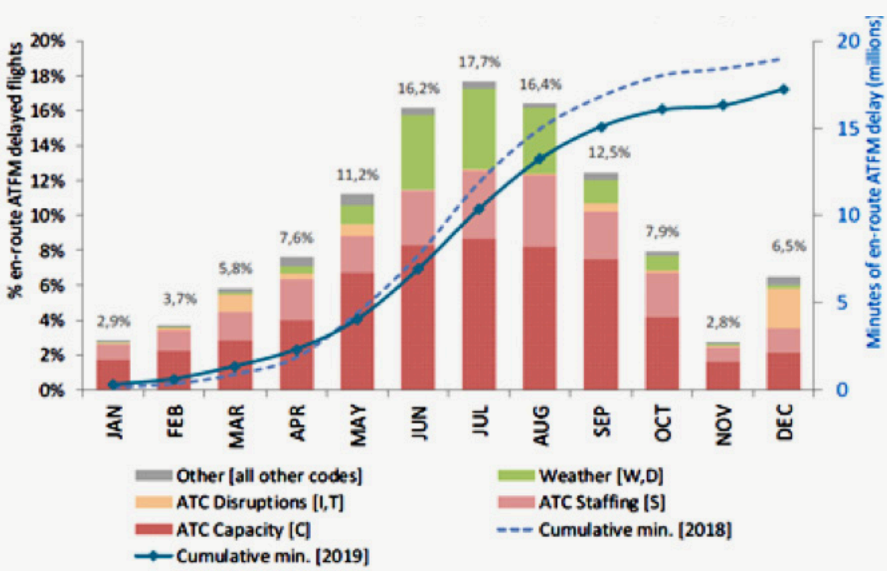


Figure 2.4. *Monthly evolution of European en-route air traffic flight management delay by attributed cause, 2019. (Source: EUROCONTROL (2020))*

Benefits of aviation weather services in Finland were evaluated at around 81 million Euros per year in 2008, through reduced accidents, more efficient operations, time saved by travellers and reduced emissions[76]. The economic value accrued by airlines from the provision of airfield forecasts at two main airports in Switzerland was estimated at 18 to 28 million Euros per annum in 2012[77]. All of these studies pre-dated the rise in oil prices since 2020, which will further multiply the economic benefits from meteorological services as long as prices remain high. Using the UK and Finnish analyses and scaling by GDP, a conservative estimate of the **annual economic benefit of aviation weather services to EUMETSAT Member States is 8.1 billion Euros**. The resultant improvements in fuel efficiency also have a beneficial impact on the carbon emissions of the aviation industry, contributing towards Europe's net zero goals.

Road transport

In 2021, the European road freight market was approximately 410 billion Euros, an increase of 27.5% compared to 2010[78]. An earlier report from 2007[79] estimated the total turnover of the EU road sector at almost 3,300 billion Euros, with 650 billion Euros of value added. Adverse weather, including snow, ice, floods and high winds causes delay and disruption to road transport with significant economic impacts.

Weather and climate services help road authorities and transport operators on all timescales – from road design and climate adaptation strategies through to warnings of severe weather for proactive traffic management. The World Bank has identified 12 billion Euros in annual potential benefits to road transportation from weather forecasting globally[80]; the costs avoided through use of forecasts for winter transport in the UK have been assessed at 190 million Euros[81]; and in Switzerland the benefits from winter road services have been quantified at 85 million Euros[82]. Applying the World Bank's methodology, and taking into account variations in winter climate across Europe, gives an **estimated benefit from winter road services of 3.4 billion Euros** to EUMETSAT Member States. This aligns very closely with an EU-funded study that found annual benefits amounting to 3.5 billion Euros[83].

Rail transport

The rail sector similarly benefits from weather and climate services for strategic and operational planning and risk management. The same EU study found **annual benefits of 65–170 million Euros** from travel time saved due to weather services.

Shipping

European shipping directly contributed 65 billion Euros to the EU's GDP[84] in 2018. Taking into account the spill-over effects onto other sectors such as supply chain and worker spending impacts, the total contribution stands at 180 billion Euros. The industry directly employs 685,000 people, and supports up to two million jobs when including the impact on other sectors. Similarly to aviation, the main economic benefits of weather and wave forecasting for shipping are reduced fuel consumption due to improved routing – by around 5% globally, according to the World Bank[85]. Based on a bunker fuel price of 472 Euros per tonne, their 2021 study estimated an annual global benefit from forecasts of 9.4 billion Euros, of which approximately 15%[86] would accrue to Europe. Using the November 2023 Rotterdam fuel price of 611 Euros per tonne, it is estimated that the economic benefits to EUMETSAT Member States of weather services for ship routing are **1.6 billion Euros per year**.

2.2.2. Energy sector

The energy sector includes exploration, extraction, and transportation of oil, gas and nuclear materials, along with energy generation (both renewable and non-renewable) and transmission. Energy risks are now amongst the highest concerns for both businesses and the public in Europe and these, along with geopolitical factors, are likely to accelerate the transition to a low-carbon economy[87]. Electricity demand is projected to triple by 2050 as sectors electrify and hydrogen and hydrogen-based fuels increase their market share. Weather and climate increasingly pose both opportunities and risks for the energy industry, with renewable generation projected to reach 80–90% of the global energy mix by 2050, as global build rates for solar and wind grow by a factor of five and eight respectively[88]. Nuclear generation will continue to make a substantial contribution, with its dependency on adequate supplies of water for cooling. To respond effectively, decision-makers require accurate and reliable information on weather and climate on all timescales.

As electricity and gas storage capacity are limited, a balance between supply and demand has to be maintained at all times. Extreme events such as windstorms, floods and droughts can have dramatic consequences on the production capacity of a country – or even at continental scale for the largest weather phenomena. But normal day-to-day weather variations also have impacts on supply and demand, and on pricing. On the demand side, air temperature and wind are normally the most important factors, as cold conditions imply heating, and warm conditions imply cooling.

In winter In France, for example, at temperatures below 15°C a fall of 1°C leads to an increase of the order of 2,400 megawatts of consumption (approximately 3%). In Great Britain a 1 °C daily temperature drop typically gives a ~1% increase in daily electricity demand and a 3-4% increase in gas demand, while the 1 in 20 year peak day electricity demand is 15% and the gas demand is 46% above their winter day average. In summer, rising temperatures and the increasing use of air conditioning are driving up energy demand for space cooling faster than for any other energy service in

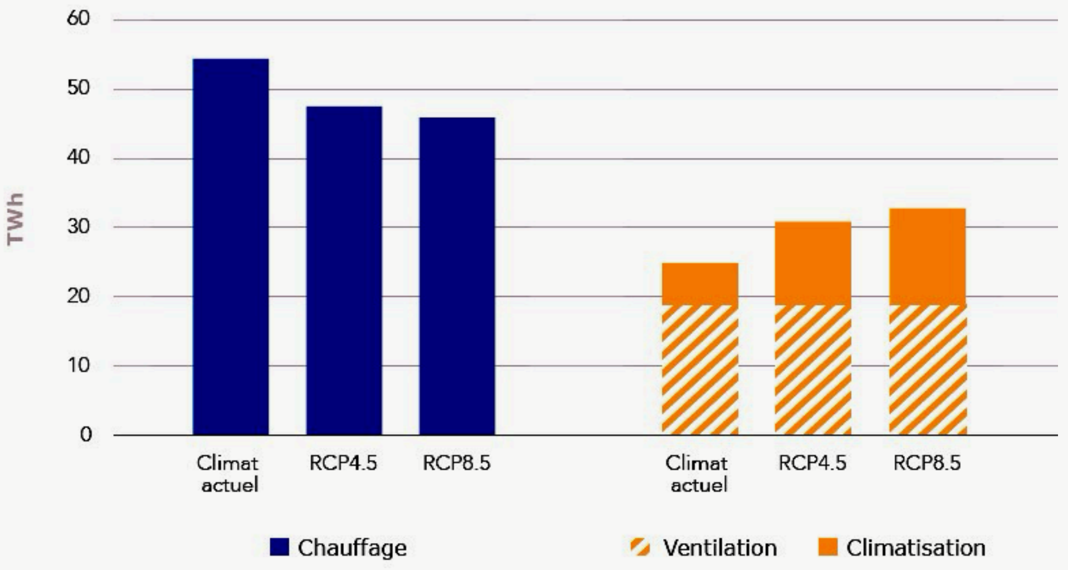


Figure 2.5. *Annual electricity consumption in France due to heating in winter (left) and to ventilation (hatched) and air conditioning in summer (right), in the current climate and in two different IPCC scenarios. (Source: Réseau de Transport d'Electricité (2022))*

buildings (Figure 2.5). Global demand increased three-fold between 1990 and 2016 and cooling now accounts for about 20% of the total electricity use in buildings worldwide:[89] in France, electricity demand for air conditioning is expected to double by 2050.[90]

On the supply side, nuclear energy generation is highly dependent on the availability and temperature of water used for cooling, while renewable electricity generation is highly weather-sensitive: hydro-power is dependent on precipitation (water and snow) and temperature (which controls snow-melt in spring), while wind and solar energy production fluctuate in accordance with atmospheric conditions. As the contribution of renewable energy increases, so does the challenge of maintaining supply through variable weather conditions. Shifting away from thermal power plants as the main providers of electricity makes power systems more complex. Multiple services are needed to maintain a consistent electricity supply. In addition to supplying enough energy, the challenges include meeting peak capacity requirements, keeping the power system stable during short-term disturbances, and having enough flexibility to ramp up and down in response to changes in supply or demand. Technological solutions, such as energy storage, will provide some limited contribution, but better demand forecasting will be essential for the further development and optimum use of renewable energy sources.[91]

A number of studies have sought to quantify the benefits of weather and climate services to the energy sector[92], but none provides a comprehensive assessment. The World Bank estimated the annual global benefits of weather forecasting to the electricity industry to be at least 34 billion Euros[93]. Scaling this by GDP would give a benefit of 7.5 billion Euros per year to EUMETSAT Member States. Benefits to fossil fuel exploration and production have not been quantified, but are likely to be substantial, especially for offshore operations.

2.2.3. Agriculture, forestry and fishing

The value added by agriculture, forestry and fishing in 2022 global was 4,900 billion Euros, and in the EU was more than 250 billion Euros[94]. 20–80% of the inter-annual variability of crop yields globally is associated with weather phenomena and 5–10% of national agricultural production losses are associated with climate variability[95]. The European summer drought of 2022 alone resulted in crop losses estimated at 6.6 billion Euros, of which only 0.6 billion Euros was insured[96].

The global demand for food will increase by 50% and, in the absence of ambitious climate action, yields may decline by up to 30% by 2050[97]. In the area of agriculture and food security, 85% of countries surveyed in 2019 identified climate services as being foundational for planning and decision making[98].

The agricultural sector is a major driver of climate change, as well as being seriously affected by it. Within Europe, policy efforts are therefore geared to climate mitigation in agriculture, while making the sector more robust and minimising climate change impacts[99]. This should include effective use of weather and climate services across all decision timescales. In recent years seasonal and sub-seasonal forecasts have become more skilful across parts of Europe, and are particularly applicable to agriculture, enabling farmers to better adapt decisions to upcoming weather conditions.

Several studies have attempted to quantify the value of weather services to this complex and widely variable sector. The economic benefits of the Bureau of Meteorology's agriculture services in Australia have been assessed at 1.3 billion Euros per year[100]. In Finland, where agricultural cultivation is limited, the benefits of the Finnish Meteorological Institute's (FMI) services have been valued at 51 million Euros[101] (see also box below), while the services of the

Croatian Meteorological and Hydrological Service for agriculture in Croatia have been valued at 7 to 15 million Euros[102].

Globally, the World Bank[103] quantified 41 billion Euros in annual potential benefits to agriculture, forestry and fishing due to weather services[d]. Whilst there are wide variations in circumstance across the world, scaling this estimate by GDP and assuming effective application of these services in Europe would suggest a **benefit of the order of 8.5 billion Euros per year** to EUMETSAT Member States – a value broadly consistent with the Finnish, Croatian and Australian valuations above.

2.2.4. Other sectors

The weather and climate can affect almost all aspects of economic activity. As forecasts become more accurate and reliable, there is a growing application of weather and climate services to decision making on all timescales.

Water management authorities rely on weather and climate services to inform catchment management, demand forecasting, waste water management and environmental protection. Weather forecasting gives economic benefits globally of 5.6 billion Euros per year, according to the World Bank[104]. Assuming a similar level of benefits in Europe, scaling by GDP indicates an **annual benefit to EUMETSAT members states of 1.2 billion Euros**.

The construction industry is highly weather sensitive, so uses weather and climate services to anticipate and mitigate conditions that can add significant cost and time to projects. With a turnover across the EU of around 2 billion Euros[105], the benefits from weather and climate services are substantial. The World Bank estimates an annual global benefit from weather forecasts of 1.2 billion Euros[106]; scaling by GDP indicates a **benefit to EUMETSAT members states of 260 million Euros per year**.

The weather can have a significant impact on **retailer and supplier performance and buyer behaviour**: it can influence footfall, sales and product availability, and impact the whole supply chain. Weather and climate services improve decision making at all stages of the supply chain, assuring supply, improving productivity and efficiency and reducing waste. The economic benefits of the Bureau of Meteorology's services to the retail sector in Australia have been valued at 16 million Euros[107] per year. Assuming a similar level of benefits in Europe, scaling by GDP indicates an **annual benefit to EUMETSAT members states of 210 million Euros**.

Travel and tourism contributed over 2,300 billion Euros to European GDP in 2019[108]. Businesses use weather and climate services for strategic and operational planning: from major investment decisions to anticipating customer numbers day-by-day and adjusting their resources accordingly. The economic benefits of such services to Australia have been valued at 18 million Euros per year[109]. Assuming a similar level of benefits in Europe, scaling by GDP indicates an **annual benefit to EUMETSAT members states of 240 million Euros**.

The Overseas Development Institute and World Bank[110] have identified a wide range of benefits from improved disaster risk management, some of which were not considered in the above assessments, such as increased capital investment, fiscal stability and reduced future credit risks, and ecosystem-based co-benefits. These, as well as the many other sectors and sub-sectors known to benefit from weather and climate services, are not quantified here. It is assumed that the under-estimation of benefits due to these omissions, as well as a lack of quantification of potential lives saved, offsets any over-estimation of the financial benefits due to sub-optimal use of weather forecasts by decision makers[111].

d *Adjusted to avoid double-counting of benefits quantified in Section 2.1.2.*

Social and economic benefits of EPS-Sterna at high latitudes

FMI has undertaken a meteorological and economic study of the foreseeable effects of EPS-Sterna for weather forecasts at high latitudes and the consequent SEBs for Nordic countries[112].

Differential economic benefits can accrue where advances in forecasting relate to:

- improvements in timing – giving a user more time to prepare and decide, and also more opportunities to update if information frequency is high;
- reduction in the variability of the accuracy, implying reduced risk of regret for the user; and
- improvements in spatial and temporal resolution – enabling more precise optimisation of operations while avoiding unnecessary precautionary measures.

The most relevant improvement in relation to EPS-Sterna at high latitudes is expected to be enabling the provision of forecasts of equal quality earlier, thereby increasing the lead time to conditions of interest. The study looked in particular at whether this increased lead time would reach threshold levels with respect to specific operational decisions resulting in significantly increased value, within three sectors that already make extensive use of weather and climate services:

- civil aviation;
- wind power production; and
- winter road clearing & salting.

Civil Aviation

Adverse weather is a significant source of flight delays, especially in systems that operate close to maximum capacity and during winter. More accurate and frequent forecast information can reduce cost and loss through optimised functions and operations.

The study looked specifically at the de-icing of aircraft in winter – a costly and time consuming process where accurate weather information is of particular value. It is clear that earlier, reliable weather information would help de-icing management and all stakeholders to optimise their operations, delivering benefits in terms of safety, operational efficiency, cost reduction, environmental impact, resource saving and regulatory compliance.

Electricity production

In Nordic countries, weather conditions affect both the production and consumption of electricity. Wind speed and solar radiation have immediate impacts on power production; precipitation affects hydropower with a time lag; while snow and ice have immediate and, to a varying extent, lasting effects on wind and solar energy.

When considering improvements to weather forecast accuracy in relation to wind energy it is important to note that the propagation of meteorological accuracy improvements runs via compound effects on the wind power production forecast, and is therefore supplemented by the effects of other generation and consumption forecasts.

Winter road maintenance

The salting of roads to prevent ice formation is essential across all Nordic countries to maintain transportation links during the winter months. Decisions on timing, location and quantity of treatment depend on accurate weather information, to ensure roads are safe while avoiding unnecessary expense and minimising environmental impact. The time window for interpreting meteorological information is limited – road maintenance mainly takes place before dawn and in the evening after rush hour – so improving the timeliness and accuracy of forecasts can have a big impact, especially when working close to 0°C.

Satellite products are an essential tool for operational decision makers, but interpreting these products is often difficult, so would benefit from EPS-Sterna's more frequent high-resolution data. Post-processed products are increasingly utilised to identify cloud characteristics, and EPS-Sterna's higher temporal and spatial resolution would improve the identification of cloud breaks (leading to sudden temperature fall) and of areas with potential for freezing drizzle.

Quantifying the benefits

The study estimates cumulative lifetime benefits from improved decision making in European aviation de-icing and Nordic energy supply due to EPS-Sterna of 250 to 510 million Euros. Benefits are also expected across other sectors, including construction (about 1 million Euros per year in Finland), tourism and urban operational management.

2.3. Value to individual citizens

Many individual citizens use weather information and advice on a daily basis to help with planning and decision making (Figure 2.6).

Quantifying the value to citizens typically involves assessing the willingness of users to pay for this service, either directly or through taxation. Whilst this approach fails to capture downstream consumer surplus or social benefits (lives saved and the value of life for family and friends), it does provide an established rationale for assessing one of the key benefits from public weather services, which has been used in the USA, the UK and Australia.[113]

In 2014 EUMETSAT estimated the public willingness-to-pay across Member States at 20 Euros (minimum) and 80 Euros (likely) per household per year[114]. Adjusting for inflation to 2024 gives a total willingness-to-pay valuation across all EUMETSAT Member States of 6 billion Euros (minimum) and 26 billion Euros (likely). This study has assumed a conservative figure of **15 billion Euros per year**.

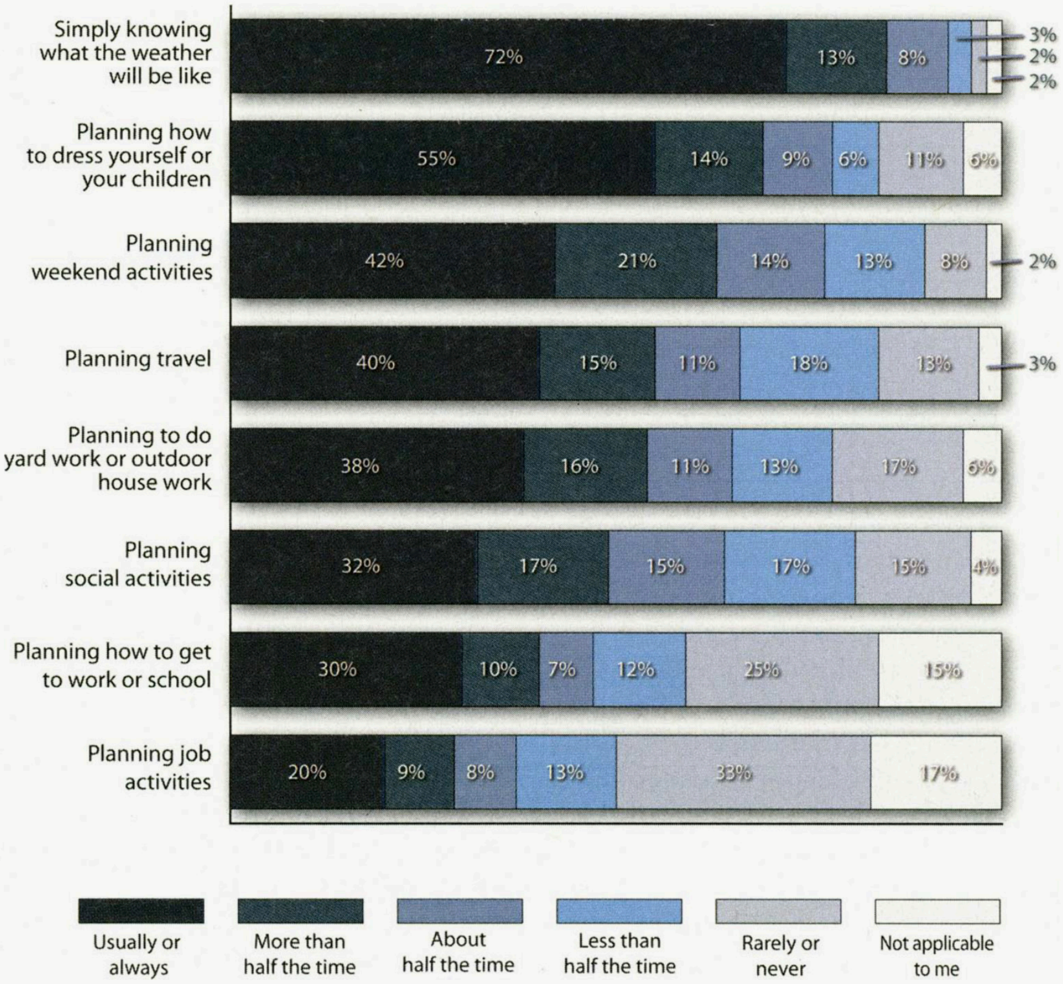


Figure 2.6 *Respondents' rating of importance for different potential components of weather forecasts. The survey question asked 1,465 United States' citizens "How important is it to you to have the information listed below as part of a weather forecast?". (Source: Lazo et al (2009))*

2.4. Summary of social and economic benefits

Weather and climate services have been shown to be among the most cost effective adaptation measures to climate change. Benefits derive from the impact of decisions that protect citizens, reduce loss and damage, improve organisational efficiency and safeguard wellbeing, accruing across many sectors over timescales of hours to decades.

