

# Strengthening National Hydrometeorological Services through Cascading Forecasting

Investing for Sustainability and Impact across Global, Regional, and National Centers

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## Abstract

Low-income countries' hydrometeorological services often face considerable constraints in delivering the information needed to effectively drive early warning and climate adaptation, which, if improved, could generate socioeconomic benefits of about US\$1.4 billion per year. Modern weather forecasting adopts a cascading approach where numerical products developed by global producing centers feed regional and national models, with national forecasters assimilating these and other data to produce information customized for local users. The system depends on global producing centers sharing their products, often through voluntary action without dedicated financing, which is not sustainable and does not fully leverage the capacity of global producing centers to provide tailored information. It would be economically viable for global producing centers to provide their full suite of services to low-income countries, producing likely global socioeconomic benefits of US\$200 million to US\$500 million per year, outweighing

the costs by about 80 to one. Existing global producing centers' capacities and their potential benefits for low-income countries fulfill the utilitarian principal. Global numerical weather prediction should therefore be treated as a global public good. However, although recent global development and climate agreements clearly suggest that improving forecasting in low-income countries should be a target of international cooperation, official development assistance financing of high-income country global producing centers to provide products to low-income countries would be considered tied aid. Specialized mechanisms, such as the Green Climate Fund, could provide legitimate means to finance global producing centers to provide global public services in support of low-income countries. However, to realize the potential benefits, significant investment is needed in regional and national forecasting, early warning, and preparedness capacities.

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# 1 Introduction

The impacts of weather and climate-related disasters are on the rise, due to human development patterns, environmental degradation, climate change and their dynamic interactions (World Bank 2013). While more than 3,500 disasters resulting from hydrometeorological hazards were observed between 2001 and 2010, only 750 were recorded in the period from 1971 to 1980 (WMO et al. 2014). These events cause not only immediate impacts through losses of life and livelihoods, they also hamper economic growth and exacerbate poverty. While future trends remain somewhat uncertain, it is clear that climate-related impacts will continue to grow due to development and climate drivers, and the impacts will be felt most acutely by the poor (IPCC 2012; World Bank 2013).

Recognized as a crucial component of disaster preparedness, weather/climate forecasting and subsequent early warning contribute to public and private risk management decision-making, thereby helping to save lives, avoid disaster costs and preserve livelihoods. However, low-income countries' (LICs) National Meteorological and Hydrological Services (NMHSs) often face considerable constraints in delivering the weather and climate information needed to effectively inform early warning and climate adaptation. It is estimated that improving NMHS capacities in all low- and middle-income countries could annually save up to 23,000 lives and prevent up to US\$ 2 billion in financial losses due to disasters (Hallegatte 2012).

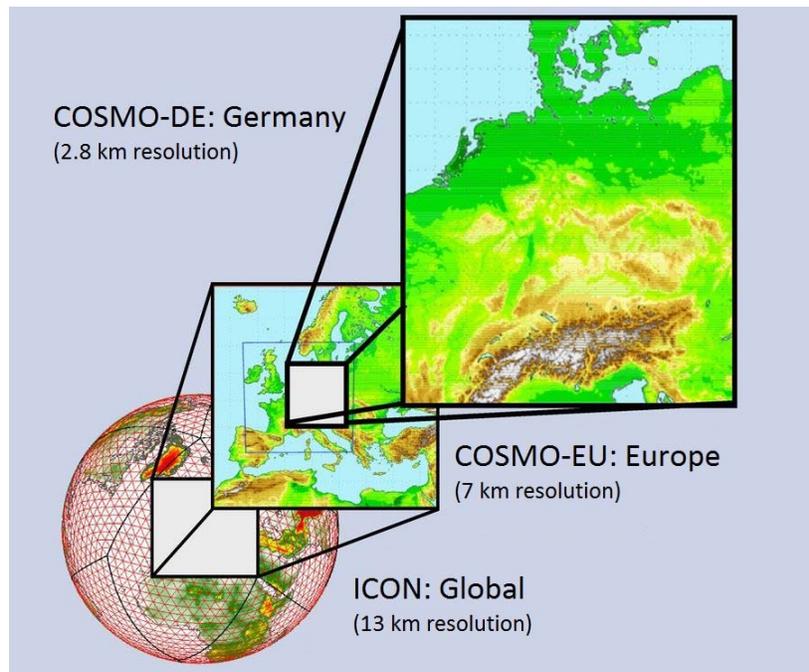
## 1.1 Numerical weather prediction

Modern weather forecasting relies greatly on the guidance provided by numerical weather prediction (NWP), utilizing advanced computer modelling techniques to analyze observations and predict future conditions based on the complex physics of the atmosphere and its interaction with the ocean and land. As the atmosphere is a chaotic system, very small changes in the initial state used for NWP can lead to large differences in the modeled future. This implies that because every detail of the atmosphere's initial state cannot be observed, production of a "perfect" NWP is impossible. Forecasters therefore utilize their experience and local knowledge ("skill") to interpret NWP outputs to produce the forecasts provided to the public and other users.

To further understand the probability of future weather scenarios, NWP are often run multiple times from slightly different starting conditions, referred to as an ensemble prediction system (EPS). The ensemble forecasts can give the forecaster a much better idea of what weather events may occur at a particular time, and by comparing these different forecasts the forecaster can assess how likely a particular weather event will be. If the ensemble forecasts show great variation, the forecaster knows that there is significant uncertainty about the future weather evolution. On the other hand, if the ensemble forecasts are all very similar, they will allow more confidence in predicting a particular event (Met Office 2016). Multi-model ensembles utilize multiple NWPs to further achieve a better understanding of the range of possible future weather, as NWPs tend to utilize different approaches and assumptions to simulate the physics and dynamics of the atmosphere, resulting in occasionally different realizations across the pool of NWP models (each of which may have particular strengths and weaknesses for different scenarios and regions).

## 1.2 Cascading forecast approach

Economies of scale and financial realities dictate that it would not make sense for all of the world's NMHSs to aim at operating the most advanced global NWP model, which requires supercomputers, highly skilled personnel and significant research and development for effective, sustainable and consistently improving processing and delivery. Modern forecasting therefore relies on a cascading approach where global NWP provides the initial and lateral boundary conditions for regional and national NWP, as shown in Figure 1.1, with national forecasters assimilating observations and model outputs to produce forecasts customized for local users.



**Figure 1.1:** Schematic of the cascading forecasting system using the German Meteorological Service as an example: ICON is the global NWP that feeds the European NWP COSMO-EU, which subsequently feeds the German NWP COMSO-DE. Image copied from BINE (2016) and amended with information and permission from DWD (2016, copyright holder).

