The Value of Surface-based Meteorological Observation Data

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Abstract

Weather forecasting generates significant societal benefits, which can be increased by improving accuracy and lead-time through better meteorological monitoring, modeling and computing. Forecasting relies on numerical weather prediction (NWP), which is significantly impacted by the availability of meteorological observations, with space-based observations being the most important. Surface-based observations also contribute substantially to NWP performance, but current availability in Antarctica, Africa, South America, the Pacific and parts of Asia is insufficient. More observations from these regions would improve global NWP and forecasting quality, particularly in the data-sparse regions themselves, but also over the rest of the globe. It is estimated that improvements in the coverage and exchange of surface-based observations to meet the World Meteorological Organization's Global Basic Observing Network (GBON) specification can deliver additional global socioeconomic benefits of over $5 billion annually. This is a conservative estimate omitting non-financial benefits such as potential lives saved and improvements to well-being, so underestimates the full benefits, particularly for developing countries. Investing in improving surface-based observations in data sparse regions is also highly economically efficient, yielding a global benefit to cost ratio of over twenty-five. Assuming sufficient observational coverage, international data exchange is a very efficient multiplier of the value of observations. However, exchange is currently insufficient across all regions. In view of the growing climate- and weather-related challenges facing humanity and recognizing that climate services similarly rely on meteorological monitoring, surface-based observations should be treated as a critical public good, with public oversight and open exchange within the meteorological and climatological communities.

1. Introduction

The nations of the world are facing unprecedented challenges, threatening lives and livelihoods and so impeding global efforts to reduce poverty and promote shared prosperity. Prior to the emergence of COVID-19, which has logically prioritized focus on global health and related challenges, the World Economic Forum again highlighted extreme weather, climate action failure and natural disasters as three of the top four risks to global economic development (WEF 2020). Moreover, the societal consequences of COVID-19 responses have further exacerbated the challenges of sustainable economic recovery, especially for the struggling economies of developing countries, further emphasizing the importance of strengthening national, regional and global collaboration and social, economic and environmental resilience.

In 2015, the United Nations set out an agenda for 2030 through securing a path toward sustainable development for all. The Sustainable Development Goals underscore the importance of environmental monitoring and stewardship in support of attaining socioeconomic benefits. The Sendai Framework for Disaster Risk Reduction noted that disasters, many of which are increasing in frequency and intensity due in part to climate change, are significantly impeding progress towards sustainable development (UNISDR 2015). The Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) lays out a pathway to enable adaptation to the impacts of climate change and toward a less carbon intensive world. Improved environmental understanding and awareness now and in the future, through better systematic observations, research, education and training and capacity development are necessary conditions to support successful outcomes, and in most cases are explicit obligations to the "Parties" of these landmark Protocols.

Also in 2015, the World Meteorological Organization (WMO), in a joint report with the World Bank Group, Global Facility for Disaster Reduction and Recovery (GFDRR) and United States Agency for International Development (USAID), noted that improvements in early warning systems and preparedness are making it possible to limit losses from hydrometeorological disasters (WMO et al 2015). Such improvements rely critically on the infrastructure and capabilities of National Meteorological and Hydrological Services (NMHSs). Considerable attention is now being given to their capacity development, including for example the World Bank Group, which is supporting a current hydrometeorological investment portfolio of around US$ 1 billion (Rogers et al 2019).

Meteorological observations form critical inputs for the forecasting and early warning of hydrometeorological hazards. Despite their importance, the collection and exchange of surface-based meteorological observations in particular is insufficient to support high quality forecasting in many regions of the world. In order to better inform global, regional and national policy and investment designs and decisions related to meteorological monitoring and data exchange, this article aims to answer two research questions:

1. Can the economic value of surface-based meteorological observations be quantified?
2. Assuming a positive answer to question 1, what is the cost-benefit ratio of investing in additional surface-based observations, above and beyond what is currently available?

1.1. Components of a National Meteorological and Hydrological Service

Traditionally, the provision of meteorological services in high capacity countries has relied on the existence of an end-to-end system consisting of four basic components, as show in Figure 1:

- A national observation network;
- A research and development effort;
- Data management and modeling/forecasting/archival capabilities; and
- A service delivery system.

These components are supported by comprehensive arrangements for international cooperation in data collection, data processing and service provision, coordinated by the WMO.

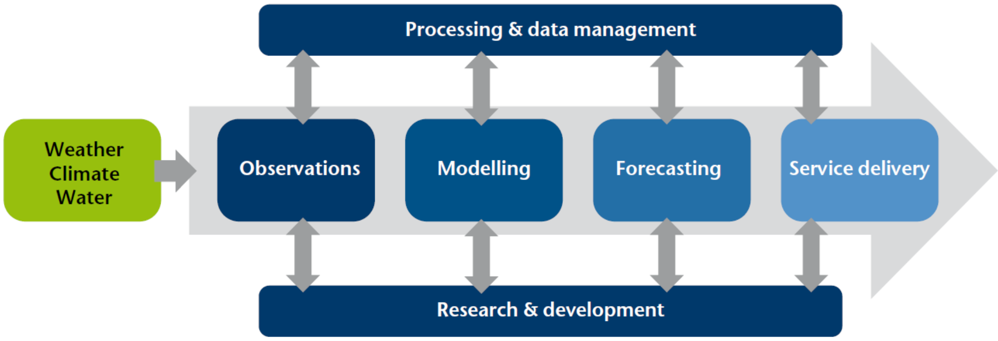

Figure 1*: Components of NMHSs' service production and delivery system (from WMO et al 2015).*

1.2. Numerical Weather Prediction

Numerical weather prediction (NWP) forms the basis of most weather and climate predictions and related products and services for decision-making on a day-to-day basis. NWP ingests current observations of weather into computer models of the atmosphere to generate forecasts of the future state of weather, as in the example shown in Figure 2. A detailed knowledge of the current state of the weather is an essential prerequisite for making accurate forecasts of its future state. Current weather observations are ingested into the computer models, through a process known as data assimilation, to produce outputs of temperature, wind, precipitation, and other meteorological variables, from the Earth's surface to the top of the atmosphere (NOAA 2019a).

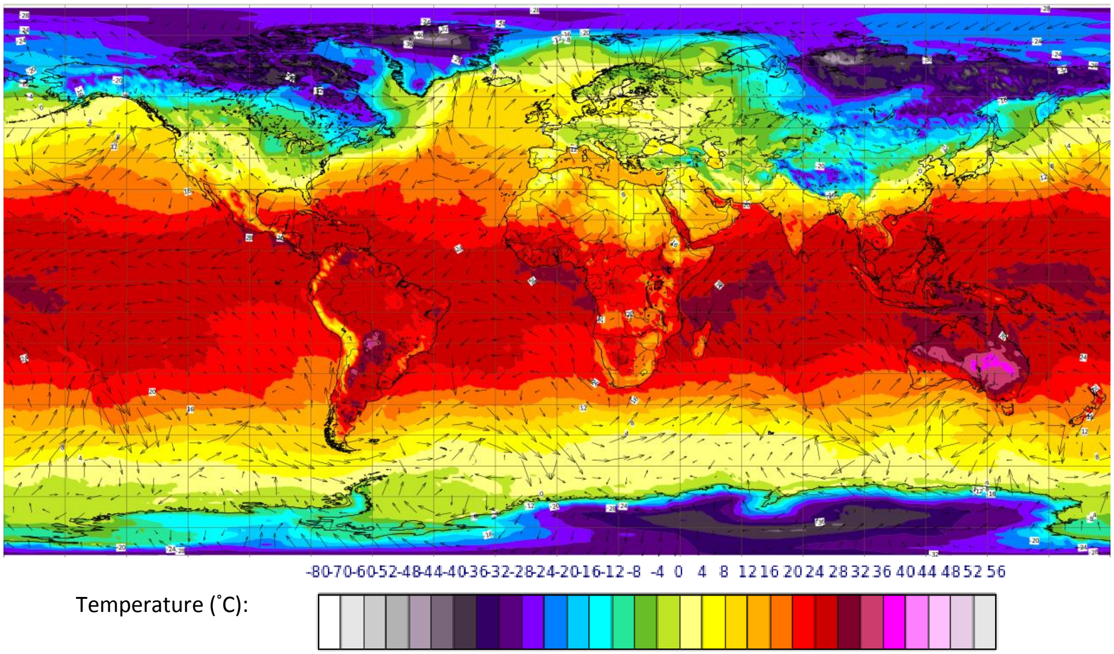

Figure 2*: Typical 36-hour global NWP forecast field of temperature (at 2 meters) and wind (at 30 meters) issued by the European Centre for Medium-range Weather Forecasting, Monday 20 January, 00 UTC T+36, valid Tuesday, 21 January 2020, 12 UTC. Source: ECMWF*

1.3. Observational data for climate services

Weather observations also play a vital role in climate monitoring, and thus in a growing range of climate services. The Global Climate Observing System[1] defines and monitors a set of Essential Climate Variables (ECVs) required to systematically observe the Earth's changing climate. The global gathering and free exchange of these observations are essential to solving many of the challenges in climate research, and also underpin climate services and adaptation measures.

A growing range of climate services are now being developed around the world to support decision-making for climate-related risks, under the Global Framework for Climate Services (GFCS)[2]. In addition to traditional observations, climate services also rely increasingly on reanalysis of observations, using NWP data assimilation to generate global gridded fields of geophysical variables that are spatially and temporally complete and consistent, and which describe the recent history of the atmosphere, land surface and oceans.

Reanalysis can also provide estimates of variables beyond the basic meteorological parameters of temperature, pressure, wind and humidity, such as ozone, greenhouse gases and aerosols. However, the quality of these measures can ultimately be traced back to the quality and quantity of the observational data ingested.

1.4. WMO global data exchange

The operational functioning of every NMHS relies fundamentally on international arrangements for observation collection and data exchange, which are coordinated by the WMO. Observational data are shared freely, in real time, in accordance with the principles of the World Weather Watch, first established in the 1960s, and later articulated in Resolution 40 of the twelfth WMO Congress:

> *Members shall provide on a free and unrestricted basis essential data and products which are necessary for the provision of services in support of the protection of life and property and the well-being of all nations, particularly those basic data and products, as, at a minimum … required to describe and forecast accurately weather and climate, and support WMO Program.* (WMO 1995)

As well as exchanging data from surface-based observing systems[3], this resolution also covers data and products from operational meteorological satellites necessary for operations regarding severe weather warnings and tropical cyclone warnings, as agreed between WMO and satellite operators. In recent years satellite data have made an increasingly important contribution to weather forecasting and climate monitoring, complementing those from ground-based instruments.

John Zillman, former WMO President, has argued that "the institutions of international meteorology provide as good a model as the world has yet devised of nations, organizations and scientific disciplines working together for the common good" (Zillman 2018a); and specifically that

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[1] https://gcos.wmo.int/en/about

[2] http://www.wmo.int/gfcs/about-gfcs

[3] "Surface-based" observing systems are considered to include all monitoring installations that are not space-based, including aircraft- and weather balloon-hosted sensors.

their comprehensive data sharing regime can fairly be regarded as "the most successful fully international system yet devised for sustained global cooperation for the common good in science or in any other field" (Zillman 2018b).