Based on the above analysis, the quantifiable economic added value for EUMETSAT Member States from weather services is at least **52.8 billion Euros per year** (Table 2.1). This equates to 0.23% of GDP, which is comparable to the World Bank's assessment of 0.19% of global GDP[115]. It is also broadly in line with earlier, less comprehensive economic benefit assessments made for Croatia in 2008[116] (0.07%, excluding storm warnings and services for individual citizens); Finland in 2009[117] (0.12%) and the UK in 2015[118] (0.15%).

Whilst no quantitative assessment has been made of the SEBs of saved lives and enhanced wellbeing, it is clear that forecast and warning information enable the saving of many hundreds of lives annually across EUMETSAT Member States, with wider economic and wellbeing benefits equivalent to billions of Euros per year.

It is to be expected that the improvements in forecast accuracy delivered through EPS-Aeolus and EPS-Sterna will significantly add to these benefits.

Section 3 reviews the impact studies undertaken to predict that improvement, in order for these additional benefits to be quantified.

Sector	Annual added value (million Euros)
Property and infrastructure	6,600
Transport	13,300
Energy	7,500
Agriculture	8,500
Water management	1,200
Other business sectors	700
Individual citizens	15,000
TOTAL	**52,800**

Table 2.1. *Quantifiable annual economic added value of weather services to EUMETSAT Member States.*

3. Contribution of EPS-Aeolus and EPS-Sterna to forecast skill

Increasing the quantity and quality of observational data used by numerical weather prediction systems improves forecast skill. A substantial body of research evidence is presented to quantify the impact of EPS-Aeolus and EPS-Sterna on NWP forecasts.

The assessment of the forecast skill impacts expected from EPS-Aeolus and EPS-Sterna builds on peer-reviewed results of recent research and on dedicated studies. It includes assessment of the additivity of their respective impacts and comparisons of different EPS-Sterna constellations.

Although the assessment is largely global in scope, the analysis of results concentrates on the areas of greater interest to EUMETSAT member states – the Northern Hemisphere mid-latitudes and the Arctic.

For the sake of robustness, the approach combines different scientifically validated methods (see Annex I) for interpreting or extrapolating the measured forecast skill impacts of existing proxy observations, and for assessing the impacts of the simulated addition of EPS-Sterna and EPS-Aeolus to reference observing systems. The main results, expressed in percentage contribution to the reduction of forecast errors, are interpreted in a rather conservative manner whilst taking into account the shortcomings of simulations.

The two sources of proxy observations are the ESA Aeolus precursor mission, which delivered Doppler LIDAR observations of line-of-sight wind profiles from September 2018 to April 2023, and several ageing legacy sounders that were in surplus in the observing system of 2018–2019. Their measured forecast skill impacts in current forecasting systems allow an assessment of the extent to which EPS-Aeolus and EPS-Sterna would compensate for their loss, if replacing them in the same observing system. In addition, the measured Aeolus impact has been extrapolated, as far as is practicable, to the higher measurement accuracy expected from EPS-Aeolus.

3.1. Contribution of EPS-Aeolus

Like the Aeolus prototype, EPS-Aeolus will analyse the signals backscattered by molecules (Rayleigh observation mode) and aerosol and cloud particles (Mie observation mode) to extract the Doppler shift produced in the line-of-sight direction by wind-transporting molecules and particles. The forecast skill impact is the sum of the impacts from observations in both Rayleigh and Mie modes.

EPS-Aeolus Rayleigh mode observations will be two to three times more accurate, with double the vertical resolution up to 30 km altitude, while Mie mode observations will become exploitable in the planetary boundary layer, in the presence of aerosols and in the absence of clouds, which will multiply their number by more than three (see Figure 3.1). Thus EPS-Aeolus will have a full line-of-sight profiling capability.

Unfortunately, it has only been possible to simulate observations at a capacity delivering the same quantity of usable observations as Aeolus but at the higher measurement accuracy of EPS-Aeolus. This ignores the large volume of additional high-quality measurements achievable with EPS-Aeolus, and hence underestimates forecast skill impacts. This simulated observation capacity is referred to as 'EPS-Aeolus minus'.

3.1.1. Skill impact of the Aeolus precursor

The Aeolus contribution to error reduction in the ECMWF 24-hour forecast was evaluated using the FSOI[e] metric (see Annex I) – an energy integral calculated over the depth of the atmosphere. Between July and November 2019 the Aeolus FSOI contribution was 4.59% of the error reduction due to the full observing system available. It was highest over the mid-latitude oceans, the Tropics and the Polar Regions. This made the Aeolus Doppler LIDAR the third most impactful space instrument – and the single most impactful source of wind observations over the ocean.

ECMWF and Météo-France calculated the normalised error reduction due to Aeolus in forecasts of several key variables from Day 1 out to Day 10. Observing System Experiments (OSEs, see Annex I), a more conservative metric than FSOI, simulated the loss of all usable Aeolus observations in their respective operational NWP systems[119,120]. Their consistent results show that the reduction in the 24-hour forecast error propagates to longer range for many variables (see Figure 3.2).

[e] *Forecast Sensitivity to Observation Impact.*

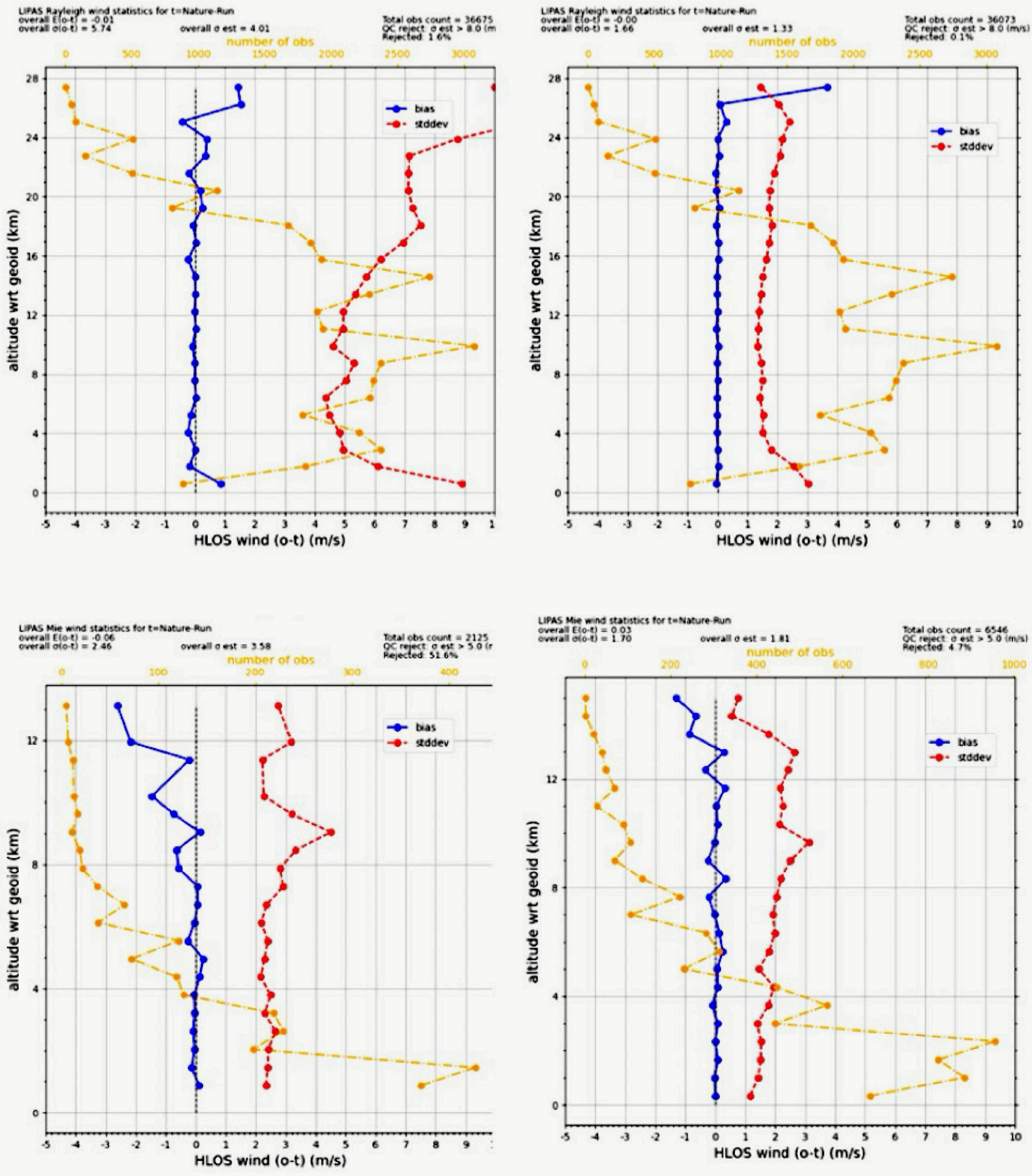


Figure 3.1: *Observation numbers (orange), measurement biases (blue) and accuracies (red) in Rayleigh (upper panels) and Mie modes (lower panels) as a function of altitude, for Aeolus and EPS-Aeolus, at the same vertical resolution. The lower panels do not visualise the much higher number of EPS-Aeolus observations in Mie mode, due to the use of a more compressed scale on the upper x-axis than for Aeolus. (Source: KNMI/LIPAS simulations)*

Whilst the positive forecast skill impact decreases with range in the Tropics and the Arctic, as observed for other types of observation, an impact of around 1% in the troposphere persists at mid-latitudes for up to six days – and may even increase with range for some variables. This seems to be a unique feature of Doppler LIDAR observations, which may be explained by couplings between the Tropics, the Arctic and the mid-latitudes producing large-scale, high-impact weather events over Western Europe. This is illustrated by a DWD case study[121] of the active hurricane Fay, in which reduced errors in the Tropics in the short-range led to reduced errors at longer range over Europe, as the remains of the hurricane were injected into the mid-latitude circulation (Figure 3.3).

The highest Aeolus contributions to the improvement of Day 3 to Day 6 forecasts over Europe occurred during extratropical transitions, and also where large-scale weather phenomena are influenced by the upper air jet stream and its variations, and where convective activity is organised on a large scale. Another original feature seems to be the positive impact in the lower stratosphere of the tropics up to Day 10 (not shown).

Aeolus brings substantial improvements to analyses and short- to medium-range forecasts of the wind field in the upper troposphere, especially in jet stream area and at the cruising altitude of airliners.

The impact of Aeolus observations was not affected by the collapse and subsequent recovery of air traffic and observations from airliners at cruising altitude due to the COVID-19 pandemic, nor by the substantial increase in the number of radio occultation observations produced by the COSMIC-2[f] and Spire[g] constellations. This confirms their unique, original contribution to forecast skill – in particular the ability of the Doppler LIDAR to characterise large-scale upper air circulations and the outflow from mesoscale convective systems much better than other observing systems.

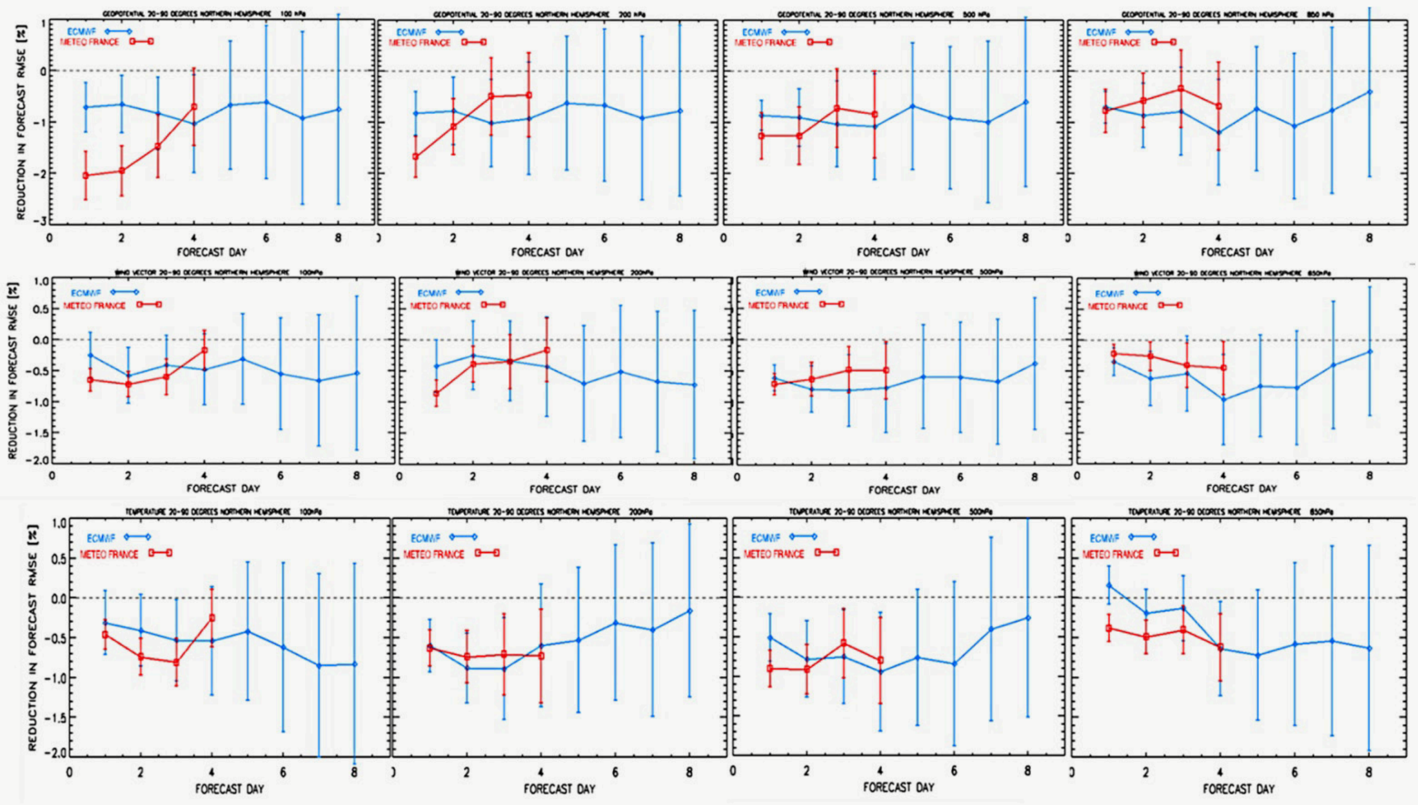


Figure 3.2. *Normalised reductions of errors due to Aeolus data in Météo-France (in red, up to 4 days) and ECMWF (in blue, up to 8 days) short- to medium-range forecasts of geopotential height (upper row), wind vector (middle row) and temperature (lower row) at 100, 200, 500 and 850 hPa in the Northern Hemisphere, as a function of forecast range. Error bars reflect statistical significance at 95% level. (Source: ECMWF and Météo France OSE data)*

f *COSMIC-2 is the United States' National Oceanographic and Atmospheric Administration's Global Navigation Satellite System Radio Occultation mission.*

g *Spire is a USA-based provider of radio occultation data for NWP.*

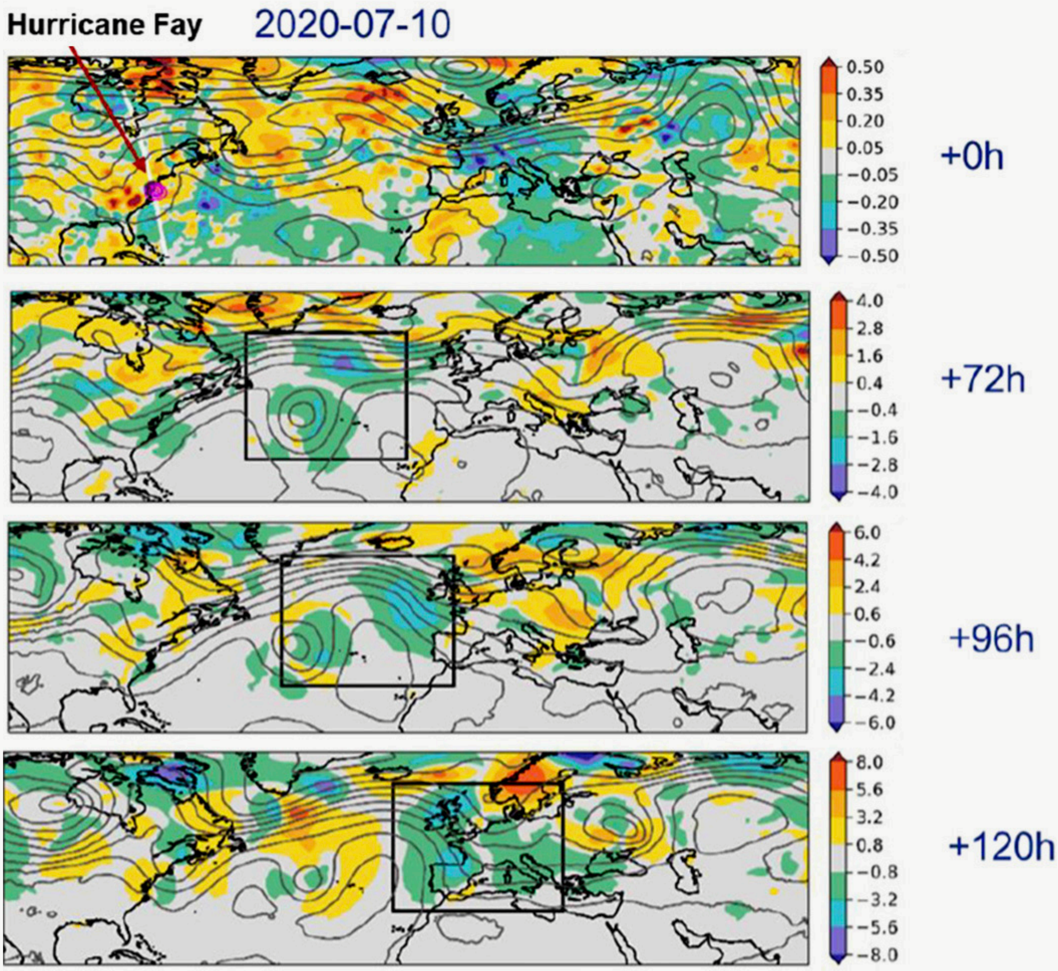


Figure 3.3. *Impacts of the assimilation of Aeolus observations for an extratropical transition linked to hurricane Fay: reduced forecast errors (green colour) in the tropics in the short-range turn into reduced errors at longer range over Western Europe, from three to five days ahead. (Source: DWD)*

In addition to the skill impacts through global NWP, EPS-Aeolus will also increase the skill of regional short-range forecasts, through improved boundary conditions. Preliminary analysis of such an impact on Mediterranean extreme storms has been performed using the COSMO NWP system in hindcast model[122]. In this case, the additional wind data from the Aeolus prototype is considered to have improved the representation of the atmospheric dynamics, leading to an overall better description of the extreme Mediterranean storm. Nevertheless, this is a single case, and such a conclusion needs to be corroborated by further studies.

3.1.2. Extrapolations of impact measurements to EPS-Aeolus

All these original impacts are expected to be delivered and amplified by the more capable EPS-Aeolus.

It has been possible to extrapolate to the higher EPS-Aeolus measurement accuracy by utilising the robust correlation observed over the period 2019–2023 between the measured Aeolus forecast skill impact and the slowly degrading measurement accuracy in Rayleigh mode.

The extrapolations of the results of ECMWF and Météo-France OSEs predict that Mie and Rayleigh observations of an 'EPS-Aeolus minus' system would have two to three times the forecast skill impact of Aeolus observations, depending on the variable, i.e. 2% to 3.5% (Figure 3.4).

3.1.3. Impact of simulated observations

Ensemble Data Assimilation (EDA) experiments enable measurement of the forecast skill impact from the addition of any source of real or simulated observations to a baseline observing system, through the normalised reduction of the spread of an ensemble of very-short-range forecasts. Experience has shown that the normalised spread reduction is consistent with the normalised reduction of error in 24-hour forecasts. ECMWF used this technique to assess the impacts of adding real (Aeolus) or simulated ('EPS-Aeolus minus') Doppler LIDAR observations to a real backbone observing system comprising five microwave sounders.