This cascading approach, as for example promoted and practiced through the World Meteorological Organization's (WMO's) Severe Weather Forecasting Demonstration Project (SWFDP – see Box 1.1), ensures NMHSs have access to products from the latest forecasting technology and approaches, with a longer-term vision for utilizing these approaches at national level (requiring also increased national capacity), without having to invest excessively and avoiding duplication of efforts. The cascading approach offers a means to improve weather forecasting and early-warning capacities in LICs without significant capital investments and requiring limited recurrent budget, which NMHSs often find challenging to mobilize.

### **Box 1.1: Severe Weather Forecasting Demonstration Project**

The World Meteorological Organization (WMO) has developed and implemented a series of Severe Weather Forecasting Demonstration Projects (SWFDPs) which are designed to demonstrate the usefulness of global numerical weather prediction (NWP) products, particularly ensemble prediction systems (EPS) - produced by global meteorological centers and regional specialized meteorological centers (RSMCs) - in improving severe weather forecasting services in countries where sophisticated model outputs are currently not used. These projects directly link improvements in NWP with improvements in forecasting skill at the national level and in services delivered to stakeholders through a cascading approach: global NWP outputs are delivered to RSMCs, who in turn disseminate regionally adapted outputs to the participating NMHSs. These then utilize the information to generate local forecasts and warnings. This technical approach is complemented by regular discussion and backstopping between forecasters at the national, regional and global levels.

Currently SWFDPs are running in Southern Africa, Eastern Africa and the South Pacific, with projects in various stages of development for Southeast Asia, Central Asia, and the Bay of Bengal. RSMC Pretoria, operated by the South African Weather Service, continues to support the first established SWFDP in Southern Africa. RSMC Pretoria has helped NMHSs improve their use of global modeling products to (a) predict severe weather events, such as heavy rain and strong winds, (b) improve alerts, (c) improve interaction between NMHSs and civil protection, and (d) improve the global data-processing and forecasting system and service delivery overall.

*Sources: Rogers and Tsirkunov (2013), WMO (2016).*

The cascading forecast approach is not possible without global numerical weather products developed by global and regional forecast producing centers. The WMO coordinated Global Data-processing and Forecasting System (GDPFS) is organized as a three-level system of World Meteorological Centers (WMCs), Regional Specialized Meteorological Centers (RSMCs) and National Meteorological Centers (NMCs), which carry out GDPFS functions at the global, regional and national levels, respectively (WMO 2015a). The WMO membership has agreed formal requirements and definitions for designation of WMCs and RSMCs.

This current research is concerned primarily with global producing centers, some of which are not WMO-designated WMCs. As such we herein use the term “GPCs” to refer to all public organizations that operate global NWP models. It must be highlighted that while RSMCs play a critical role in the cascading system, they are not the subject of this research.

Currently, the system depends on the willingness, often through voluntary action, of a number of advanced GPCs to share their data and products. While the status quo is manageable, it provides limited guarantees in terms of sustainability, as most GPCs are not specifically tasked or financed to ensure product delivery to LICs.

## **1.3 Arguments to support LICs**

This paper therefore explores the arguments and potential solutions for guaranteeing LIC NMHSs’ access to the full suite of forecasting products of GPCs. It should be noted that many middle-income countries (MICs) would also benefit from such GPC access, however as some MICs are able to

purchase GPC services or even host GPCs, we focus on the LICs as being most in need of support. We aim to produce pragmatic evidence and guidance regarding the true costs, socioeconomic benefits, public service imperatives, and potential financing models to facilitate LICs' access to the full suite of services delivered by GPCs. We address the research question: "How can the provision of global weather and climate products for LICs be justified and secured in the long term?" Three hypotheses are put forward to answer this:

### *1. Do the benefits outweigh the costs?*

Cost-benefit analysis is an important metric to inform investment decisions. If the benefits of providing forecasting products to LICs' NMHSs outweigh the costs of providing these products, from a global welfare perspective it makes economic sense to pursue the needed investment. The costs considered in this limited research (see Section 1.4) are primarily defined as the costs of GPCs to produce and disseminate products for LICs, while the socioeconomic benefits (SEB) are the lives saved, damage avoided and other gains due to improved information for decision-making in LICs.

### *2. How can we justify global public service imperatives?*

Open and unrestricted access to data is often recognized as producing socioeconomic benefits (GEO 2015). Based on the documentation reviewed in this paper, assumptions on the many diverse societal and economic benefits that come from the provision of GPCs products can be made. However, while all countries should be able to benefit from these tools which deliver services with significant global value, they are currently limited in their access due to costs and policy limitations, as well as limited local capacity to interpret the products. We therefore address the fact that there must be an ethical case supporting the "responsibility" of higher income countries<sup>1</sup> to ensure the availability of these vital products as a global public service.

### *3. What would be a sustainable financial source?*

At present, several GPCs offer some products and services to certain LICs. However, the sufficiency and continuity of financing for providing these services is often far from secure. In most cases, GPCs do not have a clear mandate with a distinguished budget line to offer services to LICs, both of which would be needed to guarantee sustainability. As improved forecasting has been shown to contribute to the development and growth of LICs, the question of whether the provision of forecasting products should be financed through official development aid (ODA) is considered.

## 1.4 Investment needed primarily at regional and national levels

This research focuses on the imperative and potential approaches to ensuring LICs' access to GPC products solely from a supply perspective. In reality, there is far greater need and therefore demand for support (capacity, financing, etc.) to improve forecasting, early warning and risk management at

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<sup>1</sup> "Higher income countries" here refers to middle and high income countries that host GPCs and/or contribute official development aid. It should not be confused with the official World Bank Group definition of a high income country (HIC).

the regional and national levels. As such, this research should be understood as a contribution to the broader effort to strengthen the GDPFS for the benefit of all, particularly LICs.

Global experts and representatives from GPCs, RSMCs, NMHSs and donors observed and concluded during a 2013 WMO-World Bank Group-GFDRR workshop that RSMCs, particularly those hosted by MICs and LICs, generally need major investment to ensure they are able to provide the required forecaster guidance and develop specialized numerical products. The incremental cost of providing global products is far lower than the cost of producing regional products. Further, and building on past and current assessments of NMHS capacities, without significant investment in NMHSs, the cascading forecast system will not succeed in delivering national benefits and/or be sustainable (WMO et al 2013).

A practical example is the situation with Myanmar's Department of Meteorology and Hydrology (DMH). The European Centre for Medium-Range Weather Forecasting (ECMWF) has provided DMH access to its entire suite of graphical products and provided the tools to extract the most useful information for Myanmar. However DMH has difficulty accessing these products due to limited Internet bandwidth (WMO 2015b). The cost to ECMWF to make this service available is financially small, however the policy and resource issues that need to be overcome domestically in Myanmar potentially come with significant costs. National investment in information technology, communications and NWP expertise is needed, even if an NMHS is not running NWP, to be able to access and utilize these products.