As recognized by the WMO, "…behind every weather, water and climate condition forecast, every disaster mitigated, and every prediction debated, are the observational data" (WMO 2010). However, whilst many regions provide a good and robust supply of surface-based observational data, some areas of the world, notably Africa, parts of Asia, South America and Small Island States currently lack the infrastructure necessary to provide enough observational data to meet the basic requirement for NWP and the GCOS specification for monitoring ECVs (WMO et al 2016). The lack of observational data has adverse impacts not just locally but can also reduce the accuracy of the global NWP and climate analyses upon which almost all weather and climate services rely (WMO 2019), even in areas far from the missing data.

Given the growing social, economic and environmental risks facing humanity and the critical role played by NMHSs in providing accurate and timely information to support decision makers, there is a compelling case for optimizing the global availability and exchange of real-time data, and in particular to fully satisfy the requirements of today's global NWP and climate modeling systems.

Recognizing this as an urgent priority, the 18th World Meteorological Congress (WMO 2019) adopted two important resolutions that are directly related to the provision of systematic observations:

1. the Global Basic Observing Network (GBON, Resolution 34) defines the obligation of WMO Members to implement a minimal set of surface-based observing stations for which international exchange of observational data will be mandatory in support of global NWP and climate analysis;
2. and the Country Support Initiative (Resolution 74) aims to develop options for innovative financing to address the perennial sustainability issue of investments in and maintenance of observational infrastructure in the Least Developed Countries.

Subsequently, a group of organizations including the members of the Alliance for Hydromet Development[4] discussed the idea of creating a Systematic Observations Financing Facility (SOFF) specifically to support the implementation and sustained operation of GBON in the poorest and most data-sparse parts of the world. WMO is currently working together with roughly 30 institutions in the international development and climate finance community on further developing the concept for the SOFF.

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[4] The Alliance for Hydromet Development includes 12 founding members: Adaptation Fund, African Development Bank, Asian Development Bank, Climate Investment, Funds, European Bank for Reconstruction and Development, Global Environment Facility, Green Climate Fund, Islamic Development Bank, United Nations Development Programme, United Nations Environment Programme, World Bank, World Food Programme, and World Meteorological Organization. The Climate Investment Funds joined in October 2020.

1.5. Assessment methodology and critical assumptions

The central purpose of this paper is to shed light on the economics of acquiring and exchanging observations for global NWP. What are the costs of establishing and maintaining the GBON? What are the benefits? Is the cost/benefit ratio favorable enough to justify the investment?

Figure 1 shows that observations and modeling (in this case NWP) are foundational activities in meteorological service delivery. In terms of generating socioeconomic benefits, they remain as critical steps in what is often termed the "hydrometeorological value chain." However, as shown in Figure 3, many activities beyond observations and modeling need to be pursued to realize the full potential socioeconomic benefits of weather forecasting through the full hydrometeorological value chain.

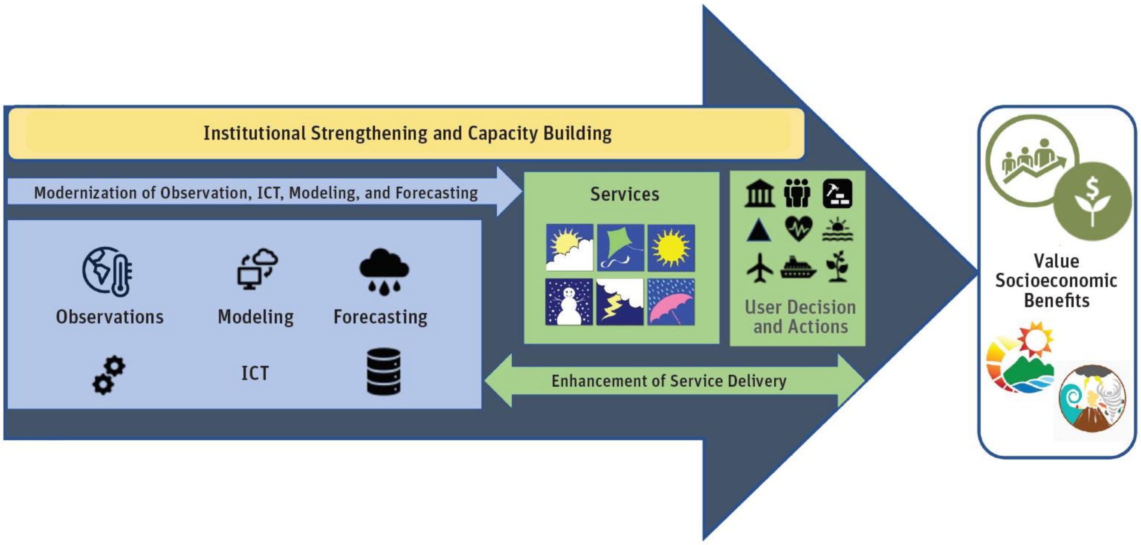

***Figure 3**: Schematic of the hydrometeorological value chain. Source: Kootval and Soares, 2020*

This paper explores the potential increases in socioeconomic benefits if the volume of available surface-based observations is increased, thereby leading to an increase in the accuracy of modeling (NWP). These improvements would occur within the technical meteorological activities underpinning the value chain, on the left side of Figure 3. However, to realize the potential benefits from these improvements, service delivery and use of improved forecasts need also be successfully achieved (right side of Figure 3). This represents a critical assumption of this paper that consumers, whether public, private, individual, institutional and/or commercial, access and use weather forecasts for decision-making to the fullest possible degree. This is currently a somewhat utopian assumption, as described for example in Rogers et al (2019).

Section 2 of the paper describes the utility of global NWP and the role observations play in it, while Section 3 estimates the global potential socioeconomic benefits of weather forecasting. Section 4 then estimates the potential improvements to global NWP accuracy that additional surface-based observations could deliver, with Section 5 translating these potential improvements into socioeconomic benefits. Section 5 also compares the benefits with the costs of increasing surface-based observations to a satisfactory level. Section 6 summarizes the results and translates them into policy recommendations.

2. Global Numerical Weather Prediction (NWP)

Global NWP is the foundation upon which almost all of the spectacular progress in meteorology achieved over the last few decades has been built. A global NWP system ingests tens of millions of observations taken all over the globe every day, it translates this heterogeneous dataset into coherent estimates of the atmospheric state (surface pressure, wind, temperature and moisture content) at every location on the planet and at every level between the earth's surface and the top of its atmosphere, and it predicts the evolution of the atmosphere, forward in time, out to two weeks or even longer into the future.

A global NWP capability supports a large variety of critical applications:

- its output is directly used for short-range global forecasting (e.g. in support of global aviation) and medium-range forecasting (beyond 3-day forecast range);
- it can be post-processed into a range of specialized meteorological data products at global, regional, national and sub-national scales;
- the system provides first-guess fields and lateral boundary conditions for a hierarchy of fine-scale models used for shorter-range forecasting and for various specialized purposes in early warning and disaster risk reduction; and
- it provides an integration tool for the generation of coherent climate data set for monitoring a wide range of variables including greenhouse gases, aerosol and ozone concentrations.

Since the introduction of global NWP in the 1980's, significant skill improvements have been accomplished through a combination of ever-increasing computing power, improved models with more accurate representation of atmospheric processes, and increasingly sophisticated algorithms that ingest ever-increasing volumes of observations in to the models (WMO 2015b). The Ensemble Prediction Systems now operated by many advanced NWP centers use these models to quantify forecast uncertainty and indicate the range of possible future states of the atmosphere.

For example, Figure 4 shows the evolution of skill over the last four decades of the NWP models at the European Centre for Medium-range Weather Forecasts (ECMWF). 5-day forecasts today are as accurate as 3-day forecasts two decades ago; the same holds true for 7-day forecasts verses 5-day forecasts and 10-day forecasts verses 7-day forecasts two decades ago. Greater improvement is observed in the Southern Hemisphere due to the increase in satellite observations across areas where the surface-based observing network is sparse (Zhang et al 2019).

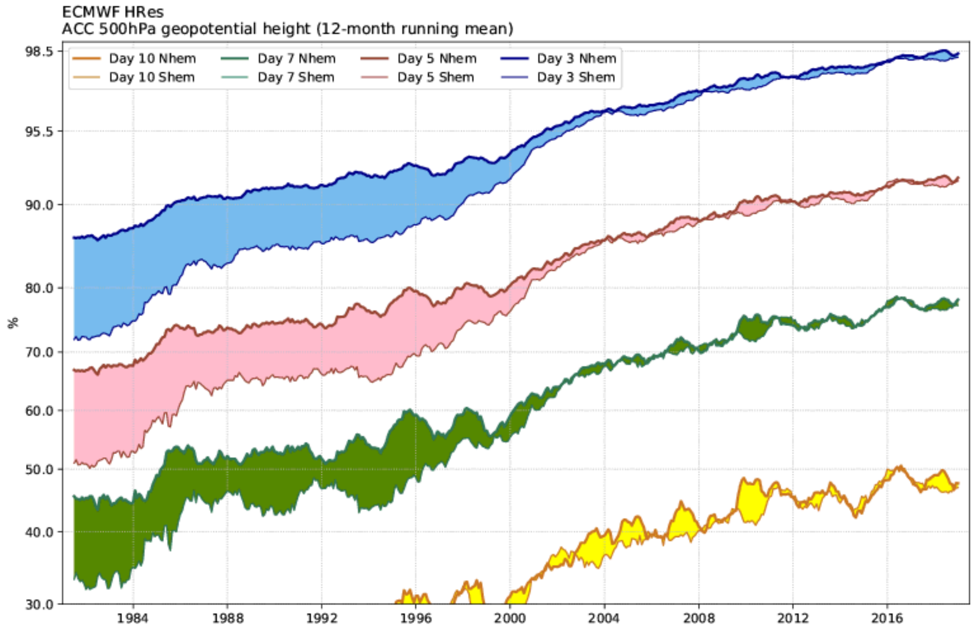

***Figure 4**: Evolution of forecast accuracy in terms of anomaly correlation of ECMWF's 3, 5-, 7- and 10-day forecasts in the Northern and Southern Hemispheres (Nhem and Shem, respectively)[5]. The anomaly correlation coefficient (ACC) of 500-hPa geopotential height between the forecasts and observations is shown. An anomaly correlation of 100% would represent a perfect match between forecast and observations.*

2.1. Operating NWP

As pointed out by the World Bank (2018), developing, maintaining and operating a global NWP capability is a major endeavor in terms of financial, scientific, technical and human resources, and as such it is beyond the reach of all but the most affluent countries or groups of countries. Currently, an estimated 12–15 global NWP systems are operated by government entities worldwide. However, all nations around the world reap the benefits from these systems because the outputs are routinely accessible to all WMO Members.

It may seem surprising that these countries all choose to run their NWP systems on a global domain: why not instead develop more localized NWP systems with complementary strengths, e.g. polar meteorology, mid-latitude storms systems, tropical meteorology, etc.? The reason is that the earth's atmosphere and the mathematics of simulating it dictate that it be so. Both atmospheric disturbances and numerical errors in atmospheric models propagate at a speed such that weather prediction for any region beyond roughly a 4 to 5 days range must involve the entire global domain, even though one might only be interested in a very small part of it. It has proven to be impossible to develop truly stand-alone models for smaller regional or national domains capable of producing accurate weather predictions. All successful implementations of so-called "limited area models" must be embedded within global models that continuously feed them with information about the expected weather outside the domain of interest. This means that irrespective of forecast range and specific area of interest, a global domain is required.