In the Northern Hemisphere the simulated 'EPS-Aeolus minus' observations have impacts on 12-hour forecast skill that are two to three times those of Aeolus. The impacts are 1.5% to 3% depending on variables and altitude, highest for wind (see Figure 3.5), and 2% to 2.5% averaged over the depth of the atmosphere. This is fully consistent with the independent extrapolation of the measured Aeolus impact to 'EPS-Aeolus minus' accuracy shown in Figure 3.4. The impact is higher in the Arctic, up to 3% to 4%.

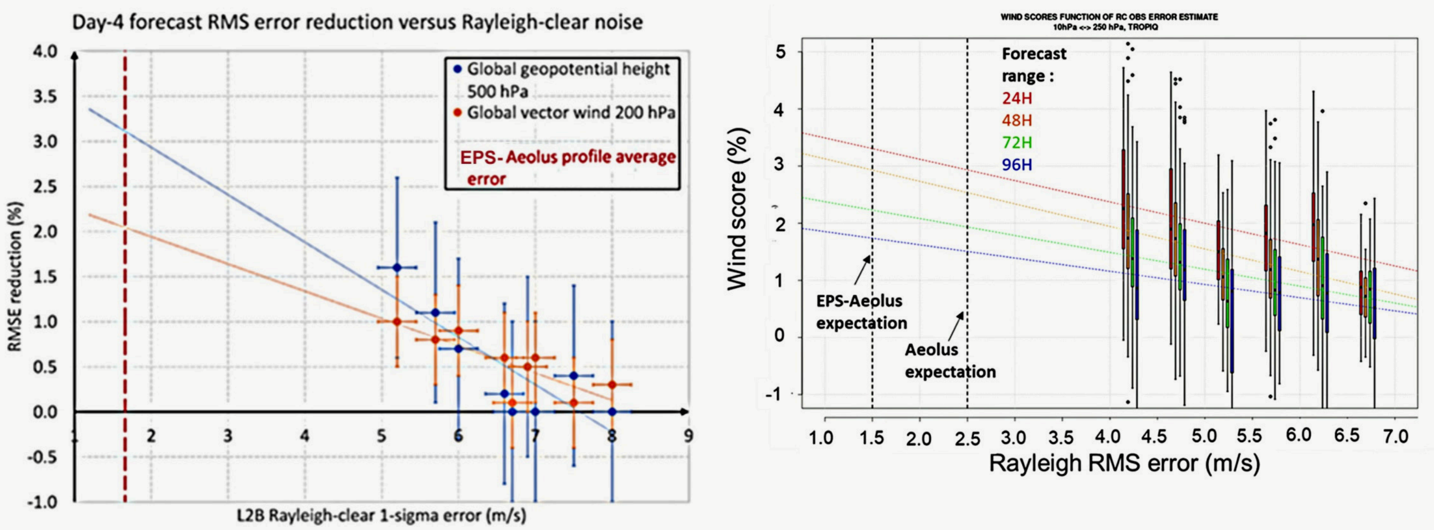


Figure 3.4. *Extrapolation of OSE results from Aeolus to the EPS-Aeolus Rayleigh measurement accuracy predicting 2.0–3.5% error reductions in ECMWF Day 4 forecasts of wind at 200 hPa and geopotential height at 500 hPa (left) and in Météo-France Day 1 to Day 4 forecasts of wind in the upper troposphere (right). (Sources: ECMWF and Météo-France)*

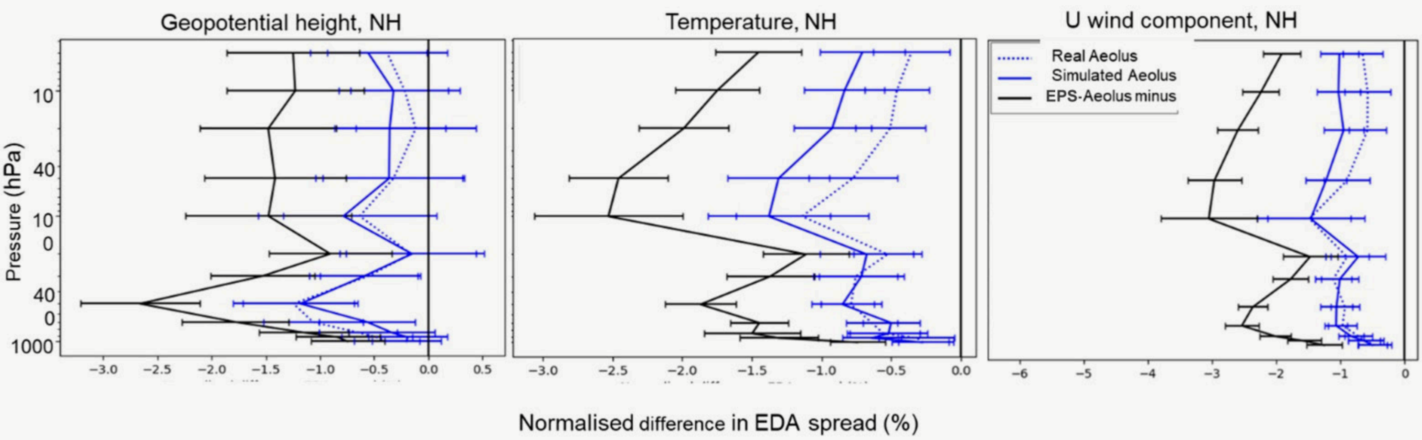


Figure 3.5. *Normalised reductions of EDA spread in the Northern Hemisphere for geopotential height, temperature and zonal wind as a function of pressure, due to the addition of real Aeolus data (blue dotted line) and simulated 'EPS-Aeolus minus' observations (black), showing 'EPS-Aeolus minus' impacts two to three times larger than those of Aeolus. A profile for simulated Aeolus observations (blue) is added for reference to check the realism of the simulation tool used for simulating 'EPS-Aeolus minus' observations. (Source: ECMWF)*

Based on these studies, the socio-economic benefit assessment assumes a **forecast skill impact of 3%** for the addition of EPS-Aeolus to the backbone observing system. This is consistent with the 2% to 3.5% skill impact of the lower 'EPS-Aeolus minus' capacity estimated by extrapolation of measured Aeolus impacts.

With EPS-Aeolus, Europe will fill a critical gap in the Global Observing System identified by WMO[123] by establishing the first pillar of a future international constellation of Doppler LIDARs, as it has done with the InfraRed Atmospheric Sounding Interferometer (IASI) for the hyperspectral infrared survey.

3.2. Contribution of EPS-Sterna

The microwave sounders of the EPS-Sterna microsatellites are of the same third generation as those on the future Metop Second Generation (Metop-SG) A satellites, and share most of their 19 channels, with very close measurement performances. They also include 325 GHz channels comparable to those of the Ice Cloud Imager of the future Metop-SG B satellites (see Table 3.1), which are expected to improve water vapour sounding due to better characterisation of ice clouds.

For all shared channels, the EPS-Sterna microwave sounders have comparable or higher performance than the AMSU-A/MHS[h] and ATMS[i] sounders currently in operation. The forecast skill impacts of these systems were the subject of several studies in June–September 2018 and July–November 2019, within observing systems which then comprised up to five ageing microwave sounders in surplus of the nominal backbone of three (see Figure 3.6).

Study results can be interpreted for the purpose of assessing the minimum value of EPS-Sterna satellites as replacements for ageing microwave sounders after their end of life, by considering one set of legacy sounders as a lower performance proxy for the same number of EPS-Sterna satellites.

The impact of all components of the observing system of July–November 2019 on the ECMWF 24-hour forecast skill, has been assessed using the FSOI metric. This shows that if five EPS-Sterna satellites were to replace five ageing sounders in that observing system, their total contribution would be at least 113% that of the three remaining sounders of the three-orbit backbone comprising one EUMETSAT, one United States' and one Chinese satellite (Figure 3.7). Likewise, if three EPS-Sterna satellites were to replace only three ageing sounders, their total contribution would be at least 38% that of the five remaining microwave sounders of a backbone comprising two EUMETSAT, two United States' and one Chinese satellite.

ECMWF OSEs simulating the loss of one, three, five and the full set of seven microwave sounders in the observing system of June–September 2018[124] showed that the first three sounders reduced the error of Day 1 and Day 2 forecasts of geopotential height at 500 hPa by around 4% in the Northern Hemisphere and that four more sounders further reduced the error by around 2% (Figure 3.8). In the Arctic, the corresponding error reductions on Day 1 forecasts were 10.5% and 5.5% respectively (not shown).

Centre frequency (GHz)	MWS channel	AMSU-A/MHS channel	Bandwidth (MHz)	Footprint size at nadir (km)	NEDT (K)
50.3	3	AMSU-A 3	180	40	0.85
52.8	4	AMSU-A 4	400	40	0.60
53.596±0.115	6	AMSU-A 5	2x170	40	0.60
54.4	8	AMSU-A 6	400	40	0.60
54.94	9	AMSU-A 7	400	40	0.60
55.5	10	AMSU-A 8	330	40	0.65
57.290344	11	AMSU-A 9	330	40	0.65
89	17	AMSU-A 15/MHS 1	4000	20	0.25
164-167	18	MHS 2 (157GHz)	2800	20	0.55
183.311±7.0	19	MHS 5	2x2000	10	0.65
183.311±4.5	20	-	2x2000	10	0.65
183.311±3.0	21	MHS 4	2x1000	10	0.80
183.311±1.8	22	-	2x1000	10	0.80
183.311±1.0	23	MHS 3	2x500	10	1.05

Table 3.1. *List of EPS-Sterna and (numbered) microwave sounder channels that could be assimilated by current NWP systems, and identification of those available on the AMSU and MHS legacy sounders of Metop. Channels 20 and 22 can be assimilated as they are already available on the United States' ATMS third generation sounders. The 53.246 GHz and the 325 GHz channels of EPS-Sterna are not listed as NWP developments are needed for their assimilation. (Source: ECMWF)*

h *Advanced Microwave Sounding Unit-A and Microwave Humidity Sounder operated by EUMETSAT.*

i *Advanced Technology Microwave Sounder operated by the United States' National Oceanic and Atmospheric Administration.*

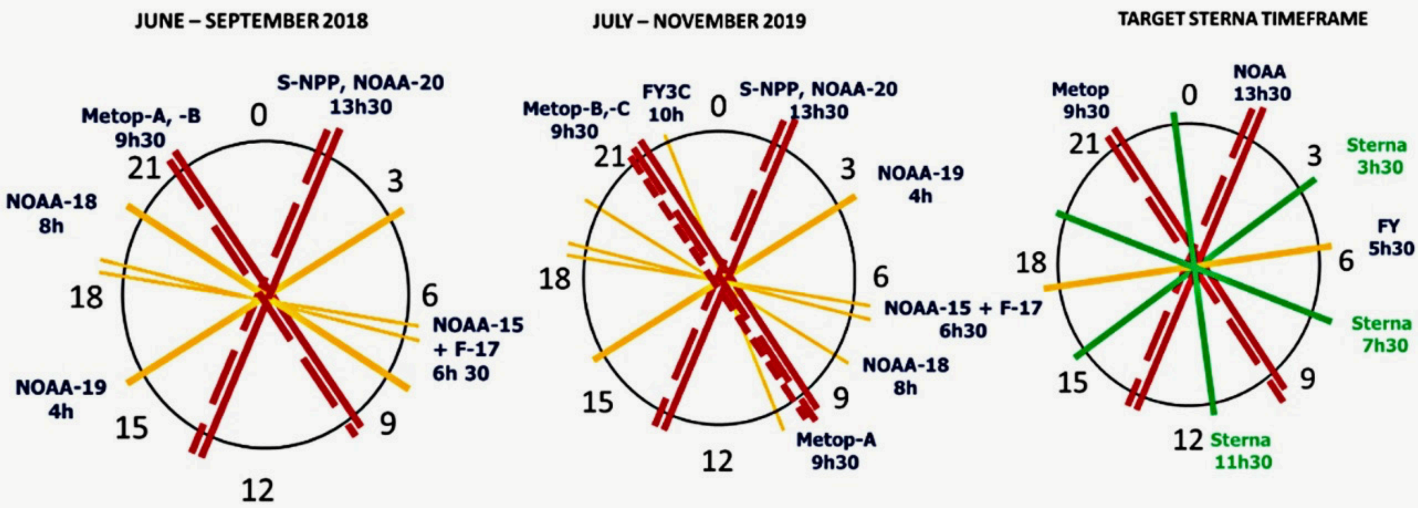


Figure 3.6. *Orbits and equatorial crossing times of the satellites carrying microwave sounders in June–September 2018 (left, seven sounders), July–November 2019 (middle, eight sounders) and in a fictive configuration including the EPS-Sterna constellation and a four-satellite IJPS (eleven sounders, right). Ageing/secondary IJPS satellites (Metop-A, Metop-C, Suomi-NPP) are shown in dotted line. (Source: EUMETSAT)*

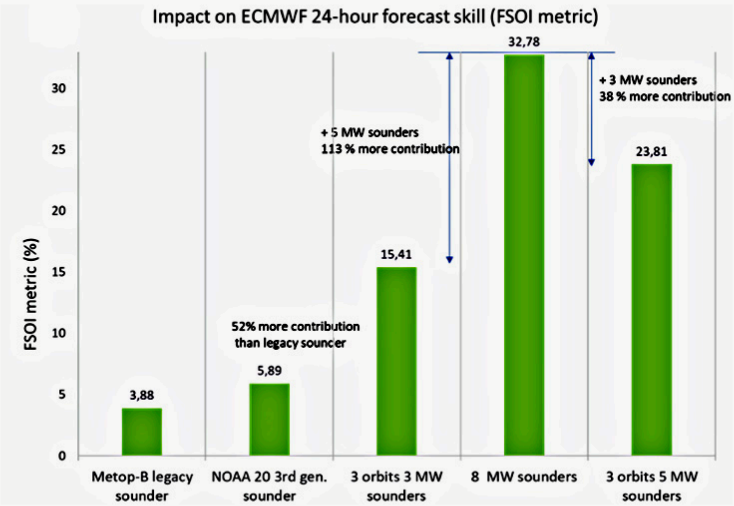


Figure 3.7. *Comparison of Day 1 forecast skill impacts (FSOI metric) of Metop-B legacy sounders, the NOAA 20 third generation sounder, three, eight and five microwave sounders in the observing system of July–November 2019 (from left to right, calculated from ECMWF FSOI data). (Data source: ECMWF)*

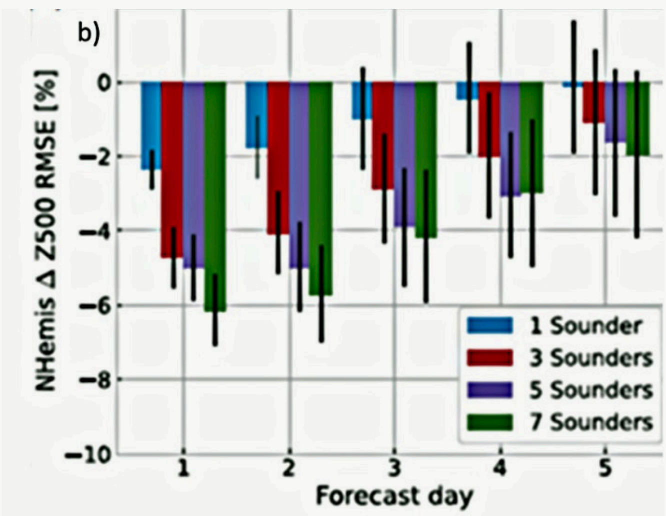


Figure 3.8. *Normalised error reductions in Day 1 to Day 5 forecasts of geopotential height at 500 hPa for latitudes above 20° N, produced by the introduction of one, three, five and seven microwave sounders in the observing system of June–September 2018. (Source: Duncan, et al. (2021)[125])*

Although in principle these figures can neither be directly compared nor extrapolated up to six EPS-Sterna satellites, it can reasonably be inferred that the impact of the addition of six EPS-Sterna satellites to a remaining backbone comprising three sounders should be at least commensurate to the impact of that backbone, i.e. 4% in terms of normalised error reduction in the Northern Hemisphere. This takes into account that one EPS-Sterna third generation microwave sounder could have 52% higher forecast skill impact than one ageing sounder, as is the case of the ATMS sounder, the only third generation sounder in the current system.

3.2.1. The impact of adding EPS-Sterna to baseline observing systems

The impacts have been assessed of the simulated addition of EPS-Sterna constellations of between three and eight microsatellites, distributed across two, three and four orbital planes, to different baseline observing systems. ECMWF undertook EDA experiments combining real and simulated observations, while Météo-France used Observing System Simulation Experiments (OSSE) with simulated observations for current and future systems. Both experiments simulated the higher accuracy expected from EPS-Sterna instruments for channels that can be assimilated by the current NWP systems, as opposed to the measured impact of legacy microwave sounders.

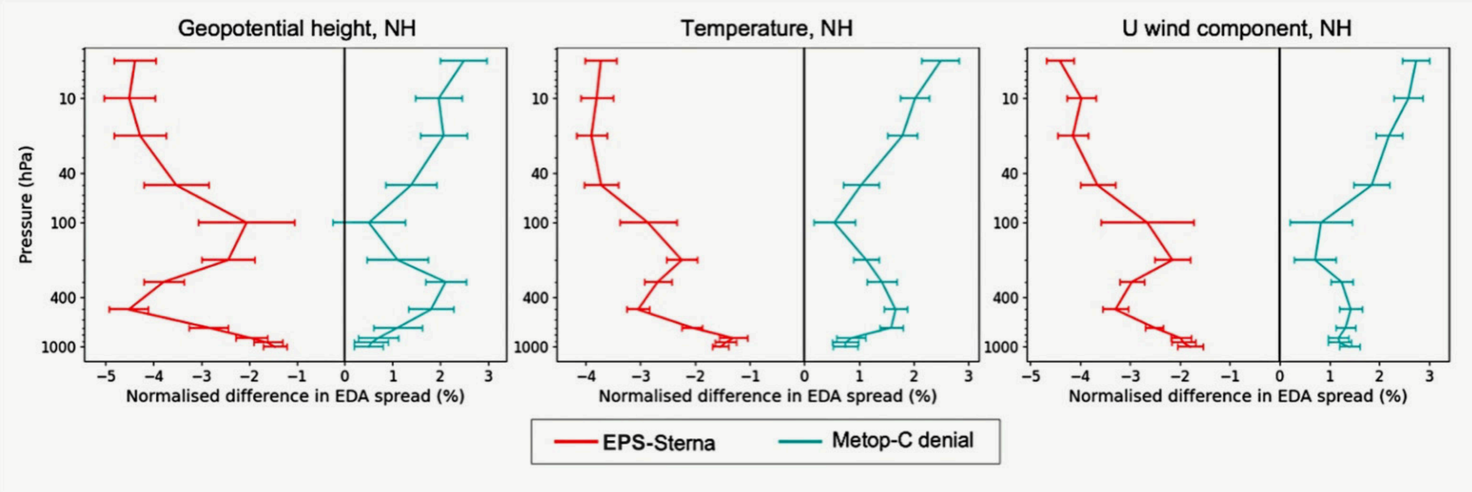


Figure 3.9. *Vertical profiles of normalised EDA spread reduction due to EPS-Sterna for geopotential height, temperature and zonal wind (from left to right) in the Northern Hemisphere (in red), compared with the profiles of EDA spread increase due to the simulated loss of Metop-C, the secondary Metop satellite (in blue). (Source: ECMWF)*

	Météo-France OSSE (12h)	ECMWF EDA (12 h)	Météo-France OSSE (12h)	ECMWF EDA (12 h)
Z500	-3,789	-3,3	-2,85	-2,94
T500	-2,765	-2,2	-2,043	-2,09
U500	-2,075	-2,5	-1,725	-2,29
U200	-1,839	-2	-1,693	-1,575
T200	-1,918	-1,8	-1,067	-1,56

Table 3.2. *Impacts (%) of adding six microwave sounding satellites (two left columns) and four satellites (two right columns) to a baseline system comprising seven sounders, based on the comparison of two systems comprising 13 sounders (five baseline plus eight EPS-Sterna satellites for ECMWF EDA, and seven baseline plus EPS-Sterna for Météo-France OSSE) against the impact of seven sounders calculated by both. The impact against a five sounder baseline is higher (4.28% for ECMWF) but cannot be calculated for OSSE.*

The ECMWF baseline observing system comprised five sounders: those of the four-satellite IJPS[j] system, plus NOAA 15[k]/DMSP F17[l] sounders as a proxy of the sounder of the planned Feng Yung FY-3E Chinese early morning orbit satellite. The Météo-France baseline included two more microwave sounders, as proxies of the planned FY-3H and FY-3F Chinese morning and afternoon orbit satellites.

The ECMWF EDA experiments show that the addition of the full EPS-Sterna constellation to a baseline system comprising five microwave sounders would reduce the errors of twelve hour forecasts of geopotential height by 4.28%, temperature by 3.2% and zonal wind at 500 hPa by 2.96% in the Northern Hemisphere (see Figure 3.9), which is more than the negative impact of the loss of Metop-C, the secondary Metop satellite.