This represents a major caveat for the current research in that only one component of the cascading forecast value chain (see Figure 2.1) is explored, with the assumption that the other components are able to deliver sufficiently to produce the benefits offered by improved access to NWP in LICs through a cascading forecast system. While such assumptions are needed when resource-limited assessments are performed on individual components of a broader effort, it must be stressed that sufficient capacity is needed, and currently often lacking, at all levels and across actors to realize the potential benefits.

## 2 Background

### 2.1 Global hydrometeorological system

This section draws extensively from Rogers and Tsirkunov (2013). The global hydrometeorological enterprise is composed of several institutions that contribute to the production, delivery, and use of weather, climate and water information products and services. Since atmospheric and hydrologic processes know no boundaries, the provision of hydrometeorological products and services by public institutions relies on information exchanged from the global to the local level; a process that is coordinated by the WMO. Data gathered across scales and boundaries provide complementary information, which are assimilated to deliver as accurate a picture of weather and climate as possible. The main institutions involved in this global enterprise and relevant to the current research are reviewed here from national to global:

### *National Meteorological and Hydrological Services (NMHSs)*

At the heart of this enterprise lie the National Meteorological Services (NMSs) and National Hydrological Services (NHSs), which are collectively referred to as National Meteorological and Hydrological Services (NMHSs: Zillman 1999; Rogers and Tsirkunov 2013). As public agencies, they are responsible for monitoring, analyzing and providing information at the national level, particularly for disaster management services, the general public and key economic sectors. They carry out functions in support of the safety, protection and livelihoods of the general population and in line with their international obligations under the conventions of the WMO and related international weather and climate commitments (Zillman 1999).

### *Regional Specialized Meteorological Centers (RSMCs)*

At the regional level, WMO-designated RSMCs are responsible for the distribution of information, advisories and warnings for specific programs (tropical cyclones, environmental emergencies, etc.) as part of the WMO coordinated World Weather Watch. Some also play a crucial role in the cascading forecasting process. The RSMCs take numerical data from the GPCs and interpret the information received in order to prepare daily guidance products for the NMHSs, running limited area models to refine products on a finer time scale, while coordinating certain tasks with participating NMHSs. At the global scale, each RSMC has different, yet specific duties, from monitoring atmospheric radiation to tropical cyclone forecasting, among others (Rogers and Tsirkunov 2013).

### *Global Producing Centers (GPCs)*

Global Producing Centers (GPCs) are at the top of the cascading forecast process. Each center is a WMO certified institution that aims to support RSMCs and NMHSs with the provision of forecasts on the global scale (Rogers and Tsirkunov 2013). They are an essential part of the process because they possess the capacity for computing long-range forecasts covering all of the earth (Rogers and Tsirkunov 2013). The provision of global scale products and services by GPCs enable WMO members to focus on the national and local end user needs to generate early warnings and actionable weather, climate and water information.

### *World Meteorological Organization (WMO)*

With 191 member countries, the WMO provides a framework for international cooperation to ensure the development of hydrometeorological forecasting, including access to data, processing and standardization of related data, technology transfer, training and research. WMO fosters collaboration between NMHSs and contributes to the application of hydrometeorology to public and private services. WMO's basic mandate has been expanded to strengthen the capacity of NMHSs to generate and provide operationally updated climate forecasting and information products intended for climate services.

## 2.2 Production and delivery of climate and weather services

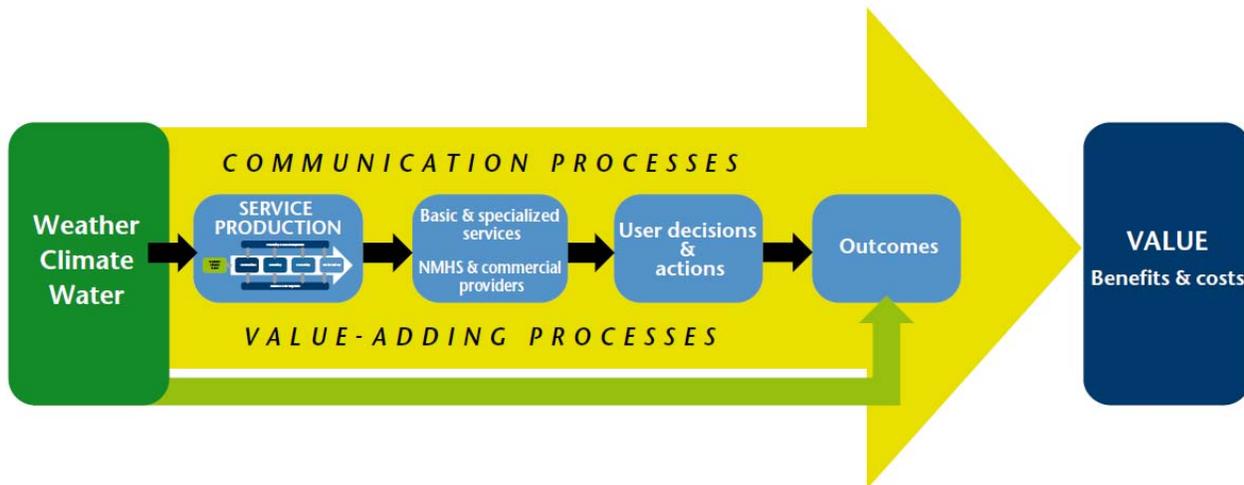
The provision of hydrometeorological services depends on a complex set of processes starting with essential observations of the atmosphere, land and oceans for such elements as temperature, precipitation, pressure and wind. These observational fields are overlaid with initial estimate NWP products in a critical first step, and then using the skill of forecasters and other techniques and approaches such as trend analysis, experience, local climatology, etc., forecast products (services)

are produced for a range of users. The result of this process depends on the characteristic of the weather/climate phenomena, as some form over shorter scales in space and time than others (e.g. tornados vs. tropical cyclones). Whether rapid- or slow-onset, warnings of hazardous weather are issued with different levels of urgency and risk based on the severity of past occurrences, highlighting the importance of climate data for forward-looking early warning and early action.

Based on the bulk of information from the previous steps of observation and monitoring, a first early warning assumption can be made about upcoming hazardous or extreme meteorological events. Human proficiency is required to analyze complex numerical forecasting data and translate them into concrete information that is easily communicable to end-users (Météo France 2015; Rogers and Tsirkunov 2013). This results in a varying degree of qualitative interpretation or adjustments by forecasters.

### 2.3 Value chain

To understand the benefits that derive from the provision of weather and climate services, we must look at how information is produced, communicated and utilized through a value adding-process. Value is generated through more informed risk management decisions across different sectors, however there are numerous actors and interactions involved within the processing chain that finally result in the creation of value. The main components of this system are broadly captured in Figure 2.1. It is important to consider the role of communication in the process of influencing user decisions and actions, which then lead to actual outcomes and value (WMO et al 2015).