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[5] Sourced from https://www.ecmwf.int/en/forecasts/charts/catalogue/plwww_m_hr_ccaf_adrian_ts

The use of a common global domain for all system has two important implications. First, it has enabled the development of common verification methodologies and stimulated the routine international exchange and comparison of analysis and forecast fields, both of which have been hugely instrumental in the progress made. Second, it means that the observational data requirements are common to all global NWP systems – and thus indirectly also to their users; they can be summarized as: frequent measurements of the basic variables (wind, temperature, humidity and surface pressure), available in near-real time from the entire globe at temporal and spatial resolutions commensurate with[6] those of NWP models.

2.2. The role of observations in NWP

The observational data requirement for global NWP and the critical role played by global NWP as a basis for all meteorological services are widely understood among meteorologists. Thus, WMO regulations require all Members to acquire certain sets of standardized, quality-assured observations over their territory on a routine 24/7 basis and to make them available free of charge to all other WMO Members.

As mentioned earlier, the observational data requirements for global NWP are largely uncontroversial. However, not all the required observations are equally important and different users may not agree about which observations are the most important. The priority of certain observations over others will depend on the specific forecast range and the geographic location of the area of interest. For, say, a 24-hour forecast, observations taken over a relatively small area – e.g. located within 1,000 km from the region of interest - will be the most important ones, while for a five-day forecast, observations taken far upstream of the verification area, at times even on the opposite side of the globe, will be more important.

One of the most compelling aspects of global NWP is that it provides estimates of current and future weather “everywhere” on the globe. This is directly exploited by a variety of public bodies and private institutions that provide targeted weather forecasts for any location in the world on the web or via smartphone apps by post-processing readily available global NWP output. Furthermore, many Services responsible for forecast and warning systems especially in the developing world rely on global NWP output, sometimes in the absence of a robust national observing system. However, it is important to realize that locally the quality of forecasts, especially at short range, will be severely affected by the lack of local observations. Due to the shorter predictability of tropical weather phenomena in general, this problem is particularly pronounced in areas where many developing and small island countries are located. The meteorological service delivery capabilities of these countries are therefore affected disproportionately by a lack of local observations.

It should also be noted that there is significant value in observations beyond their use in NWP. They provide important real-time situational awareness for operational meteorologists and other users, they feed into a range of automated nowcasting and warn-on-detection systems, and they are the basis of climate datasets with a wide variety of applications. They also play a key role in

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[6] “Commensurate with” does not here mean “identical to” – there is a large body of experimental NWP work devoted to identifying the most appropriate mix of observations, much of it coordinated via the WMO Rolling Review of Requirements (RRR), and the resulting requirements are recorded in the official RRR databases of WMO (WMO 2015a).

the calibration of satellite-based observations. However, for the purposes of this study, we shall focus on their value within NWP systems.

3. Value of weather prediction

Weather prediction delivers economic, environmental and social benefits, across 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. Efforts toward further improvements in our weather prediction capabilities, whether related to strengthening our understanding of meteorology or improving information technology to model it, generally deliver commensurate and measurable increases in the associated socioeconomic benefits.

Quantification of the socioeconomic benefits produced by weather prediction generally seeks to explore the issue of whether an investment in meteorological services yields significant returns. Detailed socioeconomic benefit assessments, which sometimes attempt to disaggregate the benefits produced at different points of the value chain and/or for different users of weather prediction, can be used to prioritize and design targeted interventions within a hydrometeorological modernization program.

Taking European hydrometeorological information and early warning systems as a baseline, Hallegatte (2012) determined that if such systems in all low- and middle-income countries (LMICs) were modernized to the level of Europe, globally on average an additional 23,000 lives could be saved per year, and between US$300 million and US$2 billion of annual asset losses could be avoided. In addition, between US$3 billion and US$30 billion of additional economic benefits could be generated through optimized management of weather-sensitive economic sectors such as agriculture, water resources management, energy, etc.

Recognizing that Hallegatte (2012) only examined how disasters affect people with assets to lose and therefore did not properly consider the benefits of improved weather prediction and early warnings can provide to poor people, Hallegatte et al (2017) refined the global analysis. By additionally quantifying the benefits to “well-being”, the analysis moved beyond strictly financial issues, considering longer-term socioeconomic factors such as poverty, health, education and livelihood productivity. Hallegatte et al (2017) found that by providing universal access to improved weather forecasting and early warning, globally US$22 billion in additional benefits could be produced on average per year.

The current assessment aims to further refine past efforts with a focus on potential improvements to economic sectoral performance. A critical assumption is that the improved quality of weather forecasts directly translates into socioeconomic benefits, meaning that systems are in place to translate NWP outputs into actionable information, and that appropriate decisions and actions are pursued based on the forecasts. This is a significant assumption that likely does not hold true across much of the world, so the results should be considered as aspirational under an ideal scenario.

Due to analysis constraints, a financial approach is taken, not taking into consideration the well-being benefits explored by Hallegatte et al (2017). In addition, due to moral considerations, no financial value is assigned to lives saved, which would be significant. The results should therefore be considered as conservative estimates, likely under-estimating the potential socioeconomic benefits and to some degree offsetting the aspirational nature of the assessment.

3.1. Avoiding losses

Hallegatte (2017) estimated that additional avoided asset losses of US$13 billion per year could be achieved by providing universal access to early warnings. This figure represents the benefits that could be generated through improved services in lesser developed countries. Therefore, in order to estimate full global disaster management benefits, and so estimate the global avoided assets losses, assumptions are made about the current level of forecasting and early warning across the different World Bank-defined country income levels[7].

Hallegatte (2012) assumed the ratio of current to potential benefits to be 10% for low-income countries, 20% for lower middle-income countries, 50% for higher middle-income countries, and 100% for high-income countries. For the current assessment, these figures are updated based on expert opinion and WMO (2016): 20% for low-income countries, 40% for lower-middle income countries, 60% for higher middle-income countries and 95% for high-income countries. Weighted by GDP, this results in a global average ratio of 80%, such that the potential global disaster management benefits are estimated at US$66 billion.

3.2. Optimizing production

To generate an order-of-magnitude estimate of how much economic production can be improved through the application of weather forecasting, highly weather-sensitive sectors including agriculture, water, energy, transportation and construction are assessed. The assessment is not considered exhaustive or robust, aiming only to generate rough global estimates. When appropriate, sectoral benefits are reduced by 20% to avoid double counting with disaster risk management benefits, as per the assumptions of Hallegatte et al (2017).

Agriculture

At present, 5-10% of national agricultural production losses are associated with weather variability (FAO 2019). Studies in various countries have shown that availability and use of weather and climate forecasts can reduce the impacts of weather variability by 10%-30%, for example in India (Rathore & Chattopadhyay 2016), Peru (MeteoSwiss & SENAMHI 2015), West Africa (Tarchiani 2019), Ethiopia and Kenya (Cabot Venton et al 2012), and Argentina, Australia, Canada, Chile, Costa Rica, Mexico, Philippines and USA (Meza 2008).

The global value added by agriculture, forestry and fishing in 2019 was US$3.49 trillion[8]. Average annual yield variability of 7.5% and average potential reduction of 20% of variability due to weather forecasts is applied. It is further recognized that livestock, forestry and fishery productivity in most cases can benefit less from forecasts than crops, with an assumption of half as much, and make up about 40% of the value added jointly by agriculture, forestry and fishing[9]. To avoid double counting with the benefits attributed to avoided losses in section 3.1, the result

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[7] https://datahelpdesk.worldbank.org/knowledgebase/articles/906519

[8] World Bank (https://data.worldbank.org/)

[9] Food and Agriculture Organization - FAO (http://www.fao.org/faostat/)

is further reduced by 20%, resulting in US$33 billion in annual potential benefits in agriculture due to weather forecasting.

Water Supply

To avoid potential double-counting, the benefits of weather forecasting for optimizing water use in agriculture and energy are included in those sectoral estimates, and therefore excluded from this water supply assessment. Hutton and Varughese (2016) estimate that the annual operational cost of providing safe and affordable drinking water to all (as per Sustainable Development Goal 6.1) is about US$40.4 billion. FAO reports global industrial water use of about 750 km^3 in 2010[10], with projections estimating that current use is about 1,000 km^3 per year[11]. Fixed water supply tariffs vary significantly around the world[12], so as a minimum and therefore conservative estimate of cost, US$0.05/$m^3$ is used, which results in global annual industrial water consumption costs of US$50 billion. It is noted that this price significantly under-estimates the full socioeconomic costs of industrial water use, in particular waste-water treatment and other environmental externalities.

Studies and experiences across multiple contexts and climates indicate that using forecasts to optimize water supply system operations can result in up to 33% or more in performance improvements (see for example Anghileri et al 2016 and Sankarasubramanian et al 2009), also considering improved forecasting of demand (see for example Bakker et al 2014). Therefore, a conservative assumption of 5% improvement and therefore cost savings due to weather forecasting is applied to the combined annual costs of household and industrial water supply, resulting in an annual benefit of about US$5.0 billion.

Energy

Global electrical power generation is currently estimated at about 27,000 TWh per year (McKinsey 2019). An average global wholesale price of about US$57/MWh is applied based on global average retail prices (from IEA 2019), pro-rated according to US wholesale prices per electricity generation source (USEIA 2020) and global estimates of the proportions of electricity generation sources[13]. This results in a global annual value of about US$1.5 trillion. While there are several studies that estimate the savings generated by energy optimization through the use of weather and climate information and forecasts, they generally do not report results in relative terms (see for example Haupt et al 2018 and 2014).

Based on the available information, the assumption is therefore made that the performance of energy sources for which production is directly impacted by weather and climate (hydro, wind and solar) can be improved by 5% (see also Anghileri et al 2016 and Sankarasubramanian et al 2009) and all others by 1%, the latter focusing on demand forecasting and associated production management. By pro-rating based on the portion of total electricity production by source, the total minimum benefits due to weather forecasting are estimated at US$29 billion/year.

Transportation - Aviation

Estimated fuel savings due to weather routing can be as high as 30% on short-range flights, considering the impact of convective weather and the resultant need for avoidance of holding

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[10] http://www.fao.org/aquastat/en/overview/methodology/water-use

[11] See for example UN (2011), WWC (2000) and https://www.grida.no/resources/5786

[12] http://www.waterstatistics.org/graph/8

[13] IAE (https://www.iea.org/data-and-statistics)

patterns and/or deviations (Anaman 2017). Fuel consumption of the global aviation industry is estimated to have cost about US$188 billion in 2019 (IATA 2019), and the International Energy Agency reports better flight routing could cut fuel consumption by as much as 10%[14]. Assuming only half of potential improved flight routing benefits are due to weather forecasting (which is considered a conservative assumption), US$9.4 billion in fuel savings per annum can be attributed to weather forecasting. To validate this result, the economic assessment of benefits to aviation in Zürich and Geneva from terminal aerodrome forecasts (TAFs), as assessed by Grünigen et al (2014), was scaled up to potential global benefits using flight volume statistics (ICAO 2019). As TAFs only influence landing and take-off (they are issued for an 8 km radius around airports), the estimated total global benefits of US$1.3 to US$2.1 billion in 2019 values verifies the order of magnitude of the total benefits in fuel savings due to improved routing attributable to weather forecasting.