Impacts would be much higher in the Arctic, of the order of 7% for geopotential height at 500 hPa, and highest in the poorly observed Southern Hemisphere (not shown).

Although the impacts of a given EPS-Sterna constellation could not be compared, due to the adoption of different baseline observing systems by ECMWF and Météo-France, the impacts of systems comprising eleven and 13 microwave sounders could be compared against a common reference of seven sounders, showing consistent impacts on forecasts in the Arctic – of 3.3% to 3.8% for geopotential height at 500 hPa with the addition of six sounders, and 2.9% with the addition of four (see Table 3.2).

The Météo-France OSSE showed lower EPS-Sterna impacts at mid-latitudes of the Northern Hemisphere, presumably because the French ARPEGE NWP system assimilated fewer microwave soundings, due to an earlier data assimilation cut-off time optimised for shorter range forecasts over France. This difference with the ECMWF experiment was probably less important in the Arctic due to data thinning limiting the number of microwave soundings actually assimilated by ECMWF.

j *Joint European and United States' operational polar satellite system.*

k *One of a series of NOAA's legacy polar satellites, launched in 1998.*

l *One of a series of United States' Defense Meteorological Satellite Program legacy polar satellites, launched in 2006.*

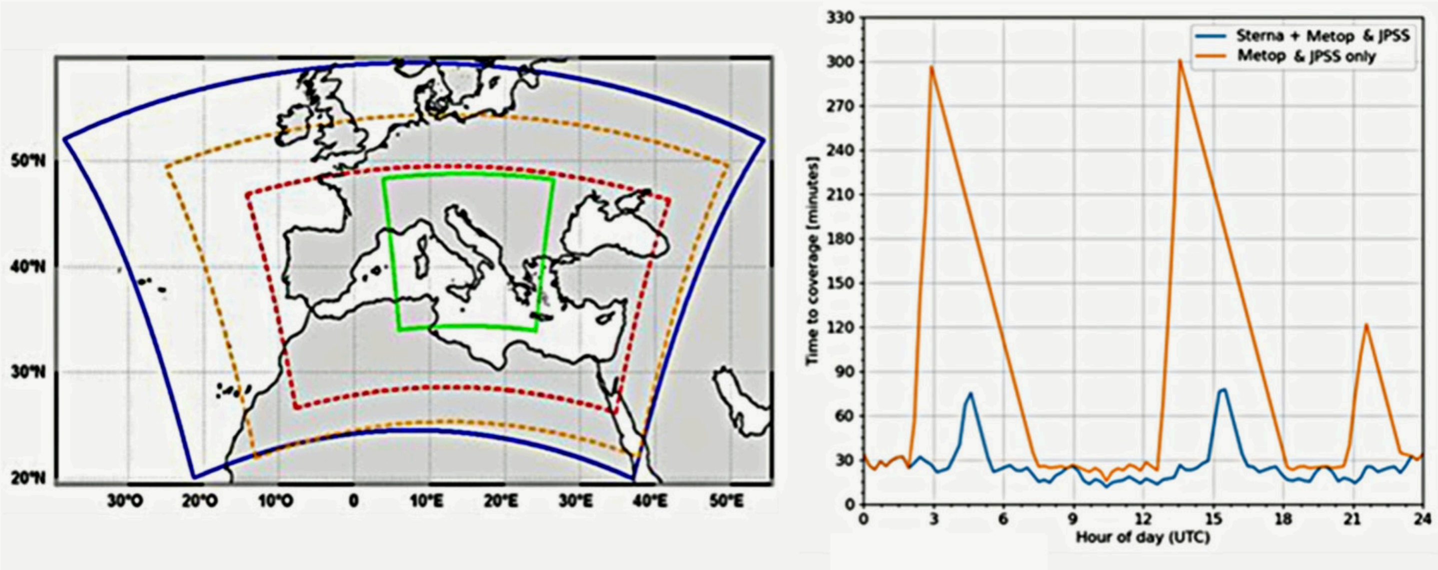


Figure 3.10. *Times between successive observations of the six-satellite EPS-Sterna and the four-satellite IJPS (blue curve) inside the area shown in green, compared to separation times achieved today with only the four-satellite IJPS (orange curve). (Source: Swedish Meteorological and Hydrological Institute)*

In the Météo-France OSSE, the positive impact of EPS-Sterna in the Northern Hemisphere was 0.7 times the negative impact of the loss of the primary Metop-B satellite. In the ECMWF EDA experiment, it was 1.7 times the negative impact of the loss of the secondary Metop-C satellite, but less than the negative impact of the loss of the pair of Metop satellites.

The conclusion of these studies is that In the Northern Hemisphere, adding the reference EPS-Sterna constellation to the two-orbit, four-satellite IJPS shared with NOAA, complemented by a Chinese early morning satellite, would have a positive impact on forecasts of all basic variables including precipitation, of the order of 4% for geopotential height at 500 hPa. Impacts would be higher in the Arctic region – of the order of 7% for geopotential height at 500 hPa – and highest in the Southern Hemisphere.

3.2.2. Additional impacts of EPS-Sterna on regional very-short-range forecasts

Regional very-short-range forecast systems usually exploit a high-resolution NWP system covering a limited geographical area and using time-dependent boundary conditions derived from the forecast of a lower-resolution, larger scale "coupler" system.

A given source of observations could have impact on such forecasts both through improvement of the forecast boundary conditions and through direct assimilation into the regional NWP system. Improvements in boundary conditions due to 'EPS-Aeolus minus' and EPS-Sterna are already captured in the forecast skill impact factors estimated above; however to assess the full benefits, it is also necessary to consider the impacts on regional very-short-range forecasts through direct assimilation.

Direct assimilation can only bring additional impact if the observation system delivers frequent, dense regional coverage and observation products with a latency of less than an hour. EPS-Aeolus, given its along-track observation geometry (no swath) and the one to three hour latency of its products is therefore unsuitable.

By contrast, the direct broadcast system of the EPS-Sterna satellites will enable all ground stations of the EUMETSAT Advanced Retransmission Service network to acquire observations in less than 20 minutes, thus satisfying the latency requirements of very-short-range and short-range forecasts. Given the swath of more than 2,500 km of microwave sounders, a very large number of EPS-Sterna observations will be available within one hour for direct assimilation by regional NWP systems.

Even in Southern Europe, the combination of the six- satellite IJPS and an EPS-Sterna constellation of six satellites would for the first time deliver observations inside any regional area every 30 minutes during most of the day (see Figure 3.10). This unprecedented capacity would be invaluable for regional very-short-range forecasts across Europe, enabling the direct assimilation of EPS-Sterna data into all regional NWP systems.

Regional OSEs were performed for two special observing periods (SOPs) of the 2018 Year of Polar Prediction (YOPP) using the AROME-Arctic NWP system (see domain in Figure 3.11) and forecast boundary conditions from ECMWF[126]. The results of previous ECMWF global OSEs[127] were used to simulate the removal of a given source of Arctic observations (above 60°N) in the production of forecast boundary conditions, and the same source could be kept or removed in the direct assimilation by the AROME-Arctic system. Thus, the normalised reductions of errors coming from improvements in boundary conditions by a given source of observations and from direct assimilation could be distinguished, in particular for legacy microwave sounders.

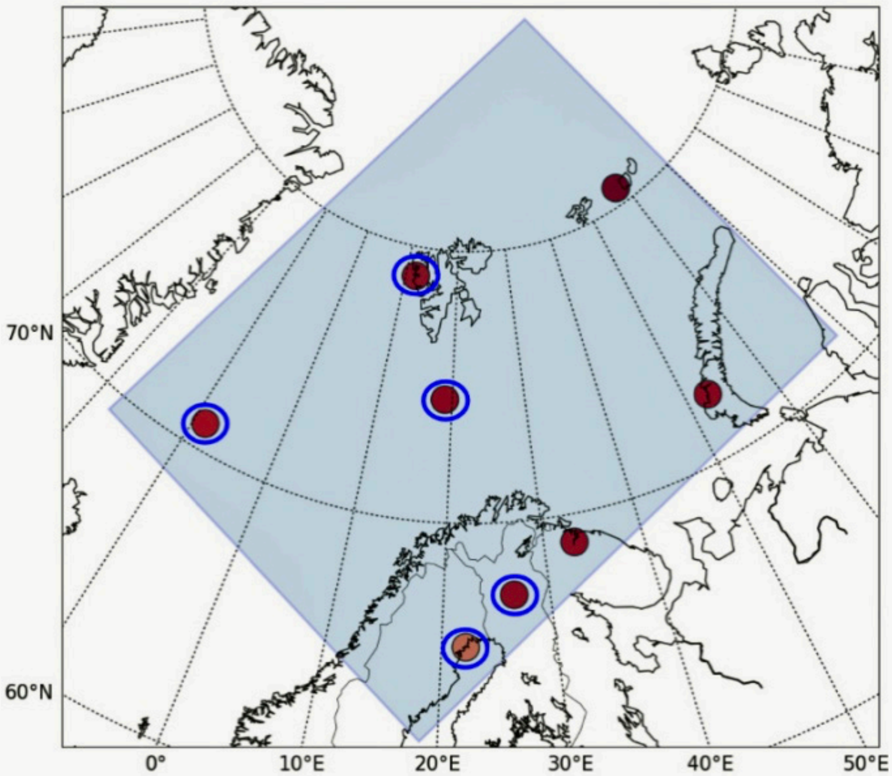
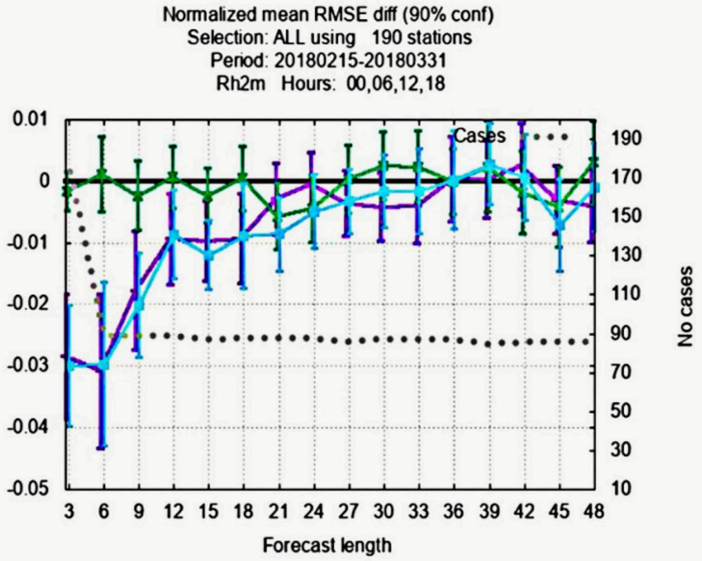


Figure 3.11. *Area covered by the 2.5 km resolution AROME-Arctic system, and positions of the eight radiosonde stations during SOP-2. All stations circled in blue provided more soundings than in operational conditions. (Source: Randriamampianina et al. (2021)).*



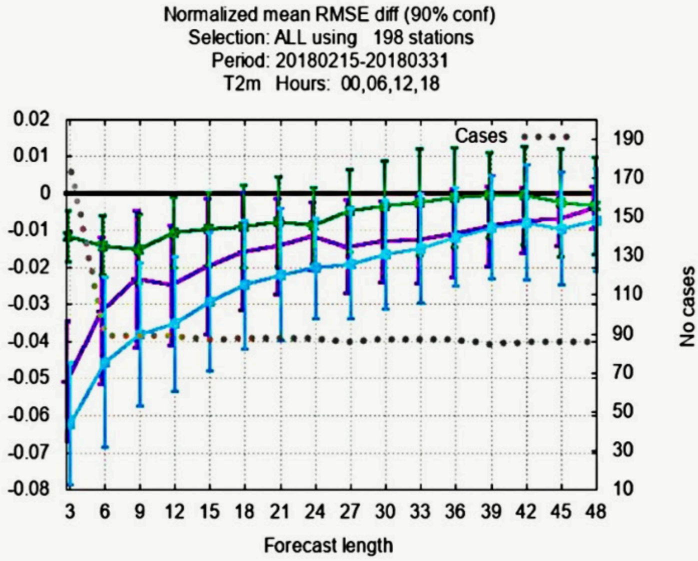


Figure 3.12. *Contributions of microwave soundings to the reduction of regional forecast error of relative humidity (left) and temperature at 2 m (right) in winter conditions. Total contribution is in blue, contribution of direct assimilation is in purple and contribution through improvement of boundary conditions is in green. (Source: Randriamampianina et al. (2021), as presented at 7th WMO workshop on the Impact of Various Observing System in NWP)*

The legacy microwave sounders were the third largest source of (total) forecast error reduction for all parameters, surpassed only by conventional observations (which were in excess capacity during the SOPs) and IASI infrared soundings. They were also the most impactful non-conventional source for forecasts of upper air humidity and 10 m wind vector.

In winter conditions, the impact up to 24 hours was mostly due to direct assimilation, and was highest on critical surface parameters. The impact of direct assimilation was in the order of 2% on average over forecast ranges of 6–18 hours and up to 5% in the first three hours (see Figure 3.12).

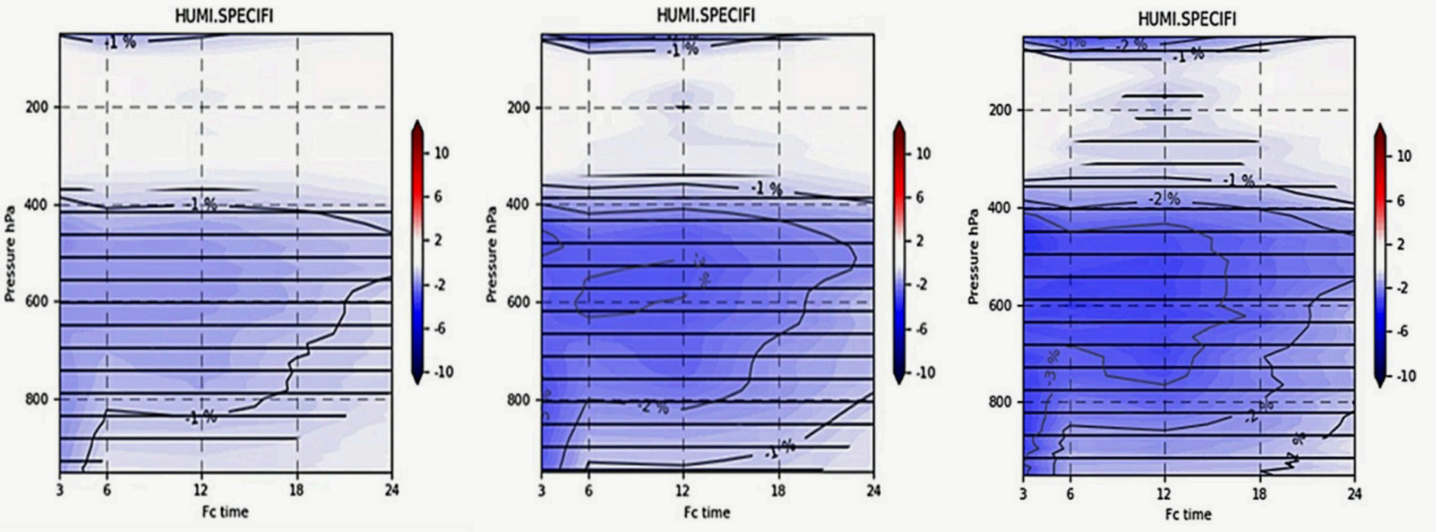


Figure 3.13. *Percentage of error reduction in three- to 24-hour forecasts of specific humidity over the AROME-Arctic domain achieved by the direct assimilation of a simulated subset of microwave channels from three, four and six EPS-Sterna satellites (from left to right) in a regional OSSE for a two-week winter period. (Source: Norwegian Meteorological Institute)*

To go one step further, the Norwegian Meteorological Institute performed a regional OSSE[128] to assess the impact of the simulated addition of EPS-Sterna at high latitudes. Constellations of three and six satellites distributed over the same three equally spaced orbit planes, and of four satellites distributed over two orbits, were added to a reference observing system including conventional observations, IJPS microwave sounders and IASI infrared sounders. The experiment used the same AROME-Arctic NWP system for direct assimilation and the "nature run" used by the Météo-France global OSSE for the provision of (perfect) boundary conditions and the simulation of all observations.

Using perfect boundary conditions, the OSSE could only assess the impacts of direct assimilation, which it should in principle underestimate. Unfortunately, the need to contain the complexity of the OSSE restricted the direct assimilation of EPS-Sterna data to the subset of microwave temperature sounding channels peaking in the medium and upper troposphere, and to simulate perfect surface observations. This de facto precluded any meaningful comparison with the impacts of real microwave soundings on very-short-range forecasts of critical near surface parameters measured by the YOPP OSE. Despite these substantial shortcomings, OSSE results available for a two-week winter period showed that direct assimilation of the simulated subset of channels of six EPS-Sterna satellites would reduce errors in three to twelve hour forecasts by 3% to 6% on average across key upper air variables (temperature, specific humidity and wind). It was also shown that a six-satellite constellation would by far outperform smaller constellations (see Figure 3.13).

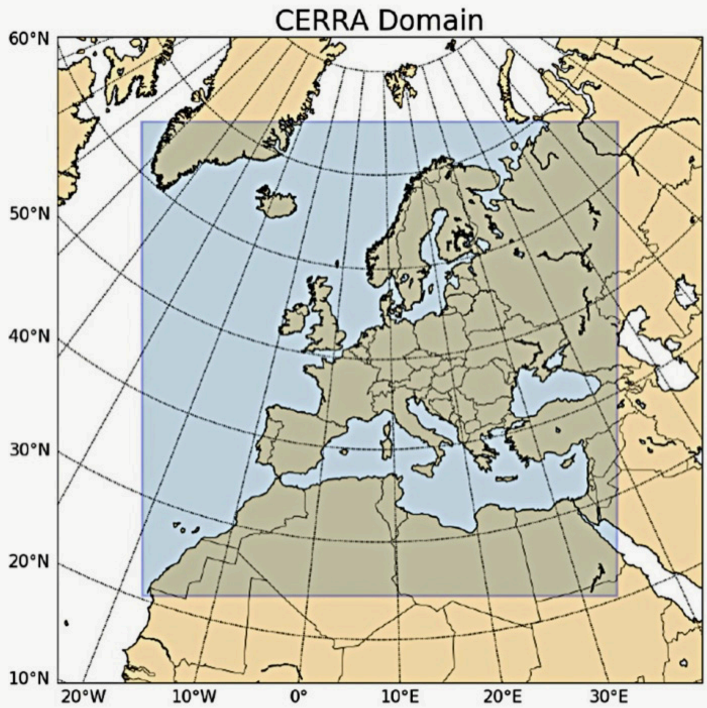


Figure 3.14. *European domain covered by a 5.5 km resolution version of AROME for development of the Copernicus European Regional Reanalysis. (Source: Wang and Randriamampianina (2021))*

Given that this positive impact of direct assimilation on forecasts of upper air variables is much higher than that measured by the YOPP OSE for fewer soundings from legacy microwave sounders, direct assimilation of the full set of EPS-Sterna channels in a more realistic regional OSSE would be expected to have a higher impact on forecasts of critical near surface parameters than the 2% measured impact of the legacy sounders.

Based on these studies, 2% is considered a conservative average estimate of the additional impact of EPS-Sterna on very-short-range NWP forecasts in the Arctic. This takes into account the lower positive impact in summer conditions and the limited range of weather situations sampled by the OSEs and OSSEs. This increases the total EPS-Sterna impact on NWP forecast skill in the Arctic from 7% to 9%.

More widely across Europe, the nature of the additional impacts from the direct assimilation of EPS-Sterna observations into regional NWP is expected to be location dependent. For instance, in the Mediterranean regions where moist convergence drives convection and heavy precipitation, forecast skill should improve as a result of the synergetic direct assimilation of frequent and dense all-weather moisture soundings from EPS-Sterna. These will complement the MTG-S infrared moisture soundings available at higher spatial resolution but only in cloud-free conditions.

Another OSE study[129] assessed the impact of the direct assimilation of satellite radiances on the Copernicus European Regional Reanalysis for two 21-day winter and late spring periods in December 2017–January 2018 and June 2018, using a lower resolution (5.5 km) version of AROME covering the whole of Europe (see Figure 3.14) and boundary conditions from the ERA-5 reanalysis.

Direct assimilation of radiances from existing satellites reduced the error in the 24-hour forecast of geopotential height below 300 hPa by 1.5% to 2.5% in winter, with lower positive impact in late spring. Although the experiment by nature ignored the timeliness constraints of an operational forecasting system, its results are consistent with those of the OSE performed in the Arctic using a convection-resolving version of AROME.

Based on this result, the additional impact from direct assimilation of EPS-Sterna observations into regional NWP across Europe is taken to be 2%, noting that this is conservative for the Arctic.

Taking this factor together with the 4% impact from Global NWP, the socio-economic benefit assessment assumes **a forecast skill impact of 6%** from the addition of EPS-Sterna to the backbone observing system for EUMETSAT member states outside the Arctic.