**Figure 2.1:** Simplified schematic of the hydrometeorological services value chain. “Service Production” includes observations, modeling, forecasting and delivery, reliant on processing and data management, and underpinned by research and development (copied from Figure 2.1, WMO et al 2015).

When forecasting information has been generated by NMHSs, the output is communicated primarily either through the media, emergency services, and public sector institutions as basic (public good)

services or through specialized (often fee-based) services to the commercial channels of NMHSs and the private sector. WMO et al (2015) describes these in more detail:

- Basic services - those services provided at public expense to discharge a government's sovereign responsibility for protection of life and property, for the general safety and well-being of the national community and for provision for the essential information needs of future generations;
- Special services - those services beyond the basic services aimed at meeting the needs of specific users and user groups and that may include provision of specialized data and publications, their interpretation, distribution and dissemination.

Some decisions based on weather, climate and water information have larger and more observable outcomes while others have more incremental and less quantifiable consequences (Davison et al 2012). There are typically three types of decisions:

1. Strategic – decisions made more than one year in advance (e.g. large scale investments based on potential for climate change).
2. Tactical – decisions made one day to one year in advance (e.g. ranges from decisions on what to wear tomorrow to which crops to plant in the coming year).
3. Operational – decisions made less than one week in advance (e.g. frequent, continuous, or daily routine decisions made in anticipation of equipment needs to prevent or mitigate certain meteorological events, such as preventing a road closure due to snow by treating the surface).

Decisions or actions lead to outcomes, which depend on whether a decision is taken or not based on the full suite of available information. Many outcomes deliver quantifiable benefits, for example avoided life and asset losses, while others are more difficult to measure and as a result are often less acknowledged or analyzed, for example inconvenience or feelings (e.g. pleasure or sadness) associated with the anticipation of certain weather events (WMO et al 2015).

The outcome is the critical piece that connects weather and climate services with the resulting value. To determine the resulting value of forecasting services, one must attempt to estimate, qualitatively and quantitatively, the effects of any changes in the outcomes that result from improvement, withdrawal, or introduction of services in a certain context (WMO et al 2015). Therefore, the aggregate value of these services can be determined by measuring the costs and benefits of providing them.

## 2.4 Research data collection

Semi-structured interviews were conducted between May and November 2015 to collect information from GPCs about the products they provide to LICs, as well as the associated costs and currently applied financing models. The original sample comprised six GPCs: the United Kingdom Met Office (Met Office), European Centre for Medium-Range Weather Forecasts (ECMWF), Météo France, German Meteorological Service (DWD), Japan Meteorological Agency (JMA) and US National Oceanic and Atmospheric Administration (NOAA); and one RSMC, the Meteorological Service of New Zealand Ltd (MetService). The interviews were conducted in a three stage-approach, whereby not every interviewee was available at every stage:

1. In the first stage, representatives from all GPCs and RSMC were contacted in person and informed about the purpose of the research during the 17<sup>th</sup> WMO Congress (May-June 2015, Geneva). Following this, each received a standard one-page description of the research, including some indicative questions.

2. In the second stage, five interview partners responded to the indicative questions via email.
3. In a final stage, participants were followed up directly with further questions. Not every participant was able to answer the indicative questions within the time allocation of this project.

Table 2.1 provides an overview of the four GPCs and one RSMC most responsive to our survey. Each institution was questioned about its total operating costs and the marginal costs needed for providing the full suite<sup>2</sup> of global products to an additional country. The budgets of the agencies in the sample varied widely and often did not indicate details on specific costs of GPC and RSMC functions, necessitating broad assumptions when estimating the costs of global NWP provision.

**Table 2.1:** Overview of interviewed GPCs and RSMC.

Name	Type	Inst. Status	Financing		Products		Additional Services
			Primary	Secondary	Forecasts	Other	
ECMWF	GPC	Intergov	Member dues	Projects (EU)	Global	Custom forecasts	Training
DWD (Germany)	GPC	NMHS	Central gov.		Global & regional	Regional advisories	NWP model support
Météo France	GPC	NMHS	Central gov.	Projects	Global & regional	Regional advisories	NWP model support
Met Office (UK)	GPC	NMHS	Central gov.	UK cont. to WMO VCP, projects	Global & regional		NWP model support, training
Met Service (NZ)	RSMC	NMHS	Projects		Regional	Regional advisories	Training

The extent of service delivery also varied from one center to another. For example, the ECMWF is able to provide products, training and verification tools directly to NMHSs, while the Met Office and MetService provide a more extensive array of capacity building services in addition to their products. Furthermore, the Met Office and NOAA have already performed socioeconomic benefit studies (SEBs) for their services while others had not (ECMWF 2015a; Met Office 2015a; NOAA 2007).

### 3 Cost-benefit analysis

The costs and socioeconomic benefits (SEB) of GPCs providing the full suite of forecasting products to LICs' NMHS are estimated and compared following the methodology described in (WMO et al 2015). The applied SEB framework consists of: establishing the baseline of the SEB analysis; identifying the relevant changes in services offered; identifying, screening, analyzing and comparing the costs and socioeconomic benefits; considering biases, omissions and uncertainties; conducting a sensitivity analysis; and communicating the results.

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<sup>2</sup> The "full suite" of products varies by GPC. As an example, ECMWF offers for up to 15 days in the future, as well as for monthly and seasonal outlooks, a wide spectrum of real-time parameters, levels and ranges; charts of weather parameters, meteograms and an Extreme Forecast Index (EFI); and archives of analyses, forecasts and climate re-analyses (ECMWF 2015b).

While this approach was designed primarily to be applied to individual NMHSs for assessing either whole-of-service or specific products, we apply it on a global scale. This results in a less detailed SEB analysis that should be considered a rough estimate of the global potential of GPCs providing forecasting products to LICs.

The baseline of this study is the status quo of weather and climate forecasting quality in LICs. Here, it is assumed that in the status quo, LICs lack full access to global forecasting products from GPCs. The relevant change is the gaining of full access to forecasting products available from GPCs.

### 3.1 Conservative approach

A critical challenge in assessing costs and especially benefits in this field is that it is difficult to attain comprehensive, robust and accurate figures. Firstly, it is somewhat ambiguous as to what exactly should be included under costs and socioeconomic benefits. Secondly, assuming the first issue is solved, it is not possible to obtain data on every aspect. This issue is difficult to solve, but its consequences can be controlled. In consideration of these limitations, we assess ranges of benefit and cost estimates, rather than singular values. Furthermore, the trend of potential biases can be managed; when confronted with data gaps, socioeconomic benefits are intentionally systematically understated, while the more robust cost data are considered more comprehensive.

Under such a conservative approach, the resulting net benefits likely underestimate the true net benefits. Assessment biases therefore affect only the magnitude and not the overall trends of the results, increasing confidence in the conclusions.