Transportation - Shipping

Like aviation, the main benefits of weather and wave forecasting for shipping are reduced fuel consumption due to improved routing. According to Avgouleas and Sclavounos (2014), the existing literature at the time claimed fuel savings ranging from 2% to over 25%, with the referenced authors' own weather routing optimization scheme reducing fuel consumption by 5%. This figure is also used by commercial forecast and routing providers to promote their services[15]. IHS and JOC (2019) estimated that in 2019, total fuel consumption of international and domestic shipping was at least 400 million metric tons. Bunker fuel prices are highly volatile across fuel types/grades and markets[16], with US$400/metric ton being a conservative estimate of the current average[17]. Applying a 5% reduction in fuel consumption due to improved routing based on weather and wave forecasts results in an annual benefit of US$8.0 billion.

Transportation - Road

Frei et al (2014) computed that the use of meteorology in the road transportation sector in Switzerland generates an economic benefit of at least CHF 65.7 million, which is currently equivalent to about US$68 million. While heavy rainfall and wind were considered, the main weather conditions to be managed in Switzerland are snow and ice. The Swiss assessment results are scaled up to global benefits by pro-rating based on national road network sizes[18], also taking into consideration the climatic context of countries, and assuming that 90% of Swiss benefits are due to managing snow and ice conditions. To avoid double counting with the benefits attributed to avoided losses in section 3.1, the result is further reduced by 20%, resulting in US$10.2 billion in annual potential benefits in road transportation due to weather forecasting.

Construction

Rashid (2014) estimated that in the warm and dry climate of the Middle East, extreme heat and humidity, as well as dust storms, leads to a 7% reduction in construction productivity. In Chile, Ballesteros-Pérez et al (2015) estimate weather-related construction delays of 10%-70%. In the cold and wet climate of the UK, Ballesteros-Pérez et al (2018) report that inclement weather

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[14] IAE (https://www.iea.org/reports/tracking-transport-2019/aviation)

[15] for example: https://www.meteogroup.com/weather-routing-essential-modern-shipping

[16] Further impacted by the International Maritime Organization (IMO) new emission standard banning use of fuel with sulfur content higher than 0.5%, compared to the previous 3.5%, which went into effect on January 1, 2020.

[17] https://shipandbunker.com/prices

[18] CIA (https://www.cia.gov/library/publications/the-world-factbook/rankorder/2085rank.html)

extends project durations by an average of 21%, but also that integrating weather and climate forecasts into construction planning could lead to average reductions in project durations of 16%. At the same time, globally weather is generally only one of many external factors causing construction delays (i.e. not triggered by construction and engineering processes including poor and changing designs, planning, financing, etc.), which as a group is considered a low-ranking source of delays (see for example in Iran, as reported by Shahsavand 2018).

Gerbet et al (2016) estimate that full-scale digitalization in non-residential construction, including better use of weather information, will lead by 2025 to annual global cost savings of $0.7 trillion to $1.2 trillion in engineering and construction. Assuming 1% of these current inefficiencies are due to weather (this does not include asset losses due to weather, which are included in disaster risk management in section 3.1), and that forecasts could reduce these by 15%, results in an annual benefit of US$1 billion.

While the assessment and quantification of the socioeconomic benefits produced by weather prediction must consider several assumptions and generalizations, significant benefits are clearly being delivered, as summarized in Table 1. It should be noted that the figures summarized in Table 1 are assumed to accrue across all actors in society, meaning by both the public and private sectors, and that forecast improvements are realized by both public and commercial weather service providers.

The total figure in Table 1, which represents about 0.185% of 2019 global GDP, is significantly higher than Hallegatte (2012), who estimated benefits of up to 0.025% of GDP. While Hallegatte (2012) described his estimate as very conservative, the figures reported in Table 1 are considered to reflect the order of magnitude of the true benefits.

Table 1*: Minimum global socioeconomic valuation of the benefits of weather prediction.*

Sector	Minimum annual benefit
Disaster management	US$66 billion
Agriculture	US$33 billion
Water Supply	US$5 billion
Energy	US$29 billion
Transportation	US$28 billion
Construction	US$1 billion
Total	**US$162 billion**

Tanner et al (2015) identified a wide range of benefits generated by improved disaster risk management, some of which were not fully considered in the above global assessments, such as increased business and capital investment, fiscal stability and reduced future credit risks, and ecosystem-based co-benefits. These, as well as many sectors and sub-sectors that are known to benefit from weather forecasting, such as tourism and rail transport, are not considered in the current analysis. It is assumed that the under-estimation of benefits due to these omissions, as well as lack of quantification of potential lives saved, offsets any potential over-estimation of the financial benefits due to the idealistic assumption of fully efficient use of weather forecasts by decision-makers.

3.3. Cost-benefit analysis

For a potential investment to be justified, the benefits it will produce should be compared to the costs involved. This is called "cost-benefit analysis", and its application for hydrometeorological services was explored in WMO et al (2015). In addition to outlining the steps needed to perform a cost-benefit analysis, as well as exploring the different methodologies and challenges used for quantifying benefits and costs, readily available cost-benefit analyses of hydrometeorological services from around the world were reviewed.

WMO et al (2015) found that in general investing US$1 in weather prediction and early warning results in at least US$3 in socioeconomic benefits (defined as a 3:1 benefit-cost ratio), and often far more. Highlighted examples include:

- Improved national meteorological and hydrological services to reduce disaster losses in developing countries resulted in benefit-cost ratios of 4:1 to 36:1.
- Improved weather forecasts in the USA resulted in benefits to households with benefit-cost ratios of at least 4:1.
- Drought early warning systems to reduce livelihood losses and dependence on assistance in Ethiopia resulted in benefit-costs ratios of 3:1 to 6:1.
- An El Niño early warning system in Mexico to improve decision-making in agriculture resulted in benefit-cost ratios from 2:1 to 9:1.

Relevant to the current topic and utilizing the approach originally applied by Hallegatte (2012), Kull et al (2016) determined that the benefits of making global numerical weather prediction products fully available to LMICs would generate global benefits of US$200 million to US$500 million per year. The analysis however did not consider well-being benefits, which as per Hallegatte et al (2017), would likely increase the total benefits by a factor of two to three. Considering the negligible additional costs to global producing centers of making their products available to LMICs, the benefit-cost ratio was estimated as at least 80:1, assuming that the improved forecasts would be fully and perfectly leveraged in decision-making across timescales and actors.

4. Impact of observations on NWP performance

To understand fully the value of different meteorological observations for weather forecasting, the impact of the observations on the skill of NWP output has been assessed. Impacts are reported in terms of changes to forecast accuracy, defined as the level of agreement between the forecast and the observed reality.

4.1. Methodologies and metrics

The impact of observations on NWP performance can be assessed in several different ways. Traditionally they are assessed using Observing System Experiments (OSEs), also called Data Denial Experiments (DDEs). In such experiments, a series of weather predictions for a given period in the past is run twice with an NWP system, firstly assimilating the full set of available observations, and secondly with a subset of the observations excluded ("denied"). Each of the two experiments provides a set of analyses and forecasts of the state of the global atmosphere. The accuracy of each forecast is assessed by comparing it with a proxy for the true state of the atmosphere (in practice either observations or analyses valid at the same time as the forecast).

The difference in accuracy between respective series of forecasts from the two runs is used to quantify the impact of the excluded subset of observations. Studies of this type continue to be run by NWP centers, and they form a key tool for assessing the impact of observations on NWP performance. However, they are expensive, and only a limited number can be afforded. It is not possible to run experiments to assess the impact of all the components and sub-components of the observing system and the various permutations of them.

In recent years a new, and comparatively inexpensive, method has been added to set of tools available to assess observation impact. This tool is called "Forecast-Sensitivity-to-Observation-Impact" (FSOI). It takes advantage of modules already available within modern NWP data assimilation systems, and it calculates the increase in forecast accuracy attributable to each observation assimilated (Langland and Baker, 2004; Gelaro and Zhu, 2009; Cardinali, 2009). Because a FSOI system provides data at the level of individual observations, these data can then be aggregated in many different ways to address a range of questions concerning the impact of observations or the behavior of the data assimilation system.

FSOI is commonly used to assess the impact of a given observation type or given observing technology. Figure 5 shows an example of this, for the Met Office (UK) global NWP system (Lorenc and Marriott, 2014). In this context, "impact" means the ability of a given observation or technology type to reduce the errors in the 24-hour global forecast. It is often expressed as a percentage, meaning that the total contribution of all observations to reducing the errors in the 24-hour forecast is 100%.

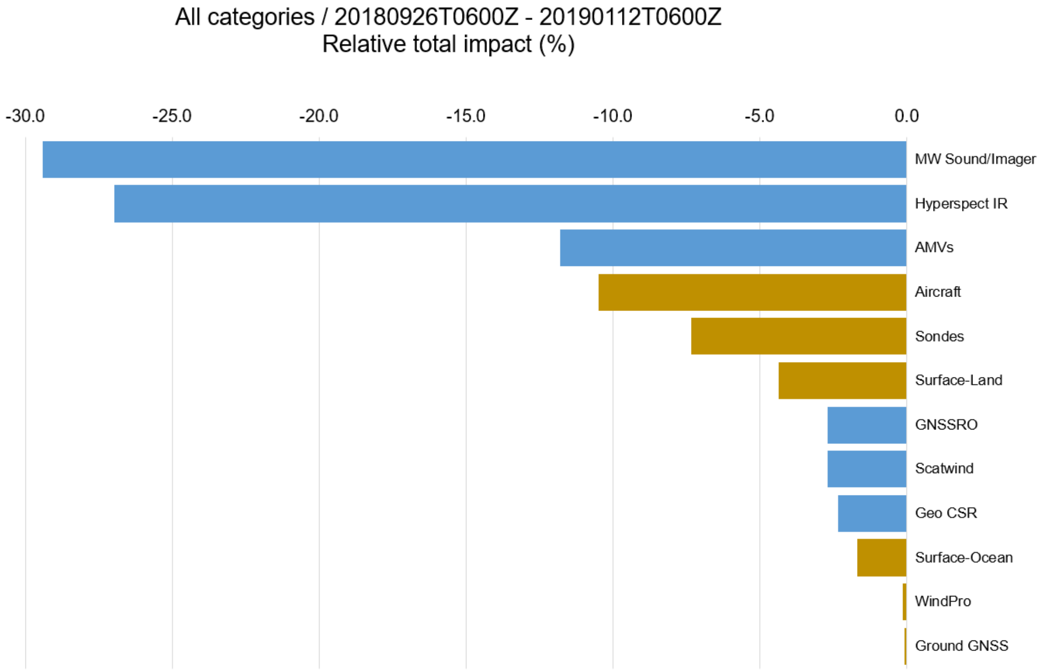

***Figure 5**: Relative FSOI for all observation types assimilated in the Met Office global NWP system. The impact is expressed as the percentage of the total impact on 24-hour forecast error. A negative value means a reduction in forecast error. Space-based observations are colored blue, while surface-based observations are gold. Annex A provides an explanation of the observation types.*

For the purposes of this report, the Met Office FSOI system has been used to aggregate observations in a different way – according to their country or region of origin. Figures 6-7 and 10-13 show results from this study, which is documented more fully in Cotton and Eyre (2019).