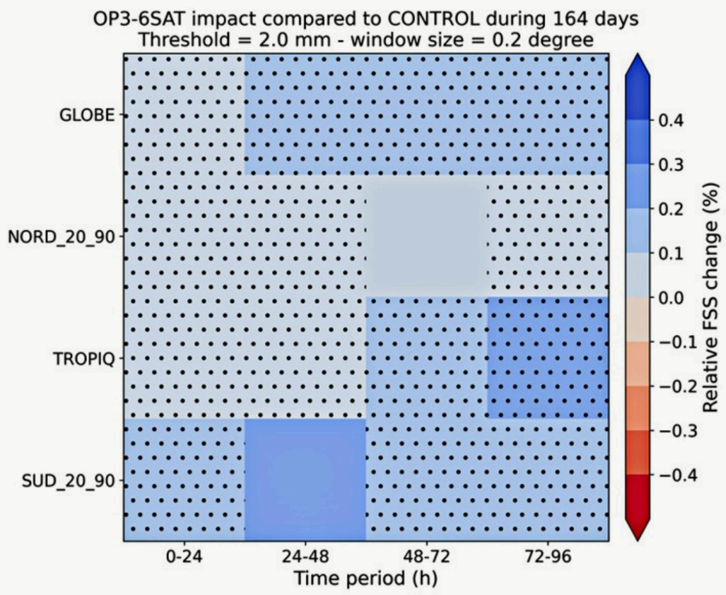


Figure 3.15. *Positive Impacts (in blue) of the addition of EPS-Sterna to a baseline observing system including seven microwave sounders on forecasts of accumulation of large scale precipitation above 2 mm for Day 1 to Day 4, globally and in different regions, with statistical significance at 95% level indicated by dots. (Source Météo-France)*

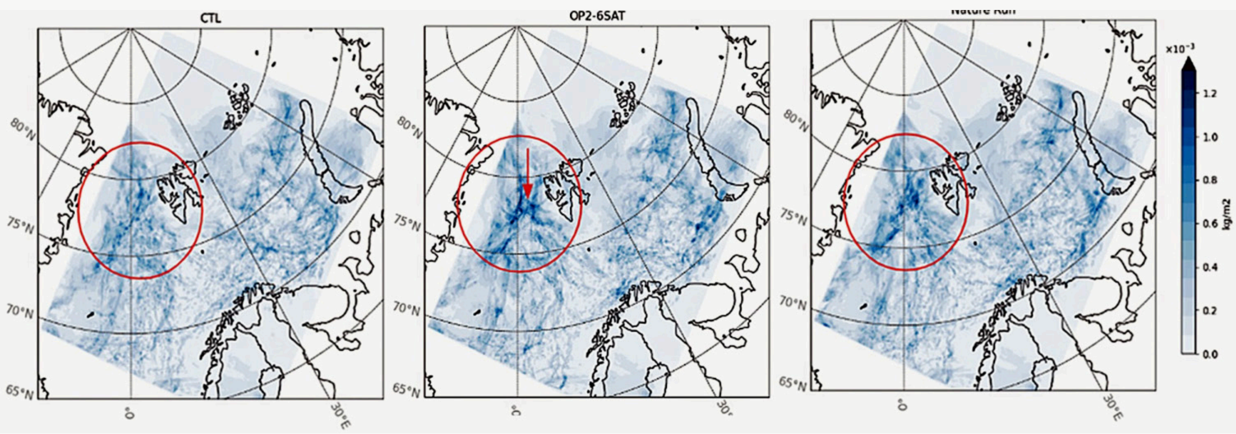
3.2.3. Impacts on forecasts of accumulated precipitation

Using specific metrics, the consistent OSSE experiments conducted by Météo-France and Met Norway at global and regional scales showed that the addition of EPS-Sterna to the current observing system would have positive impacts on very short- to medium-range forecasts of accumulated precipitation (Figures 3.15 and 3.16).

Adding the EPS-Sterna constellation to a baseline system comprising seven microwave sounders would have a positive impact on forecasts of accumulated precipitation at ranges of up to four days, globally and regionally. Direct assimilation of only a subset of EPS-Sterna channels would substantially improve the forecast of the five-day accumulation of mesoscale precipitation, in terms of both amounts and location.

A study of Italy's Civil Protection Department confirmed the added value of EPS-Sterna to the monitoring of extreme precipitation and hydrological warning systems, in the case of the Mediterranean cyclone Apollo, which impacted Sicily in October 2021 (see box).

Figure 3.16. *Location and amounts of five-day accumulation of mesoscale precipitation in 'reality' (Nature Run, right chart) and as analysed with (middle chart) and without (left chart) direct assimilation of simulated microwave soundings from the full EPS-Sterna constellation. (Source: Norwegian Meteorological Institute)*



Potential applications of EPS-Sterna in early warning systems of Italian Civil Protection

Every year, the Italian national territory faces various natural hazards, including floods, resulting in both loss of life and substantial economic damage. Italy's Department of Civil Protection plays a crucial role in operating the national alert system, offering monitoring and forecasting services for weather and flood conditions.

EPS-Sterna has the potential to deliver significant benefits to the Civil Protection Department's hydrological warning system, including the real-time monitoring of precipitation and its integration into the hydrological-hydraulic operational chain.

The Civil Protection Department's alert system leverages innovative instrumentation, including earth observation products, to enhance the provision of monitoring and forecast services for current weather and flooding conditions. Specifically, passive microwave sensors on satellites are utilised in conjunction with ground-based measurements to estimate precipitation. However, the current constellations of passive microwave sensors offer observations with varying temporal frequencies, resulting in potential errors in rainfall estimates that can surpass 50% in certain instances. The EPS-Sterna constellation's passive microwave observations have the potential to bridge this gap by providing precipitation measurements with a regular revisit time of approximately two hours over Italy. This would ensure more accurate estimates of rainfall and significantly improve the effectiveness of forecasting and monitoring services within the Civil Protection Department's alert system.

In order to evaluate the potential influence on the alert system, a synthetic experiment was conducted using two actual instances of intense precipitation[130]. The initial case study chosen for examination was the flood event triggered by heavy rainfall over Sicily due to the Mediterranean cyclone Apollo in October 2021)[131] (Figure 3.17).

To evaluate the impact of EPS-Sterna on precipitation monitoring, weather radar rain rate products were downscaled spatially and temporally to match the resolutions provided by EPS-Sterna over Italy in order to calculate accumulated precipitation. The use of two-hourly precipitation estimates (as would be provided by EPS-Sterna) was found to enhance daily precipitation estimation by up to 26% in terms of correlation compared to estimations based on six-hourly observations.

To assess the impact of EPS-Sterna on the alert phase, a synthetic precipitation dataset was used as input in the Continuum hydrological model operated by the Civil Protection

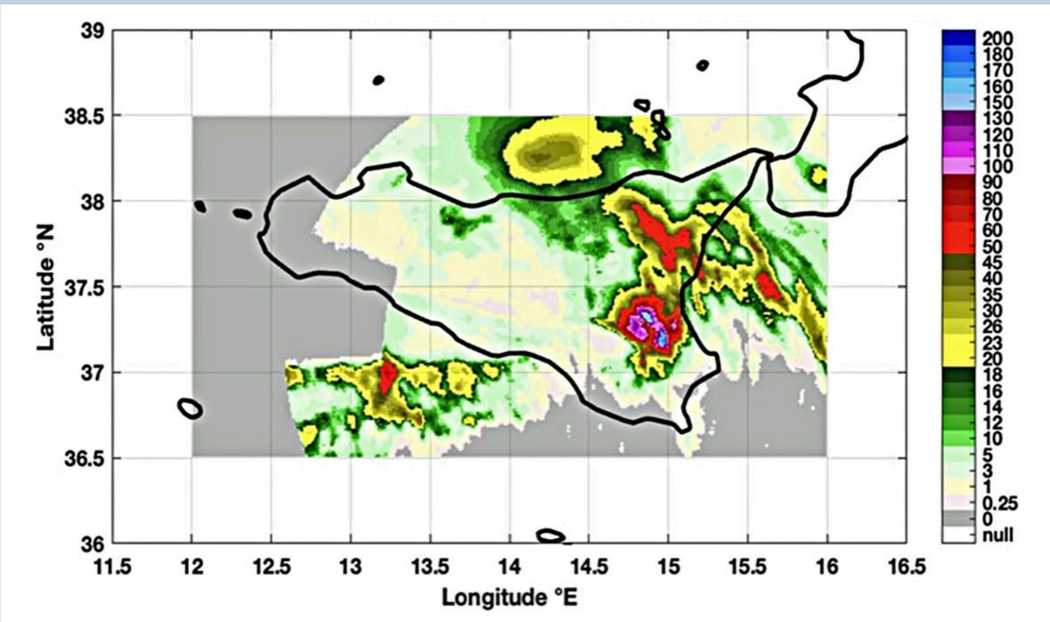


Figure 3.17. *Observed precipitation in Sicily from radar: 24-hour accumulation on 24 October 2021. (Source: Puca et al. (2023))*

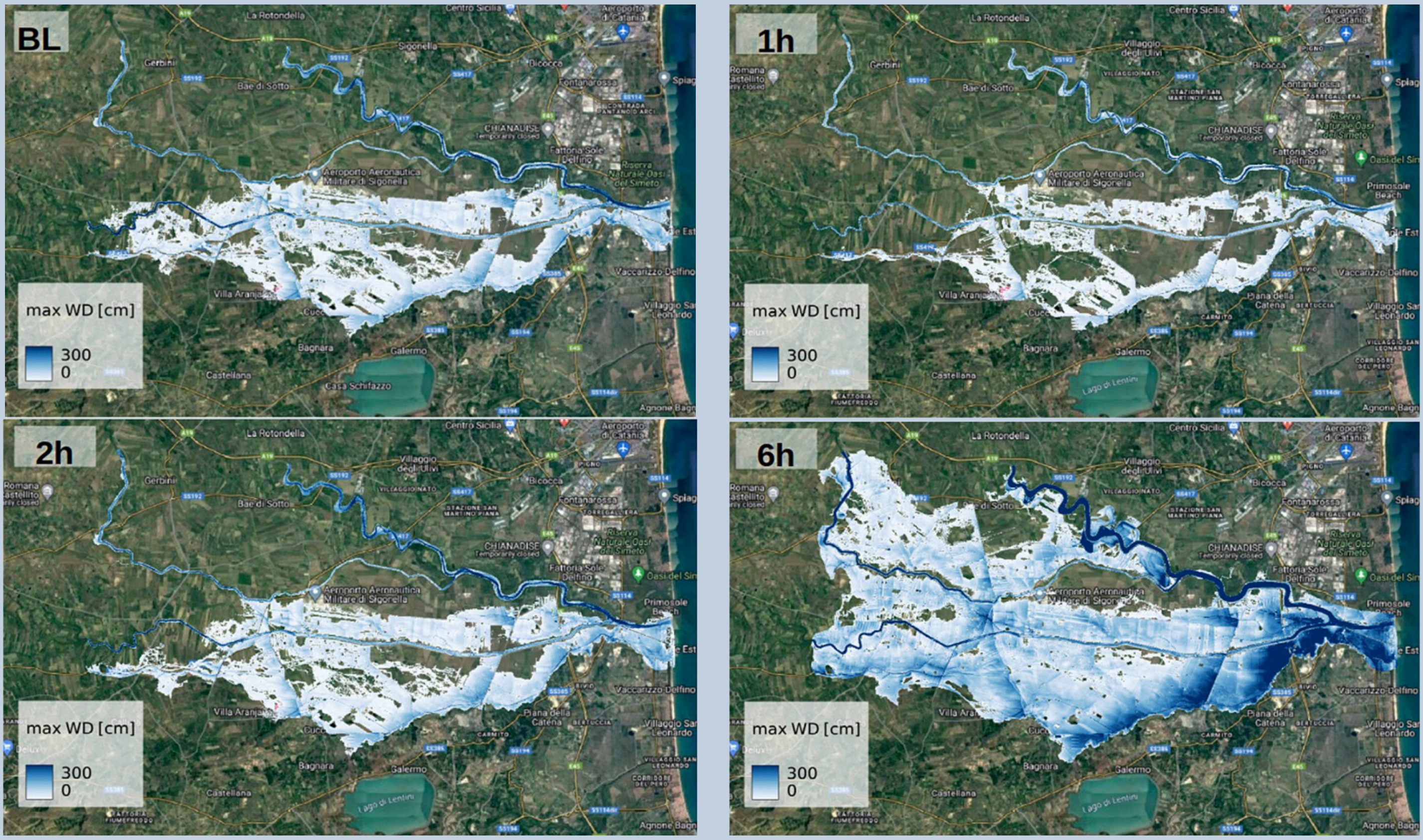


Figure 3.18. *Inundation extent for the Apollo case study, simulated by forcing the hydraulic model with the baseline dataset (BL, 1 km 1 hour) and the hydrological runs at 20 km aggregating proxy-satellite data at one, two and six hours. The two hour aggregation produced the closest estimate of total inundated area compared to the baseline. (Source: Puca et al. (2023))*

Department. Hydrological simulations were made, with precipitation data aggregated at 20 km and temporal resolutions of one, two and six hours. The most accurate match of the peak was with a temporal aggregation of one to two hours (Figure 3.18).

Subsequently, hydraulic simulations were carried out using the TELEMAC-2 model, also utilised by the Civil Protection Department, to evaluate the extent of inundation by cyclone Apollo. Comparing the different temporal aggregations, the two-hour aggregation produced the closest estimate of the total inundated area when compared to the baseline scenario. In order to evaluate the potential benefit to the Civil Protection Department's warning system, a synthetic experiment was undertaken based on the floods triggered by heavy rainfall over Sicily following the cyclone Apollo.

To supplement the analysis over the Mediterranean region, an additional case has been investigated involving a significant and localised flood event that transpired in Central Italy in September 2022.

On the afternoon of 15 September, severe and exceedingly persistent thunderstorms formed over the inland areas of the Apennines. These storms primarily impacted the Umbria and Marche regions on the lee side of the mountains. The storm's development was attributed to the orographic forcing of a potent and stationary south-westerly airflow. This airflow was highly moist, yet locally unstable. A similar analysis to the previous case was conducted, yielding corresponding results marked by a notable degree of uncertainty due to the distinctly localised nature of the case.

The findings of these simulations highlight the significant advantages that EPS-Sterna would provide during severe meteorological events. It would greatly enhance the capability for monitoring precipitation, particularly when the ground network may not be fully operational. Additionally, it would facilitate the timely alerting of municipalities, ensuring the safety of the population and the protection of the territory.

3.2.4. Constellation configurations

The ECMWF EDA experiments demonstrate that the reference EPS-Sterna constellation of six satellites distributed on three orbital planes would be far superior to a three-satellite constellation in the Northern Hemisphere (52% more impact on 500 hPa geopotential height) and to a four-satellite constellation on two orbital planes (38.3% more impact). The reference constellation had only marginally inferior impact (8.4% less) than a constellation of eight satellites distributed on four orbital planes (see Figure 3.19a).

The marginal improvement of a four-satellite constellation on two orbital planes over a three-satellite constellation on three planes (8.9% more impact) demonstrates the value of additional orbital planes. The Météo-France OSSE study arrived at the same conclusion, also showing the superiority of a four-satellite constellation on three orbital planes over four-satellites flying on only two planes.

Likewise, in the conditions of the Norwegian regional OSSE, the six-satellite EPS-Sterna constellation had much higher additional impact on twelve hour forecasts through direct assimilation in the AROME-Arctic NWP system than constellations of three and four satellites (see again Figure 3.13) and was the only constellation with higher positive impact than the negative impact of the loss of the primary Metop-B satellite – close to 1.5 times that negative impact.

The reference constellation of three pairs of satellites flying on three equidistant orbital planes thus emerges as an optimum configuration from an impact perspective. This is mainly due to the shorter time to coverage achieved by this baseline configuration (see Figures 10 and 3.19b).

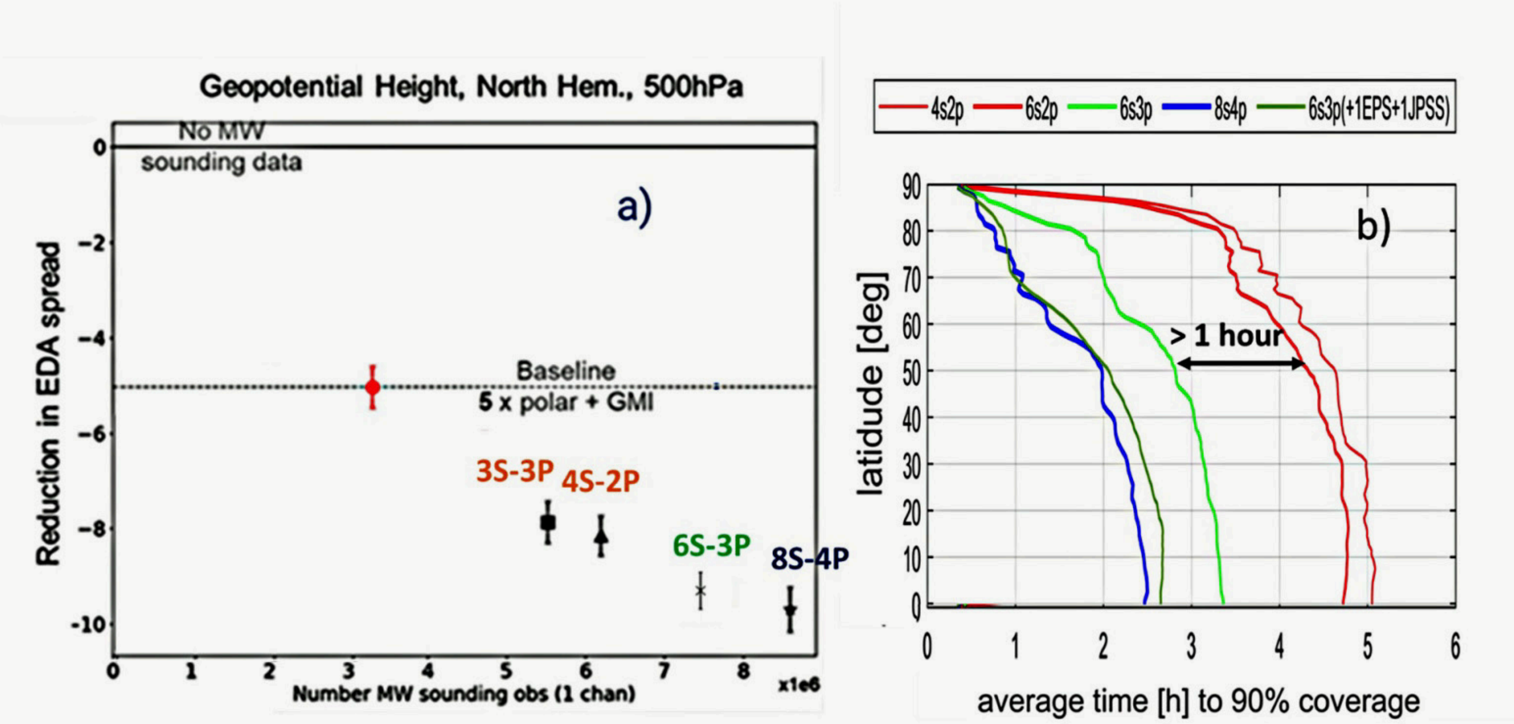


Figure 3.19. *a) Impacts of different EPS-Sterna constellations composed of N satellites distributed over M equidistant orbital planes (NS-MP) on ECMWF forecasts of geopotential height at 500 hPa in the Northern Hemisphere, as measured by normalised EDA spread reduction. b) Average time (in hours) to 90% coverage as a function of latitude, showing that the baseline 6s3p (green) constellation outperforms 6s2p (red) by more than 1 hour at 50° N. Also shown is the shorter time to coverage achieved by 6s3p plus a two-satellite IJPS (grey) which counts most from a user perspective and is equivalent to the performance of a 8s4p constellation. (Source: EUMETSAT)*

3.3. Combined contribution of EPS-Aeolus and EPS-Sterna

From a baseline observing system comprising five microwave sounders, the ECMWF EDA experiments calculated the ratio of the combined impact of 'EPS-Aeolus minus' and EPS-Sterna to the sum of their individual impacts (see Figure 3.20). The average ratio over the Northern Hemisphere and the Arctic was 93.5%. In the Tropics the ratio was 98% and in the Southern Hemisphere it was 96%.

This demonstrates that for short- to medium-range global NWP forecasts the estimated impact factors of 3% for 'EPS-Aeolus minus' and 4% for EPS-Sterna are additive at the level of 93.5% in the areas of greater interest to EUMETSAT Member States. This is a confirmation of the original, unique contribution of Doppler LIDAR observations to the skill of this type of forecast.

Moreover, the estimated 2% additional impact of EPS-Sterna on regional very-short-range forecasts through direct assimilation is original and completely independent from the inclusion of EPS-Aeolus in the observing system.

This brings the level of **additivity of the total impacts to 94.9%**, justifying investments in both systems from an impact perspective.

3.3.1. Comparison with the forecast skill impacts of Metop satellites

Simulations suggest that EPS-Aeolus and EPS-Sterna would have comparable or higher forecast skill impact than one Metop satellite, but lower impact than the pair of Metop satellites.