### 3.2 Costs

Costs are defined as the total amount of sacrifices made to accomplish a task or produce a product or service (WMO et al 2015). In the case of weather forecasting, costs occur at different stages:

- Service production and delivery (GPCs, RSMCs, NMHSs, commercial weather services, etc.) including staff, forecasting infrastructure investment and maintenance as well as the costs of buildings, utilities, etc. Taking a wider perspective, the use of public goods should be included as well. Apart from the public good use, these costs can be estimated from the balance sheets of the GPCs, RSMCs, NMHSs or commercial weather services.
- Users incur costs when accessing forecasting products and adapting their decisions accordingly. These costs are more difficult to assess quantitatively and are not relevant for this research, as we will only consider GPC costs.

As such, costs for our purposes occur at four different stages:

1. Costs of the GPCs for research, development, production and dissemination.
2. Costs of the RSMCs and NMHSs to use and adapt these forecasting products.
3. Costs of commercial weather services to process forecasting information, tailor forecasting products for the end user and communicate these.
4. Costs of users of weather services for information retrieval, interpretation as well as the cost of taking action according to the forecasting information.

It could be argued that the national weather observations that NMHSs share globally through the WMO coordinated Global Telecommunication System (GTS), which are then assimilated by global NWP, also provide a public good by improving NWP performance. However, sharing these data primarily results in improved national outputs from the GPCs, thereby most benefitting the country making and sharing the observations. Some observations like upper air soundings may also generate regional benefits. However in this assessment these instances are not considered.

As the focus of this research lies on the supply side and the majority of the costs of GPCs occur in Stage 1, we focus primarily on these stages, however also including GPC costs for training RSMCs and NMHSs to utilize their products (Stage 2). Further, as we are only interested in the additional costs incurred when using forecasting products from GPCs, we must assume the existence of basic capacities under Stages 2-4. While as reviewed in Section 1.4 this should be viewed as a major caveat of this assessment, under the constraints of this research, it would in any case be difficult to extract global NWP-specific costs from Stages 2-4. It is recognized that this assumption is particularly bold in LICs, many of whom lack basic capacities in Stages 2-4.

The costs of GPCs to provide forecasting products to LICs were analyzed using the data gathered from GPCs as described in Section 2.4. Average data ranges of the marginal set-up and running costs of providing the full suite of global forecasting products to an additional country or region were calculated. To estimate the costs of providing global forecasting products to all LICs, these figures are multiplied by the total number of LICs (31 countries). This is a very conservative estimation (resulting in higher than expected costs), as it ignores for example economies of scale when products are provided to regions. The results are shown in Table 3.1.

**Table 3.1:** Summary of costs under conservative assumptions, in 2014 US\$.

Countries	Set up costs (US\$)	Annual costs (US\$)
Single LIC	65,700 – 303,800	29,800 – 151,900
All 31 LICs	2,036,200 – 9,419,200	924,200 – 4,709,600

Based on experience, WMO (2013) estimates that the funding requirements for the implementation and sustainability of a SWFDP regional project engaging six NMHSs, one RSMC and three GPCs over five years amounts to about US\$3.4 million, averaging US\$680,000 per year (assuming no costs for infrastructure). Scaling up to cover 31 countries (all LICs), this comes to approximately US\$3.5 million per year. This assumes that the contributions from GPCs and RSMCs are provided in-kind, which has so far been the case. Comparing to Table 3.1, it is observed that the GPCs' contributions to SWFDP are of similar magnitudes of cost to the technical cooperation and coordination budget of SWFDP. In other words, the GPCs' critical role also reflects a substantial financial "donation" with respect to the full cascading system. Full engagement by RSMCs is likely also of a similar cost magnitude, with most RSMCs not accessing sufficient funding to fulfill this role (WMO et al 2013).

### 3.3 Benefits

In order to assess all added value, financial, environmental and social benefits have to be considered through a "triple bottom line" approach (WMO et al 2015). Financial benefits include both reduced asset damage and additional quantifiable economic benefits such as more efficient sectoral production and planning (agriculture, energy, transport etc.). Environmental benefits include improved

management of local environmental quality or for example water savings due to more efficient irrigation. Social benefits comprise reduced losses of lives, injuries or illnesses but also increased psychosocial well-being.

Different techniques can be used to assign values to the benefits produced by improved weather information (WMO et al 2015):

- Non-market valuation techniques like stated or revealed preference methods.
- Economic modeling methods requiring significant amounts of detailed data and knowledge about the sectors where benefits are assessed, as well as substantial statistical expertise.
- Avoided-costs assessment, which is easier to implement than other options but only considers part of the benefits of improved forecasting. Additional economic benefits such as increased production due to forecasting are ignored.
- Benefits can also be assessed by transferring the results of existing benefit studies to the context being analyzed. This method is the least resource intensive but is also less robust.

None of the methods described is able to assess the full benefits of weather forecasting, as some benefits simply cannot be expressed quantitatively. Complementary quantitative and qualitative assessments can produce a more complete understanding (WMO et al 2015). However, it is often difficult to include qualitatively assessed benefits in a benefit-cost analysis; they are therefore not considered in this analysis.

### 3.3.1 Global benefits transfer

As conducting a comprehensive analysis of the socioeconomic benefits is outside the scope of this research, the data used to estimate the benefits are calculated based on the methods and assumptions used by Hallegatte (2012) on the worldwide socioeconomic benefits of improved early warning systems. Using the benefit transfer approach, the data from Hallegatte (2012) is converted and adapted to measure the additional benefits created by improved weather forecasting in LICs resulting from the provision of global forecasting products.

Hallegatte (2012) analyzes three types of benefits of improved forecasting and early warning: reduced asset losses, reduced human losses and improved economic productivity. In a first step, he uses data from studies on Europe, the OFDA/CRED International Disaster Database (CRED 2015) and the Copenhagen Consensus on Human Life's definition estimation of life value (DALY – Value of Disability Adjusted Life Year; Copenhagen Consensus Center 2015) to estimate the benefits of forecasting and early warning in the three benefit categories in Europe.

Hallegatte (2012) then uses a benefit transfer approach to apply these estimates to LICs and MICs; the benefit of forecasting in Europe in percentage of gross domestic product (GDP) corresponds to the potential total benefit of European forecasting quality in LICs and MICs:

- The reduction in asset losses due to increased forecasting quality is estimated to be between 0.0003 and 0.017 percent of GDP. From that it is inferred that improving forecasting services to European standards would lead to avoided asset losses between US\$ 300 million and 2 billion per year in LICs and MICs.
- Using data on fatalities due to weather disasters from the OFCA/CRED EM-DAT database, the average annual risk of death due to extreme weather in LICs and MICs is 7.5 per million. After

comparing this to European data, the probability could be lowered to 3.4 per million. Applying a DALY of US\$ 1,000 and 5,000 respectively, this would lead to an annual benefit of between US\$ 700 million and 3.5 billion per year.