4.2. Impact of space-based observations

For the period studied (Sept 2018 – Jan 2019), 75.9% of the total impact came from space-based observing systems and 24.1% from surface-based systems. This should be seen in the context of the overall numbers of observations used in the data assimilation, where currently around 95% are provided by satellites. The specific impact ("impact per observation") thus tends to be higher for surface-based data, especially over areas where observations are sparse. Unusually high specific impacts of certain observations often indicate the potential for gaining significant benefits by adding more observations of similar kind. Figure 6 shows the relative impact from space-based systems according to country or region of origin (i.e. according to the space agencies supplying/operating the satellites and their relevant instruments).

It can be seen that leading contributions in this period came from the data provided by the polar-orbiting and geostationary satellites of the USA and Europe, with smaller but significant contributions from the satellites of other countries (it should be noted that additional data from satellites of China, Russia and South Korea were available during this period but were not yet ready for assimilation at the time of this study.) Figure 7 shows the corresponding impact per observation, which is computed by dividing the total impact for each observation type (Figure 6) by the total number of observations of this type.

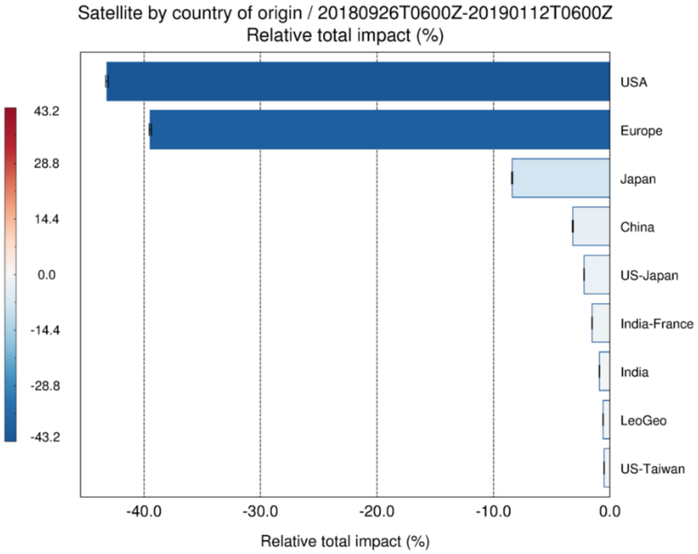

Figure 6*: Relative FSOI for space-based observations aggregated by satellite operator. The impact is expressed as the percentage of the total impact of space-based observations on 24 hr forecast error. The contributing satellites from each country/region are listed in Annex B.*

It can be seen that the highest impact per observations comes the so-called "LeoGeo" winds, derived from imagery of various combinations of polar orbiting and geostationary satellites (see Annex B). This is followed by the geostationary satellite winds from Japan and the radio occultation data from COSMIC, a joint USA-Taiwan mission (also see Annex B). In terms of impact per observation, observations from the mission of other counties/regions are not far behind and are similar to each other.

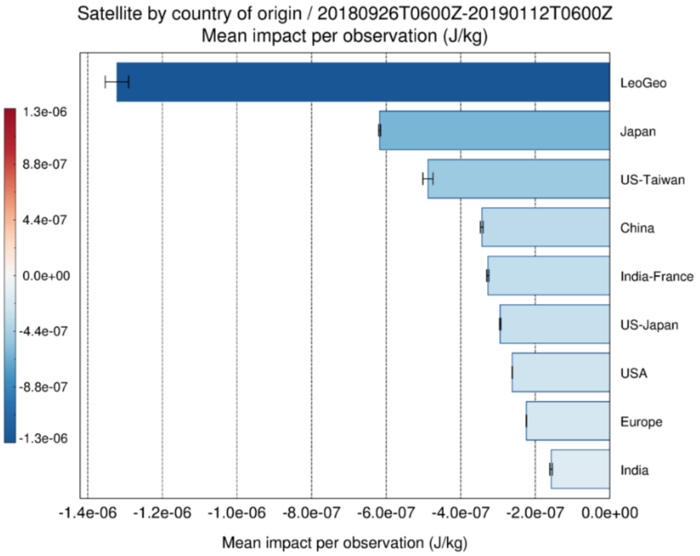

Figure 7: Mean impact per observation for space-based observations aggregated by satellite operator.

4.3. Impacts of surface-based observations from different regions

Equivalent calculations have been made for surface-based observations, according to WMO Regions. The geographical definitions of the WMO Regions are shown in Figure 8.

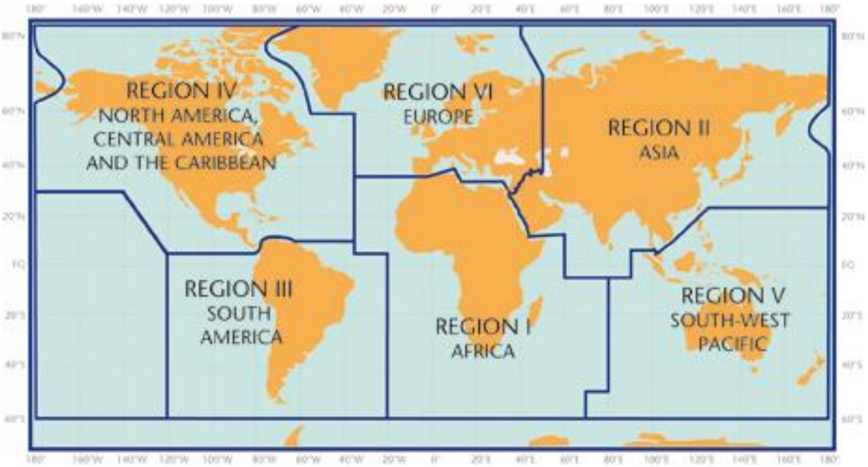

***Figure 8**: WMO Regions*[19].

In this study, the partitioning was made by latitude-longitude boxes approximating to WMO Regions and focusing on the land areas. The boundaries for this partitioning are shown in Figure

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[19] Sourced from *http://www.wmo.int/pages/prog/dra/regional_offices.php*

9. Antarctica is added as the 7th region. Region 4, comprising North America, Central America and the Caribbean, is abbreviated to “NAM CAM Carib”.

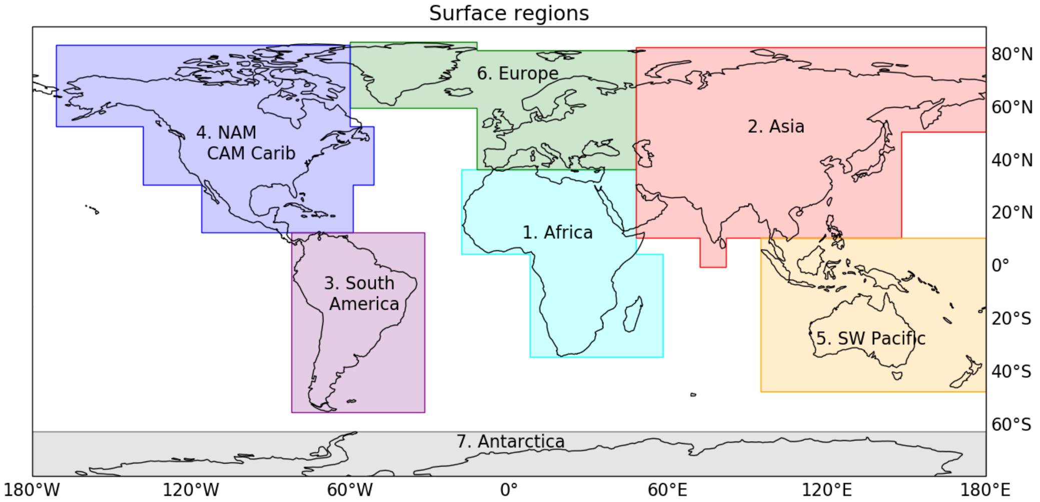

Figure 9: Map of regions used for partitioning surface-based impacts. This shows the latitude and longitude boxes used to construct each region. Note that the map projection is misleading in terms of the size of each region.

Partitioning using latitude and longitude should be a reasonable approach for “stationary” surface-based reports, but it is more approximate for “mobile” reports. For this reason, drifting buoys (1.3% of total impact from *all* observations) and ship reports (0.2% of total impact) have been excluded, as the location of each of these observations bears little relation to the country that operates these systems. Both ships and drifting buoys provide NWP with observations of surface pressure over the oceans. Aircraft, which provide much important data (10.5% of total impact from *all* observations), also move between regions. However, a large proportion of aircraft observations within a region are usually provided by the countries of that region. Since aircraft observations are one of the largest contributors to FSOI, surface-based impacts have been assessed both with aircraft data included and with aircraft data excluded.

Figure 10 shows the total FSOI impact of the surface-based observations and Figure 11 the total number of observations for each region. Figure 12 shows the FSOI impact per observation and Figure 13 the FSOI impact per unit area.

The ranking of the relative FSOI for each region is fairly similar when aircraft data are included or excluded (Figure 11). In both cases the largest contribution comes from Asia. When aircraft data are excluded, the regions that increase their impact share are Asia, SW Pacific and Antarctica. For Europe there is little change in the relative impact. The regions that see the largest drop in impact share when aircraft data are excluded are South America and NAM CAM Carib. These are the two regions for which aircraft data make up the highest proportion of surface observations (see Figure 11).

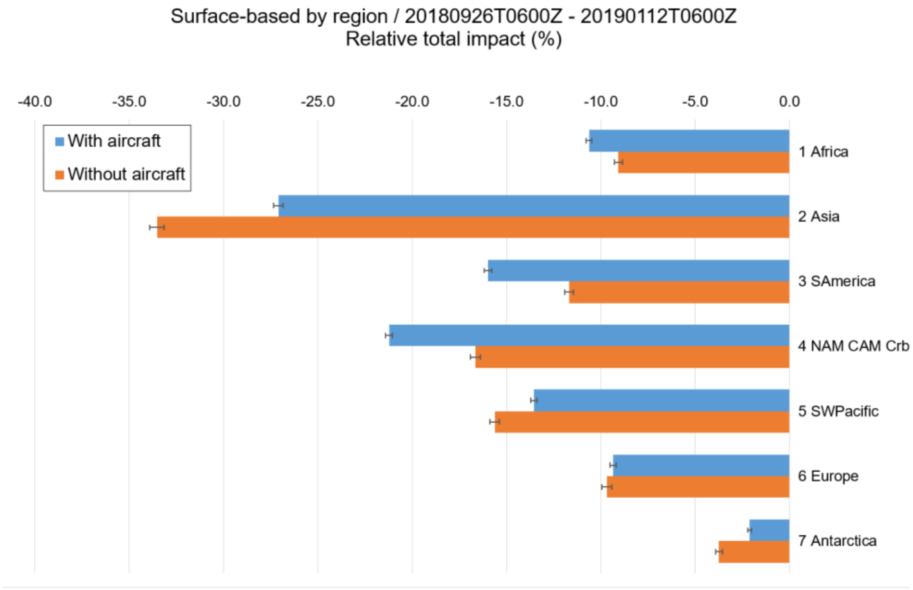

Figure 10*: Relative FSOI for surface-based observations aggregated by region. Impacts are shown with aircraft reports included (blue bars) and excluded (orange bars). The impact is expressed as the percentage of the total "surface-based impact" on 24-hour forecast error, where for each observing system (with and without aircraft) the relative impacts sum to 100%.*