It is noteworthy that the impact of the primary Metop satellite has decreased in relative terms since 2011 from 24.5% to 11.15% in the FSOI metric, as three more polar-orbiting satellites (a second Metop satellite, Suomi-NPP and NOAA-20) were added to the global observing system.

However, recalling that in 2011 the impact of Metop-A was 2.5 times that of one NOAA satellite of the previous generation in the same FSOI metric, it is expected that one pair of Metop-SG satellites equipped with novel sounding instruments will have a much higher forecast skill impact in 2030 than one Metop satellite today.

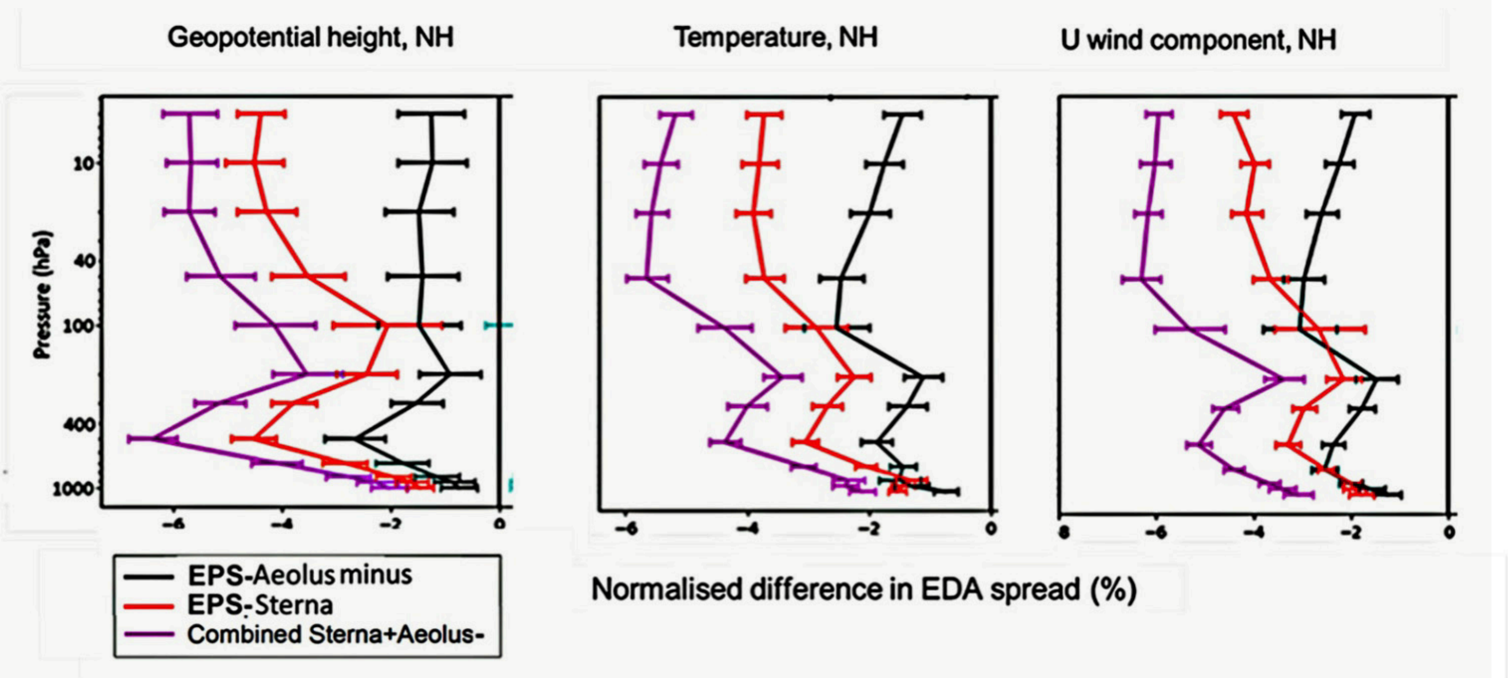


Figure 3.20. *Vertical profiles of percentage reduction in EDA spread for geopotential height, temperature and zonal wind in the Northern Hemisphere, due to the addition of EPS-Sterna (red), 'EPS-Aeolus minus' (black) and both systems (pink) to a baseline comprising five microwave sounders. (Source: ECMWF)*

3.4. Summary of findings

The findings presented above represent the outcome of several years' thorough and comprehensive testing, simulation and evaluation of the anticipated impacts of EPS-Aeolus and EPS-Sterna. The results of the operational assimilation of real Aeolus and microwave sounding data in NWP systems are consistent with those of experiments conducted using real and simulated observation for assessing the impacts to be expected from EPS-Aeolus and EPS-Sterna.

The assessment concludes that the contributions of EPS-Aeolus and EPS-Sterna to the further reduction of errors in NWP-based forecasts would be substantial across all key variables at global and regional scales, from the very short range to the medium range.

The optimum EPS-Sterna constellation from an impact perspective comprises three pairs of, satellites distributed over three equally spaced orbit planes.

Forecast skill impact factors over the mid-latitudes of Europe of **3% for EPS-Aeolus** and **6% for EPS-Sterna** have been determined for assessing socio-economic benefits to EUMETSAT Member States. Impacts for EPS-Sterna will increase to 9 % in the Arctic.

One unique feature of Doppler LIDAR observations is their persisting forecast skill impact across the medium range in the mid-latitudes of the Northern Hemisphere. The 3% skill impact factor takes no account of this, nor of unsimulated improvements over the Aeolus prototype, nor the significant scientific innovation potential of this novel instrument.

One specific feature of EPS-Sterna observations is their expected additional impact on very-short-range regional forecasts through direct assimilation in high resolution regional NWP systems, which accounts for 2% of the 6% skill impact factor. Moreover, EPS-Sterna would improve forecasts of large-scale precipitation in the medium range and mesoscale precipitation in the very short range.

The impacts of EPS-Sterna and EPS-Aeolus would be **additive at the level of 94.9%**, justifying investments in both systems from an impact perspective.

In Section 4, the quantified impacts on NWP forecast accuracy presented here will be applied to the economic valuations from Section 2 to quantify the SEBs to be derived from EPS-Aeolus and EPS-Sterna.

4. Social and economic benefits of EPS-Aeolus and EPS-Sterna

This section presents the quantifiable social and economic benefits of EPS-Aeolus and EPS-Sterna through improved weather services, in the context of projected lifetime costs.

Section 2 made a conservative assessment of the economic added value for EUMETSAT Member States from weather services: 52.8 billion Euros per year of quantifiable economic benefits to selected sectors only; as well as the saving of many hundreds of lives from weather, climate and water hazards; and economic and wider wellbeing benefits equivalent to billions of Euros per year.

Section 3 presented the findings of a comprehensive programme of impact studies, concluding that a conservative assessment of the impact on forecast accuracy over the mid-latitudes of Europe is 3% for EPS-Aeolus 6% for EPS-Sterna (including benefits through direct assimilation into regional NWP systems).

This section quantifies the projected lifetime impacts of EPS-Aeolus and EPS-Sterna in terms of the incremental increase in the benefits identified in Section 2 against the total programme costs.

4.1. Costings and assumptions

EUMETSAT's latest cost estimates[132] are set out in Table 4.1.

The relationship between improved forecast skill and economic benefit has been assumed to be linear. This takes into account on the one hand the conservative approach taken to quantification in Section 2, and on the other hand the likely incomplete translation of improvements in prediction into improved action by organisations and individuals. This assumption is discussed further in Section 5.2.5.

Assuming this linear relationship, the lifetime economic benefits and benefit-to-cost ratios presented here are based on the following NWP skill impact factors:

- for EPS-Aeolus, an NWP skill impact factor of +3%; and
- for EPS-Sterna, an NWP skill impact factor of +6%.

A discount rate of 4% and an annual GDP growth of 2% have been assumed.

Other key assumptions of the socio-economic cost-benefit analysis are documented at Annex II.

	EPS-Aeolus	**EPS-Sterna**
Total cost	905	859
Net present cost	688	641
Investment lifetime	2025-2042	2025-2042
Operational lifetime	2032-2042	2029-2042

Table 4.1. *EPS-Aeolus and EPS-Sterna total costs and net present costs, discounted at 4% (million Euros), and projected lifetimes.*

4.2. Benefits of EPS-Aeolus

EPS-Aeolus has an operating design life of eleven years from 2032 to 2042, at a projected lifetime cost to EUMETSAT Member States of 905 million Euros. The resultant improvement to forecast skill, out as far as Day 10, will enable an increased lead time and more effective decision making by users across all sectors. Extrapolating the current benefits of weather services quantified in Table 2.1 and applying an NWP skill impact factor of 3.0% gives economic benefits to EUMETSAT Member States as set out in Table 4.2.

Thus a conservative assessment of the lifetime net present economic benefit of EPS-Aeolus over its 11-year operational lifetime is **13.6 billion Euros**, with a **benefit-to-cost ratio of 20**.

4.3. Benefits of EPS-Sterna

EPS-Sterna has an operating design life of thirteen years between 2029 and 2042, at a projected lifetime cost to EUMETSAT Member States of 858 million Euros. The resultant improvement to forecast skill will further increase the lead time and effectiveness of decision making by users. Extrapolating the current benefits of weather services quantified in Table 2.1 and applying an NWP skill impact factor of 6.0% gives economic benefits to EUMETSAT Member States as set out in Table 4.2. A conservative assessment of the lifetime net present economic benefit of EPS-Sterna over its thirteen-year operational lifetime is **32.7 billion Euros**, with a **benefit-to-cost ratio of 51**.

4.4. Combined benefits

The benefits to be derived from EPS-Aeolus and EPS-Sterna would be largely independent and additive. A 93.5% additivity factor is applied to global NWP impacts in order to derive the SEBs expected from both in combination. The regional NWP impacts of EPS-Sterna are fully additive. Thus the lifetime net present benefit of EPS-Aeolus and EPS-Sterna in combination is assessed at **44.2 billion Euros**, as detailed in Table 4.2, with a **benefit-to-cost ratio of 33**.

Whilst these benefits are considerable, the methodology necessarily introduces uncertainties in the valuation of the SEB impacts. These are discussed in detail in Section 5, below.

Sector	EPS-Aeolus	EPS-Sterna	EPS-Aeolus and EPS-Sterna
Property and infrastructure	1,700	4,100	5,500
Transport	3,400	8,200	11,000
Energy	1,900	4,600	6,200
Agriculture	2,200	5,300	7,100
Water management	300	800	1,000
Other business sectors	200	400	600
Individual citizens	3,900	9,300	13,000
TOTAL	**13,600**	**32,700**	**44,200**
Benefit-to-cost ratio	20	51	33

Table 4.2. *Lifetime net present economic benefit of EPS-Aeolus, EPS-Sterna, and both in combination, to EUMETSAT Member States (million Euros).*

5. Uncertainties in the valuation of benefits

There are uncertainties in the valuation of benefits, and a range of benefits that cannot be easily quantified.

The methodology applied in Section 4 extrapolates the quantified SEBs of current weather services to the period 2030–2042, and apportions the additional benefits due to EPS-Aeolus and EPS-Sterna using the skill impact factors derived in Section 3. There are implicit uncertainties in this approach, and the methodology excludes some key benefit areas that are not amenable to quantitative analysis.

This section presents a qualitative description of these uncertainties along with indications, where possible, of their impacts on the overall benefit assessment.

5.1. Future escalation of benefits

Looking ahead to the operational lifetime of EPS-Sterna and EPS-Aeolus (out to 2042), the benefits of weather services have been escalated from today's using an assumed average GDP growth rate of 2%. This is based on the rather robust assumption that the benefits of weather services in developed countries are proportional to GDP: avoided costs increase with the value of assets vulnerable to weather, while the direct added value of forecasts for weather-sensitive sectors increases with the size of the economy. However, this 2% escalation takes no account of:

- additional avoided (and unavoided) costs from the increasing frequency and severity of weather, climate and water hazards due to the changing climate; or of
- growth in the application of forecast information across the economy as NWP skill continues to improve.

5.1.1. Impact of climate change

A joint study[133] by Caisse Centrale de Reassurance, the French public reassurance company for natural disasters, and Météo-France shows that by 2050 the annual cost of droughts, floods and coastal inundation would increase by 20–35% (depending on the IPCC[m] scenario followed), not including the cost impact of GDP-driven increases to the value of insured assets and their associated insurance premiums. This suggests an additional increase of at least 0.6–0.9% per year in avoided costs. Extending this to all EUMETSAT Member States, a 0.75% additional average annual growth due to climate change impacts on Property and Infrastructure alone would increase the 5.5 billion Euros in benefits identified in Section 4 by a further 0.5 billion Euros. In addition there would be further unquantified benefits from hazards not properly simulated by climate models and from further adaptation measures based on weather services.

5.1.2. Advances in forecast services

The SEB assessment takes no account of additional benefits during the operating timeframe due to continued improvements in absolute forecast accuracy and the capacity of weather services. It is to be expected that substantial progress will be made through advances in Earth system science, investment in further high-quality observations and the ongoing development of forecasting systems through more powerful High Performance Computing and data-driven technology. In particular, the ongoing fast integration of Machine Learning and NWP[134,135] is expected to boost forecast accuracy and significantly increase the capacity of forecasting systems to extract information content from observational data.

Such improvements will disproportionately increase the benefits from forecast information as higher accuracy renders it suitable for new decision making areas.

The weather services market has grown strongly over recent years: a recent assessment of 19 European nations[136] reports an average market growth rate of 8.6% between 2010 and 2020 (see Figure 5.1), and It is reasonable to assume that benefits to customers have increased by at least the same rate.

m Intergovernmental Panel on Climate Change

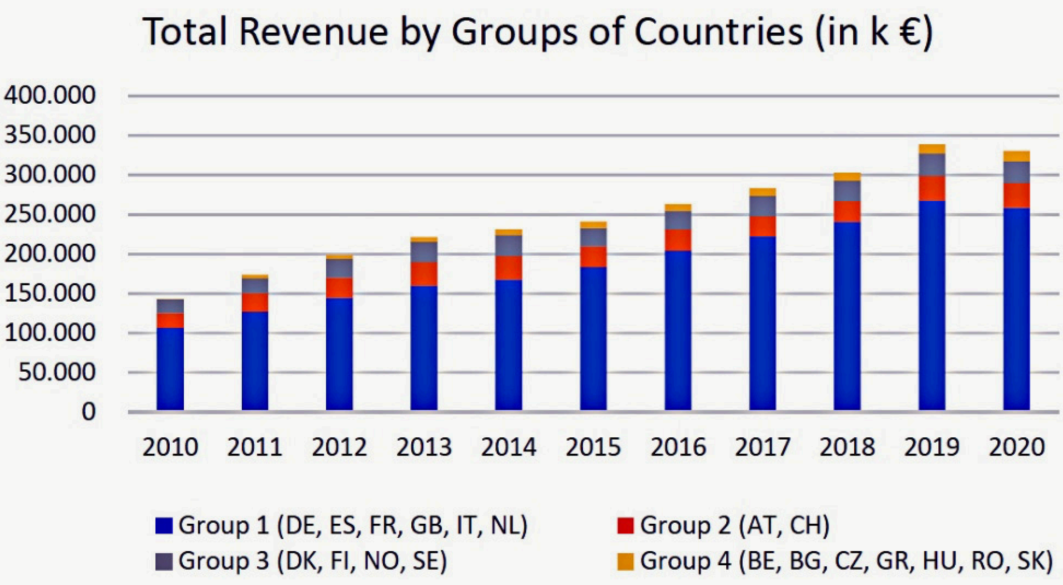


Figure 5.1. *European meteorological services private sector revenue, 2010–2020. (Source: Gruninger-Hermann (2022))*

Looking ahead, leading analysts[137] predict global growth of 7–13% per annum in this market over the next five years. This is likely to continue through the lifetime of EPS-Aeolus and EPS-Sterna as forecast skill continues to advance. If such improvements were to produce an additional average annual benefit growth of 2% in the sectors identified in Section 2.2, this would magnify the incremental benefits from EPS-Sterna and EPS-Aeolus, adding a further 7 billion Euros to their lifetime benefits, and raising the benefit-to-cost ratio from 33 to 39.

5.2. NWP skill impact assessment

As detailed in Section 3, the NWP skill impact assessments were generally interpreted in a conservative manner to avoid overestimation of benefits. Furthermore, these assessments were necessarily based on the data available at the time along with affordable observation simulations, and could therefore not capture the full extent of skill impacts expected from EPS-Aeolus and EPS-Sterna.

On the other hand, the estimated NWP skill impact of EPS-Sterna depends on the assumed backbone microwave observing constellation to which the system was added by simulation: the incremental NWP impacts would decrease if added to a more capable observing system.

The skill impact factors used in the SEB evaluation are therefore subject to several of sources of underestimation and uncertainty. These are considered below including, where possible, an assessment of their potential impact on the benefit-to-cost ratio.

5.2.1. Limitations due to the data available

The full observation capacity of EPS-Aeolus could not be simulated, and forecast skill impacts could only be assessed for the much less capable 'EPS-Aeolus minus', delivering no more usable information than the Aeolus precursor. This approach ignores two key advantages of EPS-Aeolus:

- twice the vertical resolution of Aeolus, from the surface to 30 km altitude, enabling better characterisation of vertical wind shear; and
- Mie mode in the planetary boundary layer, in the presence of aerosols and in the absence of clouds, multiplying the number of such observations by more than three compared to Aeolus and 'EPS-Aeolus minus'.

Thus EPS-Aeolus will have a true vertical profiling capability that Aeolus did not have and which could not be simulated.

Looking ahead, the scientific innovation potential of EPS-Aeolus is considerable, as it involves completely novel observations available only since 2018. Research in the coming years will improve methods for assimilating EPS-Aeolus observations and will develop further applications for their exploitation.

For EPS-Sterna, the simulations could only assess the impact of the subset of channels shared with current MW sounders, so the wider beneficial impact of the full EPS-Sterna sounding capability on global and regional NWP could not be assessed. In particular, the EPS-Sterna microwave sounders will have new capabilities for water vapour and ice water path using three high-resolution (10 km at nadir) channels in the 325 GHz water vapour absorption band, which will also be available on the Metop-SG Ice Cloud Imager.

5.2.2. Baseline definition

Defining the microwave sounder baseline to which EPS-Sterna is added has significant implications for the impact assessment.

The ECMWF studies assumed a baseline of five microwave sounders: if EPS-Sterna were considered as an addition to a baseline observing system of seven sounders, ECMWF's skill impact would be overestimated.

Looking ahead to the operational timeframe of EPS-Sterna (2029–2042), a backbone observing system of only five sounders might be viewed as conservative, but this would be the reality if a dual satellite IJPS configuration could not be maintained through the 2030s: only one pair of Metop-SG satellites would be in operation after the de-orbiting of Metop-C, and the five sounder baseline assumes that two JPSS satellites remain in orbit, together with two Chinese satellites with fully functional microwave sounders (noting that the Chinese Meteorological Administration has experienced failures of several microwave temperature sounders on board FY-3 satellites).

Conversely, the baseline observing system could comprise seven microwave sounders if, for instance, China confirmed its commitment to the early morning orbit (thus providing microwave sounders on three orbits) and if three (instead of two) JPSS satellites remained available as a result of lifetime extensions; but such a scenario cannot be taken for granted.

Should the baseline observing system comprise seven sounders instead of five, the ECMWF study suggests that the EPS-Sterna skill impact of global NWP in the Northern Hemisphere would drop from the assumed 4% to 3%.

Because of the redundancy of the orbits of two Chinese satellites, the skill impact on regional NWP should be less affected, being driven by the unique space/time sampling and timeliness of EPS-Sterna and JPS observations. At latitudes below 60° N, it may be assumed that the frequent MTG-S infrared soundings usable only in cloud-free conditions and the all-weather EPS-Sterna microwave soundings would bring complementary NWP skill impacts. The total NWP skill impact of EPS-Sterna would therefore drop from 6% to 5%, which would bring the overall benefit-to-cost ratio from 33 to 29.

The 3% NWP skill impact of the novel and unique observations of EPS-Aeolus would be unaffected.

5.2.3. The Global Observing System

Previous global NWP skill impact assessment studies of Metop satellites by ECMWF and Météo-France have shown that while the percentage contribution of Metop to forecast error reduction remains substantial, it has significantly decreased since 2011, with three more polar-orbiting satellites of the same class being added to the Global Observing System.

It is unlikely that the same could happen with EPS-Aeolus, as Doppler LIDAR observations of wind profiles are novel, unique and with such sampling limitations (no swath) that the impact of a second Doppler LIDAR should be fully additive.

In contrast, a similar decrease is likely with EPS-Sterna, as state-of-the-art instrument and small satellite technologies are available to several space faring nations; indeed, NOAA plans to start deploying a first small constellation of microwave sounders in the early 2030s as part of the preparation for its post-JPSS programme. Lifetime extensions of Metop-SG and the last JPSS satellite may also bring additional microwave soundings for some time, although this is more speculative.