- Weather sensitive economic sectors create about 25 percent of world GDP. It is assumed that improved forecasting could lead to added economic benefits between 0.1 and 1 percent in these sectors. This would lead to an increase in GDP of between 0.025 and 0.25 percent if forecasting quality is increased to western/central European standards.

We recalculated the estimations from Hallegatte (2012) of potential benefits of European-standard forecasting for LICs only, using the same assumptions but more current data on population and GDP (World Bank 2014). Unsurprisingly, the results are very similar, listed in Table 3.2.

**Table 3.2:** Potential annual benefits of European-standard forecasting in LICs, measured in 2014 values.

<b>Benefit type</b>	<b>Potential value of improved forecasting in LICs (US\$)</b>
Reduced asset losses	12-68 million
Reduced human losses	65-327 million
Additional economic productivity	99-993 million
<b>TOTAL</b>	<b>176-1,388 million</b>

Hallegatte (2012) assumes a direct relationship between improved availability of weather and climate information and improved decision-making and action, thereby attributing all potential benefits of preparedness to early warning. While forecasting and resultant early warning are critical to early action, the resultant benefits would in fact not be realized without substantially improving the ability of people and institutions to use forecasts. Therefore this is an optimistic assumption particularly in developing countries, where most, if not all, components of the disaster and climate risk management value chain lack capacity to varying degrees. WMO et al (2015) highlights that assumptions of perfect decision-making based on all available information are not realistic, advocating for simultaneous and complementary capacity building for both providers and users of weather and climate information to realize maximum benefits.

### 3.3.2 Attribution to global NWP

As providing global forecasting products alone is in most LICs not sufficient to improve forecasting quality to western European standards, the attributable benefits would only be a certain percentage of the total potential benefits estimated by Hallegatte (2012). However, defining this percentage is a difficult task and – to the authors’ knowledge – there are no publications that have determined such a percentage.

Using historical data on forecasting quality trends, combined with expert assessments, an attempt is made to estimate the percentage of potential LIC forecasting improvement due to global NWP. It must however be noted that forecasting is the value provided by the interpretation of guidance, including NWP, along with other expert knowledge and information. If the local forecasts are good, they will benefit greatly from improved guidance, in this case global NWP outputs. If local forecast capacity is limited, improved access to global NWP may not add any significant value. The analysis therefore

again assumes that RSMC and NMHS capacities are sufficient to fully exploit improved access to global NWP, which, as discussed in Section 1.4, is generally not the case in LICs.

The influence of global forecasting products can be estimated by evaluating historical forecast accuracy, as the increase in accuracy in the last decades was largely due to the utilization of global forecasting products. At the time of establishment in the mid to late 1970s, global NWP was limited by computing power and availability/access to global observations, as well as scientific understanding of key processes involved such as cloud physics, air-sea interaction, energy transfers or turbulence. It is therefore assumed that at the time of launch, global NWP was not markedly superior to traditional forecasting approaches, at least in terms of accuracy, skill and resolution.

Quantification of increases in forecasting quality were therefore estimated considering changes in forecasting quality of ECMWF operations since 1980, published by the WMO (Simmons 2011). The data from 1980 is treated as a proxy of forecasting quality without global NWP, with an increase in ECMWF forecasting quality from 1980 to 2010 of 15 to 35 percent (depending on duration of forecast and hemisphere being forecasted). Other historical records of forecasting performance lead to similar results (e.g. NOAA 2007 and Met Office 2011).

It must however be considered that modern weather forecasting for time periods longer than 24 hours is virtually impossible without any global forecasting products, at least in the high latitudes (extratropics). Therefore, the estimation of between 15 and 35 percent improvement in overall forecasting quality has to be seen as a conservative assumption for example in North America and Europe. However as most LICs are located in the tropics, where multi-day forecasts can be skillful even without NWP, we assume that the provision of the full suite of global forecasting products would increase forecasting quality in LICs by 15 to 35 percent. Improvements in forecasts in LICs over 4-5 days are likely almost fully due to global NWP.

This increase in forecasting quality subsequently leads to increased benefits of weather and climate forecasting. Assuming that any increase in forecasting quality leads to a linear increase in benefits, the results of our benefit analysis for LICs are shown in Table 3.3.

**Table 3.3:** Potential annual socioeconomic benefits of LICs due to access to global forecasting services, in 2014 values.

Annual benefits	Full forecasting improvement	Improvement due to global NWP access
Minimum range	US\$ 176 million	US\$ 26.5 – 61.8 million
Likely range	US\$ 1387.6 million	US\$ 208.1 – 485.7 million

Although standard practice in hydrometeorological socioeconomic benefit assessment, the assumption of a linear dependence on forecasting “quality” (generically describing accuracy, skill, etc.) does not consider a possibly non-linear translation from better forecast accuracy into improved decision-making. For example, a 15% increase in accuracy from 50% to 65% as compared to 84% to 99% would likely produce differing increases in benefits, as user perceptions of a generally “unreliable forecast” would not diminish for the former, while realizing near 100% accuracy for the latter would be more likely to trigger productive actions.

### 3.4 Comparing costs and benefits

To compare the costs and benefits the following model framework was used:

- Costs and benefit are analyzed over a period of 15 years. This reflects the timeframe of the 2030 Agenda for Sustainable Development.
- In the first year (year 0), GPCs start to provide the full suite of global forecasting products to all LICs, such that GPCs incur set-up and running costs while no benefits are generated.
- From year 1 on, running costs and benefits occur every year.
- Economic growth and inflation are both assumed to be zero, which is a conservative assumption.
- A discount rate of 3 percent is applied.

Within this framework, ranges of estimated costs and benefits are compared. While the primary (and most realistic) model is here described, more conservative and more optimistic models are reviewed in the sensitivity analysis (Section 3.6). For the primary model, costs at the higher end of the defined range were utilized. Benefit estimations are based on the “likely range” from Table 3.3, under the assumption that access to global forecasting products would increase forecasting quality by 35 percent.

The results from the primary model over 15 years yield total discounted costs of US\$ 67 million and benefits of US\$ 5,486 million, resulting in **a net present value of US\$ 5.4 billion and a benefit/cost ratio of 81**. While these figures should be treated as very rough estimates, despite all the limitations of this analysis, we can conclude that the socioeconomic benefits of providing the full suite of global forecasting products to LICs significantly outweigh the costs of GPCs providing these products.

### 3.5 Omissions, biases, and uncertainties

As reviewed in Section 1.4, the major omission is that we evaluate the benefits of the provision of global NWP products to LICs under the assumption that they will be used optimally, not taking into account the costs incurred by the RSMCs, NMHSs, commercial services and users to translate this additional information into benefit-generating actions. It is therefore assumed that these products allow the production and communication of better forecasts to users, and their improved conversion into concrete actions and results in the decision-making process.