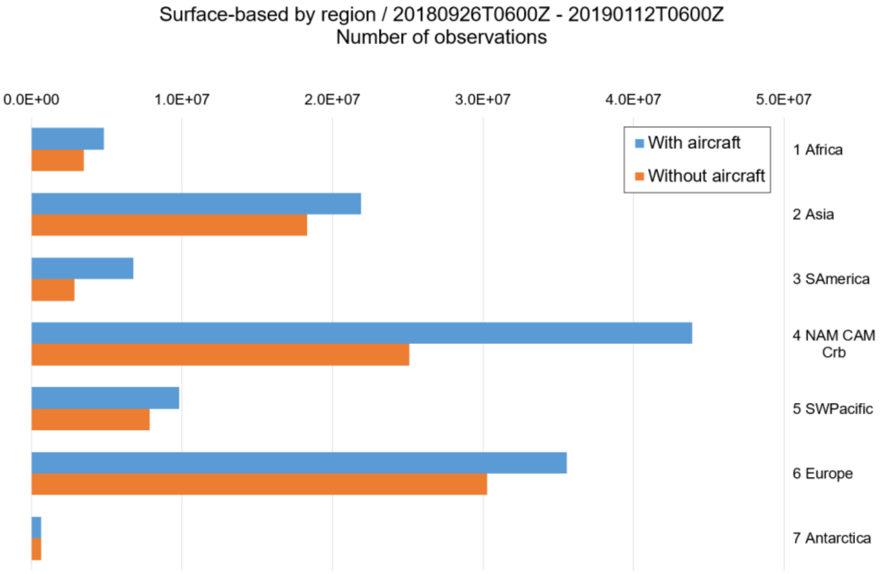

Figure 11*: Number of surface-based observations assimilated, aggregated for each region. Numbers are shown with aircraft reports included (blue bars) and excluded (orange bars).*

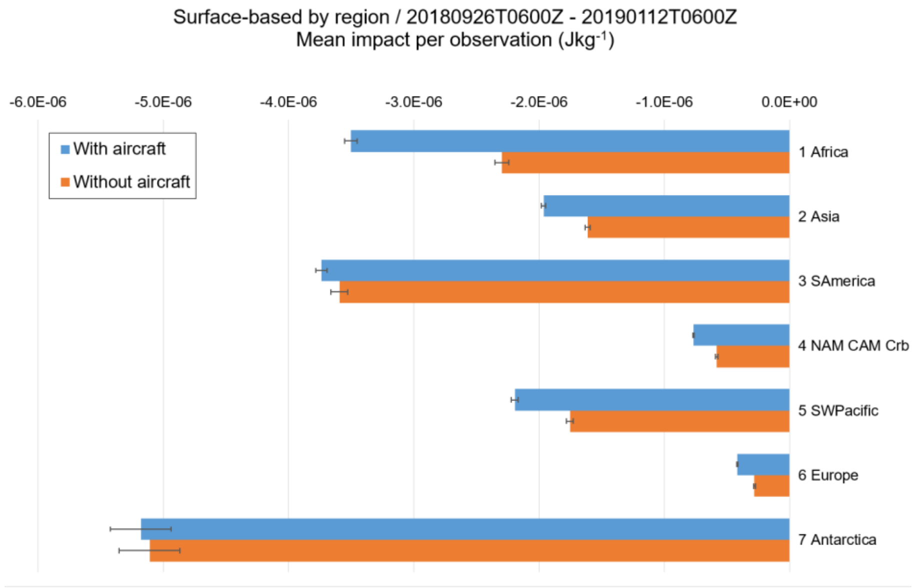

Figure 12: *Mean impact per observation for surface-based observations aggregated by region. Impacts are shown with aircraft reports included (blue bars) and excluded (orange bars).*

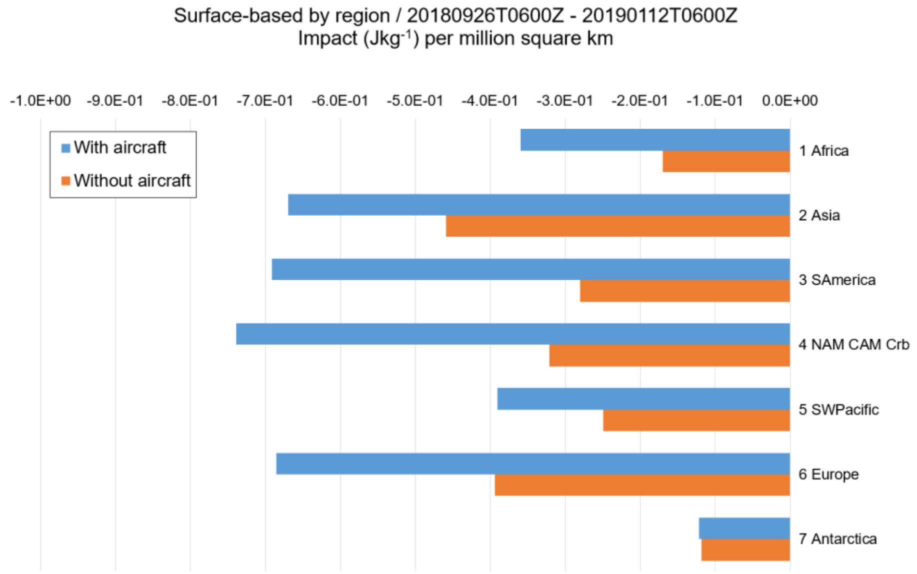

Figure 13: *Mean impact of surface-based observations per unit surface area of each region. Impacts are shown with aircraft reports included (blue bars) and excluded (orange bars).*

In terms of the mean impact per observation, the ranking of the regions is the same with and without aircraft data included (Figure 12). The highest impact per surface-based observation comes from Antarctica, followed by South America and Africa. These correspond to the regions with the lowest number of surface-based observations (Figure 11). Similarly, it is found that the regions with the lowest mean impact per observation – Europe and NAM CAM Carib – are those with the highest number of surface-based observations.

Because the seven regions are not of equal size, the mean impact per unit surface area can be considered (Figure 13). In this case the presence of aircraft data does have an effect on the ranking of the regions.

Figure 10 shows that the impacts of observations from different regions are comparable. Bear in mind that this is the impact on global NWP performance averaged over the world. Clearly the impact on forecast performance at the regional level will be much greater than this for the region of origin. Note (Figure 12) that the impacts per observation of data from Antarctica, South America and Africa are much higher than the average. This supports the expectation that disproportionately high benefit would be expected from additional observations from these regions. Impact per observation is lowest for Europe, suggesting that, for this application (global NWP), there may be benefit from deploying some of this resource elsewhere in the world.

It should be noted that OSE and FSOI results are not directly equivalent: if a subset of observations providing (say) 10% FSOI impact is excluded, the % impact in an equivalent OSE will be considerably less than this (by a factor of 4 or more – see Cotton *et al.*, 2016). The reasons for this are complex, but it should be noted that the relative importance of different observation types as measured by FSOI and OSE are broadly similar (see, for example, Cotton *et al.*, 2016; Lawrence *et al.*, 2019). Also, FSOI is an energy metric, whereas OSE scores are often expressed in terms of reduction of RMS error in variables such as wind and temperature, and this explains a factor ~2 in the differences between impacts measured using the two metrics.

Almost all space-based observational data, of demonstrated or expected potential for impact on global NWP, are currently exchanged internationally. It is clear from the results above (Figures 5-7) that this system needs to be maintained, because it is crucial to current levels of NWP performance.

International exchange of surface-based observations is functioning reasonably well in some respects. However, many observations with potential to benefit global NWP are not currently exchanged. The results above (Figures 10-13) support the case for improving the implementation of WMO regulations and guidance in such a way that these data are exchanged. Moreover, these results support the case for enhancing the implementation of additional observing systems in some regions and for sharing internationally the observations from these new systems.

5. Public goods and net societal benefits

The 2016 World Development Report on “Digital Dividends” recognized that:

> “Many problems—climate change, ozone depletion, air pollution, epidemics, financial crises—are features of globally interconnected environmental, economic, and social systems. Addressing them requires coordinated global actions. Setting priorities and targeting actions require global information. That information is itself a global public good.” (World Bank 2016)

World Bank (2016) further stressed the need to “muster” information for global public goods, highlighting weather, climate and water data as quintessential examples of such a global public good, the exchange of which is however hampered by national capacity and policy constraints.

5.1. International data exchange for the public good

Due to the contributions they make to societal well-being, protection and climate adaptation, national public meteorological observing infrastructure and the data they produce are generally considered public goods. It is recognized that the public good characterization defined by non-rival consumption and high costs of exclusion that has traditionally been assigned to public weather observations, for example by Freebairn and Zillman (2002), is increasingly being challenged by advances in technology, access and private observation data provision. However, the absolute necessity of international data exchange, strict adherence to international standards and long-term continuity required for data for global NWP means that the provision of observations for this purpose continues to be generally accepted as a fundamental responsibility of government.

International agreement on meteorological data sharing, as articulated in WMO Resolution 40 (WMO 1995), de facto classifies “essential observational data” as a global public good. The international sharing of meteorological observations operates essentially as a non-monetized closed exchange. Observation data are shared through the WMO Information System (WIS). However, the notion of “free and unrestricted international exchange” in the WIS is limited to governments and their public meteorological agencies. Ultimately this exchange is underpinned by the common understanding that “you put in what you can, you take out what you need”. There is no penalty for not contributing data, recognizing that countries face a range of resource and capacity realities and constraints in developing and operating meteorological observation networks.

While this exchange has been working for decades and continues to function reasonably well, inefficiencies may arise when countries do not share all their observational data, thereby reducing the quality of the entire system. Most countries recognize that no matter how small their capacity for contribution, it benefits the entire system, thereby benefitting themselves. The emergence of a more active private sector in offering data services may impact this harmony among governments. For example, it may trigger critical observations being procured from a commercial data provider under licensing agreements that would prevent the buyer from participating in free and unrestricted international exchange of the data. Government commitments to the global public good, clear data policies and international protocols should mitigate any risks to the long-term international data exchange principles and commitments.

5.2. Multiplying the value of national observations

In 2018, the Ukraine started sharing observations from 130 weather stations with ECMWF, additional to the 30+ they usually share globally through the WMO Global Telecommunications System. Appreciating this significantly increased national contribution, ECWMF was quick to point out that the Ukraine itself would also benefit:

> “Both sides stand to benefit: the extra data will help ECMWF to improve its global forecasts, and better global forecasts will in turn help to initialize improved higher-resolution regional and national forecasts.”[20]

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[20] https://www.ecmwf.int/en/about/media-centre/news/2018/extra-weather-station-data-improve-ecmwfs-forecasts

Following this successful demonstration, it is expected that Ukraine will now share these observations with other global NWP centers. However, not all policy makers realize these benefits of sharing most if not all their observational data:

> "Many countries share only a small fraction of the data they collect on the misunderstanding that because these data are not designated as essential within the meaning of WMO resolution 40 and WMO general regulations, they are not important to the global network. The high resolution of global models and the need for verification of model output makes all data valuable and essential to provide the best possible NWP and forecasts." (Rogers et al 2019)

The requirements for a meteorological observation network to be fit-for-purpose and therefore economically efficient are evolving. As modeling technologies and processing speeds increase, the focus should be on assimilation in NWP, verifying forecasts, and providing long-term climate records. Particularly for LMICs, which in most cases are not able to run limited area models (LAMs) of resolution higher than global NWP, this requires access to, understanding of, and standard operating procedures for fully using global and/or regional NWP guidance (Rogers et al 2019).