Based on this outlook, it might be assumed that the NWP skill impact of EPS-Sterna would be halved in 2036 and would further decrease at the relative rate observed for Metop satellites (i.e. from 3% in 2036 to 2% in 2042). This assumption would reduce the lifetime economic benefit for EPS-Sterna by 10 billion Euros and the benefit-to-cost ratio from 51 to 36. The combined benefit-to-cost ratio would reduce from 33 to 26.

In the most unlikely case that an operational microwave sounding constellation of the same class as EPS-Sterna were to start operations much earlier, in 2030, assuming then that the NWP skill impact of EPS-Sterna would be halved in 2031, further falling at the relative rate observed for Metop satellites (i.e. from 3% in 2031 to 1.2 % in 2042), the lifetime benefit loss for EPS-Sterna would be 19 billion Euros with the benefit-to-cost ratio falling from 51 to 21. The combined benefit-to-cost ratio would reduce from 33 to 19.

This revised estimate could, however, be misleading, since additional benefits would accrue for Europe as a result of the improvements of absolute forecast accuracy enabled by these further enhancements of the Global Observing System. If the ESA and EUMETSAT Arctic Weather Satellite programme and EPS-Sterna did encourage international partners to deploy a similar constellation, the benefit-to-cost ratio of EPS-Sterna may arguably increase beyond initial expectations as a combined result of both direct and leveraged benefits.

5.2.4. Specific benefits of nowcasting

The SEBs quantified in Section 2 cover the full range of timescales, including data and information on current conditions and the next few hours ahead, referred to by the meteorological community as nowcasting.

While NWP forms the basis of almost all weather forecast services beyond a few hours ahead, this is not the case for nowcasting, making the impact of EPS-Sterna and EPS-Aeolus on nowcasting services more difficult to assess.

Nowcasting aids situational awareness, particularly for high-impact weather events. While it is critical for the saving of lives in fast-evolving severe weather – especially if not well predicted by NWP – it is inadequate for business re-planning in many sectors. Nowcasting adds specific benefits only in areas with short response times for operational adjustments, for example in the real-time management of infrastructure such as transport, where roads, railways or airport runways can be closed at short notice to minimise risk. Therefore, nowcasting is likely to account for only a few percent of the total SEB valuation in Section 2.

For the purpose of assessing the significance of nowcasting to the benefits of EPS-Aeolus and EPS-Sterna, an assumption is made that 5% of the total SEBs in Section 2 accrue from nowcasting services.

EPS-Aeolus is unlikely to make a significant direct contribution to nowcasting due to space-time sampling limitations; deducting 5% from the EPS-Aeolus SEB calculation would reduce the benefit-to-cost ratio of EPS-Aeolus from 20 to 19.

By contrast, EPS-Sterna's frequent and wide-swath observations will add significant nowcasting skill (see Section 5.3.1), which could compensate for the overestimation of benefits from NWP-based services. It is therefore uncertain whether the net impact would be negative or positive from including nowcasting in the SEB assessment for EPS-Sterna.

5.2.5. Sensitivity of SEBs to NWP skill

The methodology applied in Section 4 assumes a linear relationship between forecast accuracy and SEBs, integrated across all sectors where quantification is possible, such that a reduction in NWP error due to a new observation source will yield a directly proportionate increase in SEBs.

Forecasts would be worthless with no observations from which to construct a realistic initial state – the SEBs of current forecasts would not be achieved without the full set of assimilated observations, and it is clear that better forecasts will increase total benefits. However, the complex sensitivity of benefits to forecast accuracy across all sectors makes it difficult to judge whether the linear assumption is optimistic or pessimistic. On the one hand, the quantification of benefits in Section 2 is conservative (see Sections 5.1 and 5.4); on the other hand, it is unlikely that improvements in prediction will always translate into improved actions by organisations and individuals.

The impact of adopting a more, or less, pessimistic assumption is shown in the sensitivity analysis at Section 5.6.

5.3. Unquantified contributions

5.3.1. EPS-Sterna contribution to nowcasting

While the current specific benefits of nowcasting represent an unknown fraction of the benefits quantified in Section 4 (see Section 5.2.4), EPS-Sterna's frequent, rapidly available and wide-swath observations, combined with those delivered by the NOAA-EUMETSAT IJPS from two complementary orbits, will provide an integrated set of microwave soundings as a key asset for nowcasting applications.

EPS-Sterna offers nowcasting benefits across all mid-latitude regions, but it will bring particular benefits at high latitudes where few conventional observations are available – for example in monitoring extreme phenomena such as polar lows. Its new 325 GHz channels are particularly sensitive to the presence of snow and ice, in addition to water vapour, and would therefore improve the characterisation of low cloud and precipitation in Northern latitudes. Thus EPS-Sterna will make a key contribution to the 2023 World Meteorological Congress' commitment to monitoring the impacts of changes in the cryosphere as a top priority[138].

The application of Machine Learning techniques is expected to deliver substantial improvements in the skill, time-range and utility of nowcasting systems in the coming years[139,140], so amplifying the benefits of EPS-Sterna observations (see box).

The overall impact of EPS-Sterna on nowcasting cannot be quantified but it will contribute to saving lives and to the fraction of nowcasting-specific economic benefits, and thus compensate for any overestimation of NWP-driven benefits identified in Section 5.2.4.

Machine learning for nowcasting at high latitudes

EPS-Sterna will improve the sampling frequency of passive microwave data globally and in particular at high latitudes. This will potentially be of value for many applications, including precipitation nowcasting.

A study[141] by the Swedish Meteorological and Hydrological Institute investigated this using a data driven model. The model was trained to predict data from the Baltic Sea Region weather radar network using passive microwave data from existing weather satellites. The short range (less than four hours) forecasting performance of the model was evaluated for summer and winter periods and over ocean and mountainous areas, at times of day when the current polar orbiting systems provide good (EPS-Sterna like) data coverage.

The model was found to provide a better performance than that of a persistent forecast for all considered performance indicators – the best performance in May over the ocean, with significantly lower performance in December. (Table 5.1).

The impact of data from one satellite sensor on the model prediction was then assessed to use as a proxy to model the impact of EPS-Sterna data on prediction performance.

The study indicates that an overall benefit of EPS-Sterna for data driven precipitation nowcasting is that it allows for frequent updates of forecasts, with a prediction performance that is close to constant throughout the day. The greatest performance increase is expected when EPS-Sterna fills a gap that currently has several hours with no data – performance increasing by about 20% where the lead time is reduced by 120 minutes. At times when EPS-Sterna provides data relatively close to other observations, performance increases by approximately 5%.

	POD	FAR	POD	FAR
Lead time	15 mins		240 mins	
May (ocean)	0.75	0.2	0.55	0.3
December	0.6	0.4	0.4	0.5

Table 5.1. *Precipitation forecast probability of detection (POD) and false alarm rate (FAR) for May and December.*

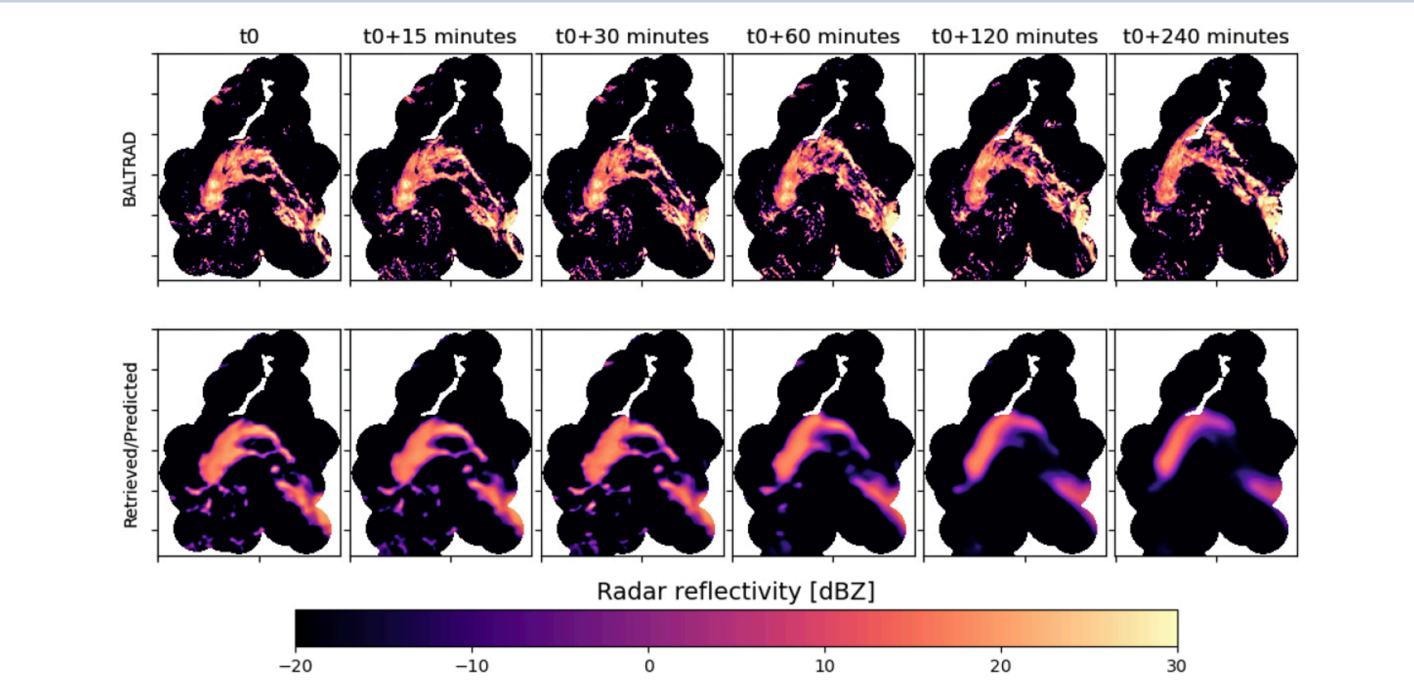


Figure 5.2. *Example prediction initiated at 12:00 UTC on 17 May 2021. Upper row: data based on evolution of radar reflectivity; lower row: predicted data (posterior mean). (Source: Rydberg et al. (2023)*

5.3.2. Contribution to sub-seasonal, seasonal and climate services

EPS-Aeolus and EPS-Sterna will deliver benefits primarily from improvements to nowcasting and short- to medium-range forecasting. However, the additional observations will also have some beneficial impact on sub-seasonal, seasonal and climate services through improved monitoring, model initialisation and reanalysis.

The skill and reliability of sub-seasonal and seasonal outlooks is greater at lower latitudes, often giving useful early indication of regional droughts, floods and other climate-related risks. Across more northern areas of Europe, forecasts at this range are generally less skilful; however, both EPS-Aeolus and EPS-Sterna will contribute to improved initialisation of sub-seasonal and seasonal outlooks. Of particular note is EPS-Aeolus' ability to characterise variations in the jet stream, vertical shear in the Tropics and the evolution of the Quasi-Biennial Oscillation.

Satellite observations play an increasingly important role in climate monitoring, and the instrument complement of EPS-Sterna has been designed to provide consistency and continuity with the current EPS-SG observations used for assessing climate variability and change over decades, and for validating the Earth system models used to deliver climate projections.

Reanalysis is a powerful technique used by ECMWF and other global NWP centres for monitoring climate change, for research and education, public information and commercial climate services (including the EU's Copernicus Climate Change Service). The quality of reanalysis data ultimately depends on the observational data assimilated, so the accuracy of future reanalyses will benefit from the assimilation of EPS-Aeolus and EPS-Sterna data, especially in data-sparse tropical and oceanic regions. This will add value that has not been captured in the SEBs quantified in Section 4.

5.4. Unquantified benefits

The SEB assessment in Section 4 is limited in scope to those impacts of EPS-Aeolus and EPS-Sterna amenable to evaluation. This section presents a qualitative description of benefits not easily quantified, and therefore missing from the assessment.

5.4.1. SEB valuation of weather services

The quantification of the benefits of weather services to Member States presented in Section 2 is incomplete, as no valuation is made of:

- the many hundreds of lives saved each year from weather, climate and water hazards;
- wider economic and wellbeing benefits to citizens equivalent to billions of Euros per year (see Section 2.1.1, final paragraph);
- benefits of weather services not included within the source studies upon which sector valuations were based (see for example Volcanic ash advisory services for aviation, right);
- increased capital investment and fiscal stability and reduction of future credit risks through improved disaster risk management; and
- the reduction in carbon emissions due to more efficient operations, for example in transport, energy generation and supply, agriculture and other industry sectors.

5.4.2. Forecasts for tropical regions and the Southern Hemisphere

Large areas of the Tropics and Southern Hemisphere are oceanic, sparsely populated or lack the observing infrastructure necessary for accurate and effective weather and climate services. In these regions, which include territories of some EUMETSAT Member States, satellite data provide vital inputs for NWP systems to analyse and predict atmospheric conditions, but forecast skill in the short- to medium-range still lags behind that for the Northern Hemisphere. EPS-Aeolus and EPS-Sterna will reduce forecast errors at all latitudes, as presented in Section 3, but the impact is even greater in these regions where conventional observations are sparse.

Thus EPS-Aeolus and EPS-Sterna will help to consolidate the United Nations' objective to achieve early warning systems for all[142], as well as benefiting EUMETSAT Member States through improved weather services in relation to distant territories, international development and global trade. Such benefits have not been quantified.

Volcanic ash advisory services for aviation

The valuation of weather services to the aviation sector (Section 2.2.1) is based on studies restricted to fuel savings and other operational efficiencies. EPS-Aeolus offers a significant additional contribution through improving the volcanic ash advisories provided by NMHSs, which predict the transport, dispersion and deposition of volcanic ash hazardous to aviation.

The eruption of the Icelandic volcano Eyjafjallajökull in 2010 clearly demonstrated the massive impact volcanic ash can have on aviation, leading to the cancellation of an estimated 107,000 flights over a ten day period, affecting ten million passengers, with a loss of revenue to the airline industry of around 2.6 billion Euros[143].

Volcanic ash forecasts use prediction systems based on NWP. The greatest uncertainties are the initial conditions at the eruption site, in terms of eruption height and mass of emission. Observations of the vertical distribution of ash help significantly in refining uncertainties in the distribution of volcanic ash and provide valuable verification data for dispersion modelling.

The Aeolus prototype demonstrated its ability to see volcanic ash during the Hunga Tonga eruption in 2022. EPS-Aeolus, with its enhanced vertical resolution and greater sensitivity, will provide valuable measurements of the altitude and depth of ash clouds and their evolution along the satellite track – essential information for adapting air traffic management to risks, in particular for ascents after take-off and descents prior to landing.

5.4.3. Economic sectors not quantitatively assessed

Weather and climate services deliver benefits to a range of economic sectors that are not quantified in Section 2, but are likely to be substantial. EPS-Aeolus and EPS-Sterna are expected to further enhance the benefits to these sectors.

Chemical, biological, radiological and nuclear services

NMHSs have an important role in supporting governments' response to major chemical, biological, radiological and nuclear incidents. Notable emergencies involving European NMHSs in the last two decades include:

- a tsunami off the coast of Japan in 2011, which led to the most severe nuclear accident since the Chernobyl disaster. The release of radioactive material into the atmosphere from the Fukushima nuclear plant prompted the evacuation of more than 150,000 people[144];
- the major explosion at Buncefield oil storage facility in the UK in 2005, resulting in the largest peacetime industrial fire to date in Europe: the fire burned for four days before it was extinguished and its smoke plume affected much of South East England[145]; and
- animal disease outbreaks from airborne pathogens such as foot and mouth disease (UK, 2001)[146] and bluetongue disease (northern Europe, 2006–2008)[147], with devastating impacts for livestock farmers.

Such incidents can present an imminent danger to citizens and livelihoods so accurate, timely advice is essential. The transport, dispersion and deposition of airborne hazards are predicted by NMHSs based on NWP forecasts. EPS-Aeolus and EPS-Sterna will contribute towards improving the accuracy of such services, and so helping to protect citizens and livelihoods.

Health

Healthcare costs amounted to more than 1,700 billion Euros across the EU in 2020 – around 10% of GDP[148]. Health services benefit from weather and climate services that support preparatory actions in health service operations and help citizens stay safe and well. Thus value accrues both to the national health burden and to impacted individuals, in terms of avoided deaths, welfare benefits including avoided hospital admissions, and cost savings from avoided accident and emergency visits, hospital admissions and general practitioner consultations[149].

A review of the impact of implementing heat health action plans following the 2003 heatwave reported lower excess mortality from subsequent heatwaves in Germany, France, Spain, Italy and the UK[150]. Whilst the economic benefits for EUMETSAT Member States have not been quantified, a recent World Bank report[151] found that heatwave early warnings in France provide significant benefits, with a mean benefit-to-cost ratio of 131.

Climate change will bring both positive and negative health impacts: a reduction in cold-related risks but an increase in heatwave impacts and other hazards, including climate-sensitive diseases such as dengue fever[152]. EPS-Aeolus and EPS-Sterna will contribute towards improving the accuracy and utility of forecast services for the health sector, and so the SEBs of weather services for the health sector will continue to increase.

Defence and security

Weather information is essential for most military and security operations, including United Nations led peace-keeping and humanitarian operations. Considering the human, geopolitical and financial challenges and the dynamic, demanding, logistically challenging and time-sensitive nature of such operations, it is crucial that they are conducted with the best possible meteorological support.

No study has yet been published to quantify the SEBs of improved weather services for defence and security operations, but given the military commitment across all EUMETSAT Member States it is clear that improving military decision making through better weather forecasts will have significant SEBs.

Copernicus atmosphere and marine services

Additional benefits are expected from specialised services of the EU's Copernicus programme, which require weather observations and forecasts as inputs – in particular, the Atmosphere Monitoring Service and the Marine Environment Monitoring Service, along with their associated downstream services provided by both the public and private sectors.

Air quality forecasts are used by public and private decision makers to maintain atmospheric pollution levels below harmful thresholds for health through emission regulation measures. Marine forecasts, in the open sea and in coastal zones, are also highly dependent on accurate forecasts of surface pressure and winds. This is the case for the prediction of sea state, storm surges, surface currents and the transport and dispersion of marine surface pollution.

It can therefore be assumed that a fraction of the benefits of relevant Copernicus services can be attributed to the performance of weather forecasts and hence to EPS-Aeolus and EPS-Sterna.

In addition, EPS-Aeolus will profile aerosols, and, if dual polarisation can be implemented, will provide information on aerosol type as a specific contribution to the Copernicus Atmosphere Monitoring Service, for assimilation into air quality prediction models and for validation of forecasts.

5.5. Wider benefits

5.5.1. Benefits to the European space industry

EPS-Aeolus and EPS-Sterna will be major investments that directly benefit the European space industry and its contribution to GDP. They will contribute to the implementation of European Space Policy, being user-driven and delivering direct benefits to European citizens. They will be a driving force for innovation, competitiveness, growth and the preservation and creation of highly-qualified jobs, thereby contributing to the EU's strategic priority of developing a strong and vibrant economic base[153].

5.5.2. Leverage benefits from other satellite operators

A further benefit referenced in Section 5.2.3 is the 'leverage' accruing from the deployment of additional Doppler LIDARs and constellations of advanced microwave sounders by international partners, encouraged by the decision of ESA and EUMETSAT to invest in EPS-Sterna, EPS-Aeolus and EPS-SG.

The benefits to Member States would evolve from the direct benefits of EPS-Sterna and EPS-Aeolus to a more attractive combination of direct and leveraged benefits. Thus both total benefits and the benefit-to-cost ratios of EPS-Aeolus and EPS-Sterna would exceed initial expectations. (It should be noted that such benefits will be realised only if real time data are shared between EUMETSAT and relevant international partners, as is the case today with the United States and China, in line with WMO's Unified Data Policy[154].)

5.5.3. Europe's International leadership

Together with EPS-SG, EPS-Aeolus' and EPS-Sterna's unique, high value, real-time datasets will deliver a substantial contribution to the global Earth observations capability and critical observational inputs to early warning systems, as weather-, climate- and water-related hazards pose increasing risks across the world.

By investing in these systems, through worldwide collaboration (assuming EUMETSAT adopts WMO's full, free and open Unified Data Policy), Europe will lead the way to a collective global realisation of WMO's Vision 2040 and the United Nations' objective to provide Early Warnings for All (Figure 5.3).

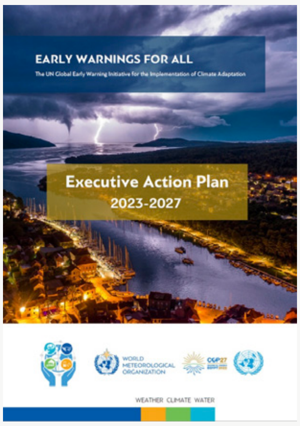


Figure 5.3. *Early Warnings for All Executive Action Plan 2023–2027 (Source: WMO)*

5.6. Implications for the benefits case

All SEB studies will be sensitive to the methodology applied and to the assumptions made for the purpose of simulations, due to missing data, or due to shortcomings of published research.

However, the discussion above shows that for EPS-Sterna and EPS-Aeolus the combined benefit-to-cost ratio of 33 reflects a fair balance between the likely underestimation of SEBs of weather services in the 2029–2042 timeframe and uncertainties that could lead to overestimation of the NWP skill impact of EPS-Sterna, if the observing system of the 2030s differs from the baseline assumptions. Even assuming no underestimation of weather service SEBs and the unlikely deployment of another constellation of microwave sounders in the same timeframe as EPS-Sterna, the overall benefit-to-cost ratio would still be 19.