To test the impacts of this assumption on the robustness of our conclusions, we apply Hallegatte’s (2012) assumption that the cost of providing appropriate early warning (including forecasting) and evacuation orders in developing countries is about \$50 million per country over a 5-year period (including maintenance and operational costs). With this, the national capacity building requirements for all LICs comes to just over US\$ 300 million per year. This does not include investments in actual response actions and longer-term resilience building to fully take advantage of improved weather and climate information, so it must be considered an under-estimation of the full cost of the preparedness value chain. While this figure is of similar magnitude to the benefits we estimate to be generated by improved access to GPC products in LICs, it is still about four times smaller than the benefits we attribute to improved forecasting in general (see Table 3.3). The conclusion that improved forecasting and preparedness “pays off” therefore stands.

Further, it should be taken into account that there is no consensus among the centers about what is comprised in the marginal costs for providing the full suite of global products to an additional country. For some centers like MetService, it mainly includes the provision of products, while for others such as the Met Office, the provision of products always goes hand in hand with further support services such as training (Met Office 2015a; MetService 2015). In order to consider this variety in services and accounting, a range of different cost estimates were considered.

While Hallegatte (2012) is the most suitable source of benefit data for this research, we have to expect inaccuracy and bias inside the benefit categories measured by Hallegatte. There are many uncertainties associated with quantifying disaster risks, as they might be correlated to other factors such as climate change, and therefore could lack direct causation (World Bank 2013; IPCC 2012).

Strong assumptions had to be made to estimate benefits, which ultimately influences the results. This was necessary due to data limitations. Nevertheless, while it cannot be claimed that the data used to measure benefits are fully accurate, the direction of any bias is known. Net benefits and benefit-cost ratios resulting from this study are considered conservative estimates of the true potential benefits of providing the full suite of forecasting products on LICs. Lack of data is addressed by using ranges instead of point estimates and by conducting sensitivity analyses, with a bias towards conservative estimations (lower benefits).

### 3.6 Sensitivity analysis

To analyze sensitivity, three models were developed:

- Primary (previously described): assumes maximal values for both costs and benefits. As the benefit estimations are in any case conservative, this scenario is assumed to be the most realistic one.
- Conservative: assumes maximal values for costs and minimal values for benefits.
- Optimistic: assumes minimal values for costs and maximal values for benefits.

All models were analyzed over a period of 15 years, with no economic growth and no inflation. Alternative discount rates of 0 percent and 10 percent were also assessed. Results are summarized in Table 3.4.

**Table 3.4:** Results of the sensitivity analysis, in 2014 values.

Discount rate	Net Present Value (US\$ millions)			Benefit/cost Ratio		
	0%	3%	10%	0%	3%	10%
<b>Conservative</b>	290.8	231.9	146.3	4.6	4.4	4.0
<b>Primary</b>	6,719.3	5,418.8	3,528.9	84.9	81.5	73.3
<b>Optimistic</b>	6,783.5	5,472.7	3,568.0	427.7	409.4	366.3

Because costs are minimal compared to benefits, changes in costs between the primary and optimistic scenarios result in minimal changes in the net present value, while the benefit/cost ratios are markedly different. Even under the most conservative scenario the benefits heavily outweigh the costs: the benefit-cost ratio would still be 4:1 and a net present value of almost US\$ 150 million would accrue over a 15 year period. It can therefore again be stated that the socioeconomic benefits of providing global forecasting products to all LICs significantly exceed the costs of GPCs to provide these products.

## 4 Moral imperatives

Having identified the many beneficial outcomes (particularly for developing countries) that can be delivered through the cascading forecasting approach at relatively low cost, WMO et al (2013) highlighted three critical factors needed to ensure sustainability:

1. GPCs are able to support the provision of relevant products on a long-term operational basis;
2. RSMCs are able to maintain an interpretation and guidance service on a similar long-term operational basis; and
3. regular capacity building and training can be maintained for new forecasters along with refresher training for experienced forecasters.

It has been highlighted that all three areas require investment, whether through domestic or international financing. In line with the global NWP focus of this research, we here further explore the social and ethical demand for global investment in ensuring GPC product delivery to LICs.

It would be difficult to justify the responsibility of higher income countries to ensure the delivery of the full suite of weather and climate forecasting data to LICs as a "public service" without discussing the ethics behind it. However, the subject of ethics tends to make many stakeholders uncomfortable. After all, is not everyone in the world entitled to the greatest "pursuit of happiness"? And aren't developed countries who claim to be moral ascendants of modern civilization responsible for sharing information that could benefit the greatest number of people?

These questions are of course debated in many contexts, but the emphasis on ethical principles is nonetheless important when dealing with a service that provides such a significant global value. Additionally, as demonstrated in Section 5 on financing, many social issues that currently necessitate development aid can benefit from improved weather and climate forecasting. The justification behind providing the full suite of weather and climate information should therefore go beyond merely comparing costs with benefits, or identifying feasible or sustainable sources of funding for these services.

In the next 15 years, the services provided by weather and climate services will play an ever increasing role, with GDP projected to double and a billion more people moving to cities (New Climate Economy 2014). Furthermore, the increasing impacts of climate change will have severe consequences on the more fragile economies of the world. This section aims to broaden the scope of reasons for improving the global weather and climate services available to the LICs by looking from an ethical perspective and addressing the public good imperative that could guide policy. Firstly, this section makes an argument in favor of GPCs' free provision of weather and climate forecasting using the utilitarian principle. Secondly, it considers the full suite of forecasting information and more broadly open data as an integral part of the global development process that should originate in countries that already possess the capacity, namely higher income countries.

### 4.1 Utilitarianism

Utilitarianism is a ubiquitous principle which can be interpreted as the greatest good for the greatest number of people (Bentham 1775). From the perspective of utilitarianism, the purpose of weather and climate information should therefore be to increase welfare and security, support economic development, and respond to pending weather, climate and water threats. Together, these can provide

the greatest social, environmental, and financial benefits societies can have from these services and help them avoid significant costs. Here, we briefly consider the purpose behind the provision of these services, how increasing their quality and use can improve decision making further down the value chain (Figure 2.1), and finally how they should meet society's expectations of appropriate management by incorporating ethical principles.

Economists and philosophers often take this utilitarian principle to put forward their argument of worth based on whether a service provides direct or indirect benefits to society. In this case, the important issue for economists and policy-makers concerned with whether a service provides actual benefits that outweigh its costs is to provide them with "objectively verifiable truths" (Kibert et al 2008). This "objectively verifiable truth" is reflected in the socioeconomic cost-benefit analysis. This shows clearly that these services hold significant economic and societal value, thereby confirming the utilitarian value of the services.

However, while these services might be accessed, they are not always used or exploited to their full value. This can be seen in the value chain (Figure 2.1) and reviewed in Section 1.4, where the actual value of the service is only realized when information or data is observed, produced, delivered, and finally decisions or actions are taken based upon it. As stated in WMO et al. (2015), "the higher the quality of meteorological services, the more value they can deliver". For example, improved modeling enables more reliable information and a reduction in the rates of false alarm to stakeholders (Pappenberger et al 2015).