It must be recognized that in most cases, the most direct path toward improved national forecasting and service delivery capabilities is to increase the number of local observations exchanged internationally for assimilation into global and regional NWP models, and to then use the output of these models, rather than to build up a LAM capability locally. There is merit also in the latter approach, but typically on a much longer time scale of a decade or more, and in any case the local LAM approach cannot succeed without the background global model having access to the same observations.

5.3. Potential benefits from improved global NWP

Based on the reviewed data and results presented above, a rough estimation of the global benefits of improving NWP can be made. Zhang et al (2019) suggest that "…we are currently still quite far from the ultimate limit of predictability, and it is apparent that we have ample room for further improvement in the day-to-day weather predictability likely for decades ahead." Specifically, Zhang et al (2019) conclude that forecasts could ultimately be improved by 5 days, meaning the 10-day forecast could reach accuracies equivalent to today's 5-day forecasts. Whilst this may be an optimistic estimate, it is clear that NWP performance, and therefore the forecast products derived from it, can be improved substantially.

Referencing Table 1 and the estimate that currently about 80% of possible benefits are currently being realized, the potential additional benefits that could be realized through improved forecasting and early warning are approximately US$32 billion per year. It should again be noted that this, as well as the benefit valuations reviewed in section 5.4, assume full and efficient use of available weather forecasts by decision-makers, which must be recognized as not reflecting the current reality, and therefore considered aspirational. However, this is offset by not considering the financial value of potential lives saved, as well as a number of economic benefits not incorporated in the analysis (see sections 2.2, 3.1 and 3.2).

5.4. Potential benefits from improved surface-based observations

For a given level of skill in modeling and data assimilation, and a given level of computing resource, the forecast accuracy is determined by the information content of the observations. Zhang et al (2019) indicate that to achieve the potential NWP skill improvement "…requires coordinated efforts by the entire community to design better numerical weather models, to improve observations, and to make better use of observations with advanced data assimilation and computing techniques".

Section 4 indicates that, of the total reduction of error in the 24-hour global NWP forecast attributable to observations, about 75% comes from space-based observations. However, current levels of coverage, resolution and data sharing of space-based observations are high. It is therefore in the surface-based components of the Global Observing System that there is scope for big improvements. In particular, this would mean increasing surface-based observations coverage and/or data sharing in Africa, Asia, South America, Southwest Pacific and Antarctica (as concluded from Figures 11 and 12). This is also supported by the fact that the impact on skill "per observation" tends to be significantly larger for surface-based observations than for satellite observations (cp. Figures 7 and 12), which would be consistent with the findings reported from the last two WMO Impact Workshops (WMO 2012, WMO 2016).

As discussed in Section 1.4, via its adoption of the GBON, WMO has taken the initiative to substantially strengthen the international exchange of observational data and thereby increase the supply of observations to the global NWP systems. A full implementation of a system meeting the GBON requirements will have to involve a combination of improved exchange of existing observations and targeted investments in improving the observing networks in the most data-sparse regions. A GBON gap analysis recently undertaken by the WMO Secretariat has led to the estimate that such an implementation would lead to a doubling in the number of surface-based observations made available to the global NWP (specifically an increase by a factor of roughly 2.5 in the number of surface observations and of roughly 1.9 in the number of upper air soundings would be expected). The largest increase would be seen over Africa where an 8-fold increase in surface observations and a 10-fold for increase in upper air soundings is estimated.

At present, the surface-based components that would be included in GBON contribute about 17% of the total information (as measured by FSOI statistics). Doubling this component would increase the total information content of observations by a similar amount, if these improvements are focused mainly on regions that are observed comparatively poorly at present, which per the GBON gap analysis is indeed the case. As reviewed in section 4.3, a smaller increase in forecast accuracy would be expected – probably about ~4% if measured in terms of a reduction in forecast error quantified using an energy metric. This would result in the potential benefits from improved surface-based observation delivered through improved NWP of about US$5.2 billion per year.

It is to be noted that the 4% increase in forecast quality is a global figure. Regions such as Africa, where coverage is currently very low, will experience greater improvements in forecasting accuracy (particularly for the short-range forecasts). This is also an average over time – much of the time the forecast is already accurate, and so the average improvement comes predominantly from improving the poorer forecasts (by much more than 4%). In addition, with modern information, communication and operational technologies, even small improvements in forecasting can produce significant benefits (see example below).

Minor increases in accuracy can yield major increases in benefits

Xcel Energy, a US wind energy producer, was able to save US$22 million from 2009-2012 by integrating higher resolution and more accurate wind forecasts into their operations control systems. This allowed Xcel to optimize its reserve planning, better manage large and fast power output variations ("ramp events" caused by extreme weather) and plan its power commitments and trading more efficiently. A 3.7% reduction in mean absolute forecasting percentage error (as measured in 2010) resulted in 17%-38% of improvements in Xcel's wind farm performance (installed capacity verses actual power production), translating to these monetary savings (Haupt et al 2014).

While all regions of the world would benefit from these improvements, currently regions with significant populations but limited surface-based observation networks would benefit the most, particularly Africa, South America and parts of Asia. Figure 12 implies but does not compute the potential regional improvements in forecast accuracies due to increased observations. To estimate the regional benefits, the total global benefits are first distributed to the regions based on percentage of global GDP in 2019, and then adjusted to regional proportions of global forecast improvements based roughly on Figure 12[21]. The results are shown in Table 2.

***Table 2**: Estimated regional benefits from improved forecasting due to improved availability and exchange of surface observations. Antarctica is omitted because it does not contribute to global GDP.*

Region	**% of global GDP[22]**	**% of global forecast improvement**	**Annual benefit (USD)**
Global	**100%**	**100%**	**$5.19 billion**
Africa	3%	26%	$350 million
Asia	36%	16%	$2,640 million
S. America	4%	32%	$670 million
NAM CAM Crb	29%	6%	$830 million
SW Pacific	4%	17%	$300 million
Europe	24%	3%	$400 million

While this considers that regions currently having the lowest coverage of surface-based observations will experience the greatest relative forecast improvements due to increased observations (column 3 in Table 2), the monetary benefits approach results in the attribution of most benefits to regions with a high share of global GDP, namely Asia, NAM CAM Crb and Europe (column 2). It must here be again noted that by only focusing on GDP, well-being benefits such as lives saved and poverty reduction are ignored, which would likely be most significant in lower GDP regions (Africa, South America and SW Pacific).

A similar assessment is performed based on World Bank country income classifications, the results of which are shown in Table 3. The portion of global forecast improvements is computed by

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[21] Regional mean impacts from observations are summed to compute a proxy global impact. The percent of global impact contributed by each region is then used to represent the regional percent of global forecast improvement due to increased observations.

[22] Based on 2018 GDP, sourced from https://data.worldbank.org/

assigning the regional forecast improvements to all countries in the given region, then averaging globally per income class (total numbers of countries per income class: high = 79, upper middle = 60, lower middle = 48, low = 30). Based on recent average insured verses total losses for weather-related events, the average annual avoided insurance loss as a portion of annual benefit due to improved forecasting driven by improved observations is further computed.

Table 3: *Estimated benefits and avoided insurance losses per country income classification from improved forecasting due to improved availability and exchange of surface observations.*

Country income class	% of global GDP[23]	% of global forecast improvement	Weather-related insurance coverage[24]	Annual benefit (USD)	Annual avoided insurance losses (USD)
All	**100%**	**100%**	**45%**	**$5.19 billion**	**$1.67 billion**
High	63%	21%	53%	$2,870 million	$1.510 million
Upper Middle	29%	28%	8%	$1,830 million	$140 million
Lower Middle	7%	29%	4%	$460 million	$20 million
Low	1%	22%	0.5%	$30 million	$0.2 million

5.5. Costs of surface-based observations

The costs of the global observing systems that support operational meteorology have not been assessed in detail. Estimates have however been made; some studies indicate that the annual costs of these systems, including both space-based and surface-based observing systems, are of the order of US$10 billion per year (Rogers and Tsirkunov 2013). The costs of those components of these systems that support global NWP have been estimated at ~US$3 billion (Eyre and Reid, 2014).

The global capital investment and annual operating costs needed to upgrade the surface-based observation networks in under-monitored countries to meet all proposed WMO Member obligations for the GBON is made based on the following assumptions, informed primarily by the WIGOS[25] Data Quality Monitoring System[26]:

- 2,500 currently “silent” surface stations, of which half require new installations and half require a telecommunications upgrade;
- 500 currently low-functioning surface stations, of which all are assumed to require full rehabilitation;
- 5,000 currently partially functioning surface stations, all requiring a telecommunications upgrade;
- 1,000 new surface stations at continental locations and 500 at ocean (small island) locations in order to meet the GBON-required minimum station density; and

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[23] ibid

[24] Based on insured verses overall losses for relevant weather-related events 2016 – 2018, sourced from https://natcatservice.munichre.com/

[25] WMO Integrated Global Observing System

[26] https://wdqms.wmo.int/

- 99 new land-based and 25 new ocean (small island) upper air (radiosonde) stations, in order to meet the GBON-required minimum station density.

The following cost assumptions are applied:

- New surface station: US$60,000
- New surface station in remote location: US$120,000
- Rehabilitation of a surface station (full): US$60,000
- Rehabilitation of a surface station (telecommunications): US$10,000
- Annual operating cost of a surface station: US$15,000
- New manned upper air station: US$400,000
- New remote upper air station: US$1,350,000
- Rehabilitation of an upper air station: US$150,000
- Annual operating cost of an upper air station: US$150,000
- Annual bulk cost of additional aircraft-based observations: US$5,000,000

This results in a total capital investment cost of US$361 million and annual operation costs of US$166 million[27]. It should be noted that through the use of modern information and communications technology (ICT) systems, the costs of sharing observations internationally are only a very small fraction of the costs of implementing and operating the observing systems themselves. It is therefore assumed that the marginal costs of sharing additional observations is negligible compared to the costs of installing and operating the systems to produce additional observations, noting that systems for disseminating observations are already in place. This is consistent with one of the key messages in the Implementation Plan for the Evolution of Global Observing Systems, namely that the most cost-effective action that WMO Members can take to improve their services is to share more widely the observations that are already made (WMO 2013).

5.6. Cost-benefit analysis

While Section 5.4 indicates there are significant benefits to be gained from improving surface-based observations coverage and exchange, it is important to assess if these outweigh the costs, based on a simplified cost-benefit analysis. While only considering the modernization and O&M costs of stations requiring upgrades, the analysis includes all global benefits of improvements including those realized by countries/regions where the improvements are made, as well as those in countries/regions where capacities are already high. This recognizes that local forecasting in any given location benefits from improved observations from all over the globe.

The cost-benefit analysis assumes that capital investments to improve observations are made over an initial 5-year period, with an equal amount of investment each year. Benefits and O&M costs accrue starting the year after investments are made, and reach a maximum in year 6, after all capital investments are completed. The analysis also assumes that the lifespan of the upgraded observation network is 20 years; following 5-years of capital investments, only O&M costs are incurred over the remaining 15 years. The analysis assumes that GDP remains constant over the next 20 years. While it is clear that COVID-19 will negatively impact GDP growth for the next years,

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[27] The costs given here are global totals based on WIGOS data quality monitoring. Assessments have been made elsewhere of the capital investment and operating costs relating only to LMICs, for example: https://public.wmo.int/en/our-mandate/how-we-do-it/development-partnerships/Innovating-finance.

in the long-term growth is still expected, albeit at different rates due to national contexts. As benefits are computed as a percentage of GDP, the assumption of constant GDP for the next 20 years is therefore considered conservative.