The main sources of unquantifiable uncertainty are the sensitivity of SEBs to the percentage reduction of forecast errors (the linear assumption), and the level of underestimation of the benefits of weather services in the 2029–2042 timeframe:

- there is no robust alternative to the linear assumption that the estimated percentage forecast skill impact of the simulated addition of EPS-Aeolus end EPS-Sterna to a realistic baseline observing system is a reasonable measure of its percentage of contribution to the SEBs; and
- the underestimation of lifetime benefits of weather services is dependent on the magnitude of unquantifiable benefits, further improvements in forecasting systems in the 2024–2042 timeframe and the response of established and emerging applications to these expected improvements.

Table 5.1 analyses the sensitivity of the benefit-to-cost ratios to both of these unquantifiable uncertainties. Varying the ratio of SEB impact to NWP skill impact between 50% and 150% gives a combined benefit-cost-ratio of between 17 and 50. Scaling SEBs by 25% or 50% to take account of underestimated and unquantified benefits increases the combined benefit-cost-ratio from 33 to 42 or 50.

This analysis makes clear that the full potential impact of EPS-Sterna and EPS-Aeolus will only be realised if accompanied by parallel investments in the development of forecasting systems, and in 'final mile' service solutions that optimise user decision making.

	EPS-Aeolus			EPS-Sterna			EPS-Aeolus and EPS-Sterna		
SEB impact to NWP skill impact ratio	Impact of underestimated and unquantified lifetime benefits								
	100%	125%	150%	**100%**	125%	150%	**100%**	125%	150%
50%	10	12	15	25	32	38	17	21	25
75%	15	18	22	38	48	57	25	31	37
100%	**20**	25	30	**51**	64	76	**33**	42	50
125%	25	31	37	64	80	96	42	52	62
150%	30	37	44	76	96	115	50	62	75

Table 5.1. *Sensitivity of benefit-to-cost ratios to variations in the ratio of SEB impact to NWP skill impact (50–150%), and to the potential additional impact of underestimated and unquantified lifetime benefits (100–150%).*

6. Conclusion: the case for EPS-Aeolus and EPS-Sterna

There is a clear and compelling socio-economic benefit case for EPS-Aeolus and EPS-Sterna, delivering benefits of many times their cost. Investing in EPS-Aeolus and EPS-Sterna will help to maintain Europe's leadership in satellite meteorology, weather forecasting and climate monitoring from space, pioneering new approaches that will inspire other nations to follow.

Weather and climate services have been shown to be among the most cost effective adaptation measures to climate change. The SEBs of weather and climate services to Europe are very substantial, benefiting all sectors of society through decisions that protect citizens, reduce loss and damage, improve organisational efficiency and safeguard wellbeing.

The accuracy and reliability of forecasts depend on the availability of the relevant, high quality observations critical for initialising the NWP systems that are the backbone of modern forecasting. Without such observations the forecasts would have no skill.

Since the 1980s, satellite observations have been increasingly used within NWP systems. Over the past 40 years, forecasting accuracy has improved dramatically, typically with an increase of one day's predictability per decade in the medium range. The increased availability of high quality satellite observations has been one of the principal contributors to this improvement, with satellite-derived data now often contributing more than 75% of NWP forecast skill[155]. The improvement in skill presented in Section 3 exceeds the impact of one additional Metop satellite.

By assessing the SEBs of weather and climate services in a number of key areas, and then combining this information with impact assessments and NWP skill impact techniques, an assessment has been made of the likely SEBs of EPS-Aeolus and EPS-Sterna for EUMETSAT Member States.

Assuming a 4% discount rate and 2% annual GDP growth, the resultant value of the lifetime benefits of EPS-Aeolus is conservatively assessed as 13.6 billion Euros. The lifetime benefits of EPS-Sterna are similarly assessed as 32.7 billion Euros. Operating in combination, the combined lifetime benefits would be 44.2 billion Euros (Table 6.1).

When the benefit assessments presented here are contrasted with the net present cost of EPS-Aeolus (688 million Euros at 2024 e.c.), the benefit-to-cost ratio is 20. For EPS-Sterna, with a cost of 641 million Euros, the benefit-to-cost ratio is 51; and both operating in combination would give a benefit-to-cost ratio of 33.

Whilst no quantitative assessment has been made of the wider SEBs of saved lives and enhanced wellbeing, it is clear that forecast and warning information enables the saving of many hundreds of lives annually across EUMETSAT Member States, along with reduced carbon emissions and wider economic and wellbeing benefits equivalent to billions of Euros per year. Although not reliably quantifiable in economic terms, these benefits will clearly be of critical value for society.

SEBs are expected to increase over the lifetime of EPS-Aeolus and EPS-Sterna due to advances in NWP, improvements in emergency response capabilities, and the expectation of more frequent high-impact weather events. The SEB evaluation also excludes contributions due to improved nowcasting, seasonal forecasts and climate services; and from significant sectors including health, defence and security, for which benefits are not easily quantifiable. It also excludes direct benefits to the space industry.

Furthermore, the benefit estimates take no account of the leverage accruing from the availability of high-quality Doppler wind and microwave sounder observations to the worldwide user community, which will stimulate the development of comparable and complementary satellite systems by other nations. As a result of such contributions, additional observations will very likely become available for ingestion into European NWP systems, thereby achieving additional positive impacts on forecast accuracy within Europe and, consequently, further SEBs.

Sensitivity analysis shows that even with the most pessimistic microwave baseline scenario the benefit-to-cost ratio remains above 19, while varying the assumptions on the SEB impact of improved forecast skill gives benefit-to-cost ratios in the range 17 to 50.

In conclusion, there is a clear and compelling socio-economic benefit case for EPS-Aeolus and EPS-Sterna, supporting cost effective adaptation measures to climate change and delivering benefits of many times their cost

Investing in EPS-Aeolus and EPS-Sterna will deliver additional and more capable satellites, providing global coverage of vertical wind profiles not available by any other means, and filling the gaps in coverage left by ageing polar orbiters.

Deciding on these two ambitious additions to the EPS-SG constellation to enhance Europe's space-based observational capability in the 2030–2042 timeframe is a strategic investment for EUMETSAT Member States and their economies, bringing to operational fruition the investments already made by ESA in Aeolus and the Arctic Weather Satellite. This will keep Europe's leadership in satellite meteorology, weather forecasting and climate monitoring from space, pioneering new approaches that will inspire other nations to follow.

	EPS-Aeolus	**EPS-Sterna**	**EPS-Aeolus and EPS-Sterna**
Operational lifetime	2032-2042	2029-2042	
Lifetime net present costs	688	641	1,329
Lifetime net present benefits	13,600	32,700	44,200
Benefit to cost ratios	20	51	33

Table 6.1. *Summary of lifetime net present costs and net present benefits (million Euros) and benefit-to-cost ratios and sensitivity for EPS-Aeolus and EPS-Sterna.*

Annex I.
Evaluating the impact of an observation source on NWP

I.1. Assessment techniques and possible uses

There are several techniques to assess the impact of assimilating real or simulated observations on the performance of NWP systems. Whatever the technique used, the assessment of the impact of an observation source will only be robust if the NWP system and the observation system used or simulated are of high quality and well characterised in terms of error statistics.

A distinction is made between methods for assessing the impact of existing observing systems, whose data are assimilated in real time by operational NWP systems, and methods for assessing the impact to be expected from additional observations, which must be simulated. In principle, the former cannot achieve the objectives of the latter, but the interpretation of impact measurements of existing observations can give valuable indications of the contribution to be expected from a future observation system, when the latter aims to:

a. replace an existing system, improving its performance; and/or
b. increase the capacity of an existing observing system, i.e. the quantity of observations that it produces.

In case a), the measurement of the impact of an existing observation system provides an under-estimate of the impact to be expected from a future system with better performance and/or higher capacity. This is the case for EPS-SG as the replacement of EPS, and for EPS-Aeolus as the replacement of Aeolus.

In case b), the interpretation is more delicate, but one can still reason by analogy, by measuring the relative impact of an incremental increase in capacity within the existing observation system, i.e. in practice, the impact of the progressive addition of constituent sub-capacities of the existing system. This is the case for the EPS-Sterna microwave sounding constellation.

I.2. Impact of existing observation systems

The two most commonly used techniques for assessing the impact of existing observation systems are:

- the calculation of Forecast Sensitivity to Observation Impacts (FSOI) ; and
- Observation System Experiments (OSEs).

Both techniques evaluate the error of forecasts by comparing them to reference observations (radiosondes) or subsequent analyses of the NWP system, taking due account of their error statistics. Reference observations are few but system-independent and can therefore be used to assess forecast errors at all ranges, including the shortest, while analyses cannot. Indeed, the latter are partly based on a subsequent short range forecast of the same NWP system, and can therefore only be used beyond the ranges where their errors are still highly correlated with those of the forecast to be evaluated.

I.2.1 The FSOI technique

The FSOI technique uses an ‘adjoint’ model to ‘go back in time’ and attribute to the different observations assimilated by the operational NWP system the fraction of the reduction in the forecast error that is due to them, taking into account their weight in the construction of the initial state.

This technique has the unique advantage of simultaneously estimating the contributions of all observations assimilated, to the reduction of the forecast error of an energy integral (expressed in Jkg^{-1}) calculated over the entire depth of the atmosphere: the forecast error being calculated with respect to the analysis subsequently produced for the validity date of the forecast. This allows the contribution of any subset of the operational observing system to be estimated by aggregation, and the contributions of the different sources of observations to be compared directly.

However, the technique cannot evaluate the contribution of an observation source to the reduction of the forecast error of parameters other than the energy integral.

The contribution (FSOI) of each observation source is expressed in absolute (Jkg^{-1}) and relative (%) values, the sum of the relative contributions being by construction equal to 100%. Because it uses the adjoint of the tangent linear model – the closest linear model to the operational NWP system in the vicinity of the initial state – the FSOI technique is only usable for forecast ranges shorter than 48 hours, for which this model remains a good approximation.

I.2.2 The OSE technique

An OSE imposes the use of a forecast model outside its operational exploitation, in order to be able to compare at all ranges the forecast errors obtained from assimilating data from the complete observing system, and from a system deprived of the component to be assessed. The errors of the different forecasts can be calculated using reference observations, in particular for shorter ranges, or analysis, preferably for longer ranges.

The comparison focuses on the standard deviations of forecast errors of freely selectable meteorological variables, such as geopotential, temperature, humidity or wind, at standard pressure levels. For a chosen variable, the normalised forecast error reduction, expressed in %, assesses the contribution of the component of the observing system suppressed by the OSE.

The NWP systems used by an OSE to compare two observation systems are slightly different, because the error statistics of the model in the vicinity of the initial state depend on the actual observation system used. In principle, these error statistics have to be recalculated for each degraded configuration of the observation system[156].

When the OSE seeks to evaluate several sources of observations, by deleting them one after the other, the results obtained depend on the order in which the different sources are deleted. Comparisons are therefore rather hazardous, unless experiments are carried out with different sequences of removals of the different sources.

I.2.3 Complementarity and differences

The FSOI and OSE techniques address two different questions[157]:

- the FSOI technique simultaneously assesses the contributions to forecast error reduction of all observing system components that are used by the NWP system in operational conditions; whereas
- the OSE assesses the increase in forecast error that would be caused by removing the component of the observing system to be assessed, which is equivalent to assessing the error reduction induced by adding this component to a system that would be deprived of it.

The FSOI technique can only be used for 24- to 48-hour forecast ranges, whereas an OSE can handle all ranges, including the longest.

As the metrics for assessing forecast error are different, the quantitative comparison of FSOI and OSE results is problematic: the energy integral used for the FSOI calculation is quadratic in nature, equivalent to a variance, unlike the standard deviations of forecast error used by an OSE. As a result, the contribution of an observation source to the reduction in forecast error expressed by its FSOI in relative value is at least a factor of two higher than the normalised error reduction measured by an OSE[158].

On the other hand, both techniques generally rank the main observation sources in the same order in terms of impact on the forecast, when using identical high-performance NWP systems and when comparing observation systems without major deficiencies.

I.3. Impact of additional observation systems

More complex simulation methods are required for assessing the impact to be expected from a future additional observing system. They are also desirable when assessing the impact of an increase in capacity and/or performance of an existing observation system, when it is not deemed sufficient to interpret the impact measurements of existing observations of the same nature.

Two types of experiments are distinguished:

- Observing System Simulation Experiments (OSSEs) using simulations of all observations, whether from existing or future systems, and a simulation of atmospheric variability that is largely independent from the NWP system used; and
- hybrid experiments using both real observations of existing systems and simulated observations of future systems to be assessed, of which the most commonly used are data assimilation ensemble (EDA) experiments.

I.3.1 Observing system simulation experiments

An OSSE is based on a long numerical simulation that provides the best possible approximation of atmospheric variability. This 'nature run' must have been produced by a model of much higher resolution than the forecast model used for the experiments, and largely independent of it.

Long meteorological sequences are extracted from this nature run for the purposes of the OSSE. They constitute the (fictive) reality of the atmosphere used to simulate all the observations taking into account their error statistics, as well as an absolute reference for the evaluation of the errors of the various forecasts produced by OSSE.

The OSSE produces two sets of forecasts, one assimilating the simulated observations of the existing systems only, and the other those of the augmented system. For all time frames, the error reduction due to the additional simulated observations is evaluated by the normalised difference between the errors of the two sets of forecasts, calculated by reference to the nature run or a selected control run. Careful calibration must be carried out to ensure that the contribution of existing systems to the reduction of the forecast error in fictive meteorology is consistent with that measured in real operational conditions, for example by an OSE.

An OSSE is computationally very expensive, but allows, like an OSE but in fictive meteorology, the assessment of the contributions of simulated observations to the reduction of error in the forecast produced at all ranges by a well-characterised model.

I.3.2 Ensemble data assimilation experiments

Ensembles of data assimilations (EDA) are ensembles of short-range (less than twelve hours) assimilation/ forecast cycles with slightly perturbed initial conditions.

The ensemble dispersion characterises the error statistics of the very-short-range forecast used as a first guess for the assimilation of the most recent observations that determine the initial state of the operational forecast. These error statistics are an essential ingredient in the operational forecast, and reflect both the performance of the NWP system and the relevance and quality of the observations it uses. Thus, more relevant and/or more accurate observations will have the effect of reducing the dispersion of the ensemble, as measured by a variance or standard deviation.

Ensemble data assimilation experiments compare the dispersions obtained by assimilating the real observations of existing systems with those obtained by adding the simulated additional observations. Thus, these experiments make it possible to evaluate, in real meteorological conditions, the impact of simulated additional observations on the initial state and on the very-short-range forecast produced by an NWP system that already assimilates the existing observations.

The additional observations are simulated taking into account their error statistics and using, as an approximation of the atmospheric reality, the series of analyses produced by a higher resolution version of the model used in the experiment. The normalised dispersion reduction (spread, expressed in %) produced by the introduction of the additional simulated observations is a measure of the positive impact to be expected from these observations, all other things being equal.

I.3.3 Complementarity and differences

Like the FSOI and OSE techniques, the EDA and OSSE experiments are complementary, in that the former assess the impact of future observations on the initial state and the forecast at very short range, while the latter can deal with all forecast ranges. They give different answers to the same question of estimating the impact of an change in the observation system on the performance of the forecast.

The low-cost EDA experiments only deal with the impact on the error statistics of the very-short-range forecast – which largely influences the forecast at longer ranges – but are carried out in real meteorology and with real observations from existing systems. The new observations are simulated from a series of analyses produced by a much higher resolution version of the model, which is the best approximation of the meteorological reality, although this does not completely rule out correlations between the simulated observations and the forecast of the lower resolution model.

Much more expensive, OSSEs are more general in scope, but are carried out in fictive meteorology, using the known observation error statistics but without using any real observations. The forecast error can be estimated directly by comparison with a model-independent reference – the nature run – but the necessary consistency of the impact of existing observations with that measured in operational conditions critically depends on calibration.

Annex II.
Key assumptions of the socio-economic cost-benefit analysis

The following assumptions are made in quantifying the costs and benefits in this report:

- NMHSs will continue to fulfil their national role in the provision of weather and climate data and services, supported by global and regional NWP centres, through the lifetime of EPS-Aeolus and EPS-Sterna;
- sector-specific weather and climate service provision by NMHSs, other government agencies and the private sector will continue to deliver at least the current level of benefits to government, commercial and industrial users, and more likely deliver increasing benefits through time;
- sector- and country-specific SEB valuations from published studies may be extrapolated in space and time to infer likely SEBs across all EUMETSAT Member States;
- in the context of climate change, future economic impacts of adverse weather will at least equal, and most likely exceed, impacts on Member States in recent years;
- valuation of benefits from the use of weather information by individual citizens may be reasonably estimated based on survey data assessing willingness to pay, either directly or through taxation;
- the EPS-Aeolus and EPS-Sterna programmes will be implemented successfully and deliver data to meet technical specifications throughout their planned operational lifetime;
- EPS-Aeolus and EPS-Aeolus will be implemented within the cost estimates presented to EUMETSAT members in spring 2023;
- global NWP centres (and regional/national centres in the case of EPS-Sterna) will routinely assimilate EPS-Aeolus and EPS-Sterna data into their operational NWP systems;
- the impact on NWP skill will be at least as beneficial has been demonstrated in the impact assessments undertaken over a limited period for this report, based on the Aeolus precursor and on microwave sounders currently in operation, delivering an impact on forecast accuracy of at least +3% (EPS-Aeolus) and +6% (EPS-Sterna);
- improvements in forecast skill will increase SEBs to Member States through improved decision making by governments, organisations and individuals;
- the relationship between improved forecast skill and economic benefit is assumed to be linear: this takes into account on the one hand the conservative approach taken to SEB quantification, and on the other hand the likely incomplete translation of improvements in prediction into improved action by organisations and individuals; and
- the average growth in GDP across EUMETSAT Member States over the lifetime of EPS-Aeolus and EPS-Sterna will be at least 2%. A discount rate of 4% has been applied.

Annex III. Glossary

2024 e.c.	Normalised to 2024 economic conditions, using latest (Oct 23) inflation forecast for 2023
AMSU	Advanced Microwave Sounder Unit
AROME	Météo-France regional NWP system
ATMS	NOAA Advanced Technology Microwave Sounder
COSMIC-2	NOAA Global Navigation Satellite System Radio Occultation mission
COSMO	Consortium for Small-scale Modelling
DMSP	United States' Defense Meteorological Satellite Program
DWD	Deutscher Wetterdienst, German National Meteorological Service
ECMWF	European Centre for Medium-range Weather Forecasts
EDA	Ensemble data assimilation
EEA	European Environment Agency
EPS-Aeolus	EUMETSAT Polar System – Aeolus Doppler wind LIDAR mission
EPS-Aeolus minus	Simulated observations with measurement accuracy of EPS-Aeolus and capacity of the Aeolus prototype
EPS-SG	EUMETSAT Polar System – Second Generation
EPS-Sterna	EUMETSAT Polar System – Sterna constellation of microwave sounding microsatellites
ESA	European Space Agency
EU	European Union
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EUROCONTROL	European Organisation for the Safety of Air Navigation
FMI	Finnish Meteorological Institute
FSOI	forecast sensitivity to observation impact
FY-nx	Feng Yung satellite series operate by China
GDP	Gross Domestic Product
IASI	InfraRed Atmospheric Sounding Interferometer
IATA	International Air Transport Association
IJPS	Initial Joint Polar System Agreement, European and United States' operational polar satellite system
IPCC	Intergovernmental Panel on Climate Change

KNMI	Koninklijk Nederlands Meteorologisch Instituut, Royal Dutch Meteorological Institute
LIDAR	Laser imaging, detection, and ranging
LIPAS	LIDAR Performance Analysis Simulator
LTAN	Local Time of Ascending Node
LTDN	Local Time of Descending Node
MHS	Microwave Humidity Sounder
MTG-S	Meteosat Third Generation Sounder
MetOp-A,B,C	Meteosat Metop polar satellite series of three satellites
Metop-SG A,B	Meteosat Metop Second Generation polar satellite Series A and B
Mie	LIDAR observation mode for signals backscattered by aerosol and cloud particles
NMHS	National Meteorological and Hydrological Service
NOAA	United States' National Oceanographic and Atmospheric Administration
NOAA nn	NOAA series of polar satellites
NWP	Numerical Weather Prediction
OSE	Observing system experiments
OSSE	Observing System Simulation Experiments
Rayleigh	LIDAR observation mode for signals backscattered by molecules
SEB	Social and Economic Benefit
SMHI	Sveriges meteorologiska och hydrologiska institute, Swedish Meteorological and Hydrological Institute
SOP	Special observing period
Suomi-NPP	NOAA Suomi National Polar-orbiting Partnership satellite
TELEMAC-2	Two-dimensional hydrodynamic model
UK	United Kingdom of Great Britain and Northern Ireland
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
WMO	World Meteorological Organisation
YOPP	Year of Polar Prediction

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