Taking the benefit and cost estimates reviewed in Sections 5.4 and 5.5 and applying a discount rate[28] of 6%[29] results in a benefit-cost ratio (B/C)[30] of over 25 and a net present value (NPV)[31] of over $46 billion. Sensitivity analysis indicates that when the discount rate is varied between 1%-12%, costs increased by 25% and benefits decreased by 25%, the B/C ratio remains above 14, indicating the robustness of the conclusion that investing to improve the global surface-based observation network is highly economically efficient.

6. Summary and conclusions

The answer to the first of the research question posed in the introduction of this article is that *provided that surface-based meteorological observations are exchanged internationally, in particular with the global numerical weather prediction centers* – their economic value can indeed be quantified. The assessment is based on a rigorous mathematical assessment of the contribution of the observations to the quality of weather prediction products, combined with an analysis of the economic value of these products, the latter building on previous research. The value of observations acquired for purely national or local purposes, and that are therefore not exchanged internationally, is substantially more difficult to assess. Such an assessment has not been attempted here.

Concerning the second research question, the answer resulting from our analysis is that investment in surface-based meteorological observing systems measuring critical variables and intended for international exchange of data is indeed highly attractive. This is especially true in those regions where the current availability of observations fails to meet internationally agreed requirements and the input needs of global NWP, in particular in LDCs, SIDS and ocean areas in general. The overall estimated benefit/cost ratio of the additional investment required to bring the international data exchange of observational data up to WMO required standards in all countries of the world is on the order of 25 (or at least 14 under even more conservative assumptions).

6.1. Policy implications

Three important recommendations may be drawn from the analysis presented in this article, one aimed at individual countries, and two at the international development and climate finance communities. Our analysis once again demonstrates that international exchange of observations is a tremendously efficient value multiplier. This is well-known in the meteorological community

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[28] The discount rate represents societal preference for consuming in the present as opposed to saving and consuming in the future. A discount rate of 0% indicates no preference between now and in the future, while for example a discount rate of 15% represents a high preference for consuming now.

[29] As per World Bank guidance

[30] B/C ratio = present benefits divided by present costs (if the benefit/cost ratio is greater than 1.0 then the investment is considered economically effective).

[31] NPV = present benefits minus present costs (if the NPV is greater than 0 then the investment is considered economically effective).

but is perhaps less widely understood among the institutions responsible for designing and implementing projects involving meteorological infrastructure aimed at improving e.g. the climate resilience of developing nations.

For individual countries, the analysis results in a strong recommendation to exchange their observational data internationally. Observing systems – or even whole observing networks - are not early warning systems. They cannot in and of themselves provide any value unless their data are fed into the meteorological value chain via integrated data processing systems that can use them to synthesize the state of the weather and climate system and thus prepare us to understand and predict it. Global NWP is the most powerful and most successful example of such an integrated processing system, and global NWP systems underpin all subsequent quantitative data processing systems for weather and climate.

For the international development and climate finance institutions, the first recommendation is to ensure that the key observing systems feeding into the global NWP systems are included in any national development projects aimed at improving or installing hydrometeorological observing infrastructure. Any modern hydrometeorological service anywhere in the world will base its service delivery first and foremost on NWP guidance, and next on any observational data that are available for the local area, either from ground-based assets or from satellites. The quality of the NWP guidance is directly dependent on the amount and quality of observational data fed into the system, with local observation having the largest and most immediate impact, and remote observations becoming increasingly important at longer forecast ranges.

The second recommendation to these institutions is to ensure to the largest extent possible that their investment in observational infrastructure is coupled with an agreement that the recipient country will exchange the resulting observational data internationally per WMO regulations. Failing to exchange the observations will limit – or even completely eliminate - the return on the investment by eliminating the potential benefits to the quality of global NWP products. The indirect negative effects of failing to exchange observations – the lack of improvement in the quality of weather and climate services due to the missed opportunity to benefit from the additional observations – will be most pronounced in the vicinity of the observations, i.e. within the recipient country itself. However, they will extend far beyond the national borders and will in principle impact the entire global community.

6.2. Detailed conclusions

Weather forecasting provides a range of significant societal benefits. It is estimated that high quality and timely forecasts, if they are available everywhere, interpreted properly and appropriately reacted to, can generate at least $160 billion per year of global socioeconomic benefits. As concluded by Zhang et al (2019), forecast accuracy can be significantly improved, but this requires coordinated efforts by the entire community to improve numerical weather models, observations, and data assimilation and computing techniques.

Forecast quality relies on the performance of numerical weather prediction (NWP), which itself relies on the availability of global, real-time observations. NWP forms the basis of most weather forecasts on a day-to-day basis. NWP takes current observations of weather and combines these data with computer models of the atmosphere to forecast the future state of weather. The forecasts upon which society depends would not be possible without the real-time, international exchange of observational data.

Meteorological observations also play a vital role in climate monitoring, and thus in a growing range of climate services. Activities of WMO Members that require global observations, such as global NWP and climate analysis, would benefit considerably if the international exchange of existing and new observations could be enhanced. This assessment however focuses only on meteorological observations' foundational role in weather forecasting.

The impact of different types of meteorological observations on NWP performance can be quantified and analyzed in detail. Global NWP centers possess the tools to do this, and information from such studies is widely shared within the NWP community. Most impact studies focus on the impact of using observations from new observing systems and technologies, or on improved ways of using existing observations. The impact of observations partitioned according to their country or region of origin is assessed in this study.

Space-based observations are most critical to NWP performance and are currently exchanged in a robust fashion. In the studied period and for the data assimilation system used here, of the total reduction of error in the 24-hour global NWP forecast attributable to observations, about 75% comes from space-based observations. The majority of countries and regions that have the resources to operate satellite systems make their relevant observations available to the global meteorological community, thereby enabling and improving NWP all over the world. It is vital that this system be maintained.

NWP can be significantly improved, particularly for regions where surface-based observations are relatively sparse. More observations from these regions would improve global NWP, but especially NWP performance in the data sparse regions themselves. This supports the case for enhancing and/or implementing additional observing systems in some regions and for internationally sharing the outputs from these modernized systems.

Many more surface-based meteorological observations are generated at national level than are shared internationally. The results of this study support the case for improving implementation of WMO regulations and guidance in such a way that these data are more thoroughly exchanged. Sharing observations between countries and regions is one of the foundational activities on which the World Meteorological Organization (WMO) is based. It has been well established for over 50 years, and many of the activities of WMO Members depend on it.

Recognizing their importance, in 2019 the World Meteorological Congress adopted important resolutions related to improving the coverage and sharing of observations. The Global Basic Observing Network (GBON) defines the obligation of WMO Members to implement a minimal set of surface-based observing stations for international data exchange, while the Country Support Initiative aims to develop options for innovative financing to address the perennial sustainability issue of investments in and maintenance of observations.

Improvements in the coverage and exchange of surface-based observations can deliver additional benefits of at least $5 billion per year. Based on the resultant improvements in NWP performance and subsequent forecast improvements, the most significant forecasting improvements are seen in data-sparse regions such as Africa, South America, Pacific and Asia. By quantifying only the financial benefits, this study likely under-estimates the true benefits to low and lower-middle income countries, where non-monetizable (or at least non-GDP captured) benefits are not considered, for example potential lives saved.

Investing in improving surface-based observations in developing countries is highly economically efficient. It is estimated that the required capital investment and provision of increased operations and maintenance budget to improve and sustain global GBON-compliant observation network coverage and data exchange would yield a benefit/cost ratio of more than twenty-five. This means for every dollar invested, at least twenty-five dollars in socioeconomic returns could be realized.

International data exchange acts as a very efficient multiplier on the value of observations. Modern and rapidly developing ICT make exchanging even very large data sets in real-time relatively inexpensive. At the same time the requirements are evolving for a meteorological observation network to be fit-for-purpose and therefore economically efficient. As modeling technologies and speeds increase, the focus should be on assimilation in NWP, verifying forecasts, and providing long-term climate records. These results confirm the underlying rationale for the global observations systems of WMO, i.e. that the value of observations is greatly enhanced if they are widely shared between WMO Members.

In view of the growing climate- and weather-related challenges facing humanity, surface-based observations should be treated as a critical public good. Due to the herein quantified socioeconomic benefits, as well as the non-monetized contributions to societal wellbeing, protection and climate adaptation, national meteorological observing networks should be treated as public goods. The strict adherence to international standards and long-term continuity required for observations for global NWP and climate analysis means that at the very least, oversight and quality assurance of meteorological observations should be a responsibility of governments.

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Annex A: Description of observation types shown in Figure 5

MW Sound/Imager	Radiance observations from microwave atmospheric sounding and imaging instruments on low-Earth orbiting satellites, giving information mainly on atmospheric temperature and humidity
Hyperspect IR	Radiance observations from hyperspectral infra-red atmospheric sounding instruments on low-Earth orbiting satellites, giving information mainly on atmospheric temperature and humidity
AMVs	Atmospheric motion vectors – observations of wind derived from imagery sequences from geostationary and polar-orbiting satellites
Aircraft	Observations from aircraft, mainly of atmospheric temperature and wind
Sondes	Observations from balloon-borne instruments, of atmospheric temperature, humidity and wind
Surface-Land	Observations from instruments at the land surface, of surface pressure, atmospheric temperature and humidity and wind
GNSSRO	Global Navigation Satellite System – Radio Occultation, providing information on atmospheric temperature and humidity and surface pressure
Scatwind	Observations of ocean surface wind derived from scatterometers on low-Earth-orbiting satellites
Geo CSR	Clear-sky radiances from infra-red instruments on geostationary satellites, providing information on atmospheric temperature, humidity and wind
Surface-Ocean	Observations from instruments at the ocean surface (mainly on ships and buoys), of surface pressure, air temperature, humidity and wind
WindPro	Observations from wind-profiling radars at the land surface
Ground GNSS	Observations derived from Global Navigation Satellite System signals at the Earth's surface, providing information on atmospheric humidity (total column amount)

Annex B: Satellites contributing to the results shown in Figure 6

USA	Polar-orbiting satellites: NOAA-15, -18, -19, -20; Terra, Aqua; Suomi-NPP; DMSP F-17; Coriolis Geostationary satellites: GOES-15, GOES-16
Europe	Polar-orbiting satellites: Metop-A, Metop-B Geostationary satellites: Meteosat-8, Meteosat-11
Japan	Polar-orbiting satellite: GCOM-W Geostationary satellites: Himawari-8
China	Polar-orbiting satellites: FY-3B, FY-3C
US-Japan	Polar-orbiting satellite: Global Precipitation Monitoring (GPM) mission
India-France	Low-Earth-orbiting satellite: Megha-Tropiques
India	Polar-orbiting satellite: Scatsat-1
LeoGeo	Atmospheric motion vectors (AMVs = observations of wind) derived from visible/infra-red imagery from combination of geostationary and polar-orbiting satellites of various countries/regions
US-Taiwan	The COSMIC constellation of satellites for radio occultation, giving information on the vertical profiles of atmospheric temperature and humidity