The potential for outcomes from such decisions or actions can however only be effectively realized if more people have access to quality forecasting information. This increases the probability of outcomes and could eventually create economies of scale as more of the services will be used and demand increases. Further up the value chain, this might also lead to reducing the costs of the production and delivery of weather and climate forecasts as more demand creates more market for it. Consequently, the point can be made that the full suite of weather and climate forecasting capacity of higher income countries GPCs should be optimized in order to maximize benefits or utilitarian value and provide the greatest amount of good for the greatest number; taking into consideration that the more people are given the opportunity to take decisions or actions based on highest quality forecasting information, the more value they will potentially deliver when outcomes are revealed.

This is precisely what this paper attempts to demonstrate by performing a SEB analysis: to advocate for better access and to show to what extent GPC products and services are of critical value to LICs. Despite all the limitations of the analysis we can clearly state that the socioeconomic benefits of better weather forecasting by far outweigh the costs of GPCs providing the full suite of forecasting products to LICs. Furthermore, to increase use and improve the decision-making potential of the end users, improved forecasting information from GPCs should be made available to benefit the greatest number of people as this could ultimately increase the aggregate value.

Most GPCs have very clear objectives, namely to maximize benefits – social, economic, and environmental – for people and countries, which aligns with this utilitarian principle. To this end, the utilitarian case for weather and climate forecasting does not only advocate for the need to have more adequate resources for the delivery of weather and climate services, but it also favors the sustainable funding of GPCs providing these resources to LICs as part of their efforts to reach their development

goals. Finally, it also contributes to the hypothesis stating that the provision of access to improved weather forecasting should be the responsibility of higher income countries.

## 4.2 Global public service

As previously stated, value is created only when information is effectively taken into consideration in the decisions or actions of end-users. Therefore, to increase the use and resulting beneficial outcomes of decisions or actions taken from the bulk of global weather and climate products, it should be provisioned as a public service. However, effort made to increase the use of these services should come from those who possess the technology and stand at the top of the value chain, namely higher income countries. Here, the positive outcomes of open data for the promotion of capacity in LICs are considered as well as their potential to promote good leadership and to build trust and freedom at the global level.

LICs' NMHSs rely heavily on the cascading of information from GPCs and RSMCs to provide efficient information for their end-users. Consequently, the wide use of forecasting information can have far-reaching economic and other spillover effects in LICs, including political ones for the governments and organizations providing services at the global, national and local levels. In fact, policies of open data access are known to provide a level playing field and create incentives and opportunities to move out of the poverty trap (GEO 2015). More broadly, these services strengthen delivery of governments' social contract with their citizens by providing safety and protection from natural disasters, thereby further legitimizing the authority of government (WMO et al 2015; GEO 2015). Of course, LIC governments should not provide forecasting services for these reasons only, but they should acknowledge such positive externalities and demand access to this valuable information nonetheless.

In higher income countries, where the majority of GPCs are located, making products and services available can also provide an antecedent of diplomatic good practice and trust characterized by a good sense of global responsibility, and therefore by more a stringent and well-established ethical code. The building of trust in governance is important in the development process of any nation. Open and unrestricted access to climate and weather information is strongly indicative of the confidence in the public service sector, and is a testament to the maturity of the political system in place and the integrity of the government.

Along with integrity, it also showcases that the government stands for the Universal Human Rights. According to Article 19 of the declaration, the rights to freedom of opinion and expression "includes the freedom to seek, receive and impart information and ideas through any media and regardless of frontiers" (UN 1948). Another passage from Article 27(1) further supports this claim: "Everyone has the right freely to participate in the cultural life of the community (...) and to share in scientific advancement and its benefits" (UN 1948). Thus, from these two quotes we can determine that one of the ultimate goals of any society striving for development is to focus on empowering every citizen through access to and use of forecasting information (GEO 2015).

This should further incentivize governments to encourage more funding allocation to improve the performance of GPCs to provide weather and climate forecasting data to LICs by defining it as a global public service. Further, the UN Secretary-General's High Level Panel report on the post-2015 agenda called for "a data revolution for sustainable development, with a new international initiative to improve

the quality of statistics and information available to citizens“ to underpin the achievement of the post-2015 development goals (UN 2013).

However even today, supercomputers, satellite observation platforms, and other forecasting technologies typically remain the preserve of relatively few countries and regions (e.g. European Union, USA, China, etc.). While the countries investing in such capacity have determined that the national benefits outweigh the costs (see for example UK BIS 2015), this structure is neither financially sustainable nor sufficiently reliable to ensure service delivery and use in the long term for countries not owning the capacity. A major benefit of global climate and weather forecasting is that not all countries have to invest in every component of the value chain (Hallegatte 2012; WMO et al 2015). In fact, much of the information comes from satellites, which are already in place and maintained by higher income countries, and require very little extra investment to provide information to LICs (WMO et al 2015).

Thus, from a purely financial standpoint, a policy acknowledging GPCs' services as a global public service is critical to the sustainable development of LICs and contributes to promoting the principles of human rights. To support a move in this direction, global NWP should be recognized as a utilitarian service aiming to improve human life overall and not just for one individual or country to the detriment of those who do not possess these technologies. Governments of higher income countries should also be encouraged to provide the full suite of GPC services because of the many positives that open, and because unrestricted data can contribute to their image, integrity and legitimacy as high moral institutions.

This should also incentivize decision-makers in higher income countries to find more sustainable ways to cover the incremental cost of providing improved services from GPCs. In effect, it becomes clear that the provision of improved GPC services to LICs should thus be borne in higher income countries which already possess the necessary technological capacities and resources. More broadly, these services should also be considered as a global public service to enhance use, outcomes, and values, to ultimately increase global security, well-being and benefit the greatest number of people.

## 5 Financing opportunities

Having concluded that the socioeconomic benefits of providing the full suite of global products to LICs outweigh the associated costs and that a moral imperative exists for higher income countries to provide such services, we explore how to finance these services and products in a sustainable manner including potentially through development aid.

Again it must be highlighted that many NMHSs in developing countries lack the capacity to provide even a basic level of services, thereby demanding priority investment. However the problem is not limited to NMHSs; despite the recognized importance of WMO regional, specialized and global centers in helping countries reach a high level of service, their financing is currently limited. It has been shown that the high value-added segment of the production chain with regards to NWP is at the global level, quantifying the benefit of international cooperation and collaboration. At present, it is assumed that higher income economies will continue to support this segment, but this assumption comes with no guarantees (GFDRR & WMO 2013).

NMHSs often wish to develop sophisticated in-house NWP and are sometimes encouraged to do so by the research community or contracted parties outside of the WMO community. Potential national investments must explicitly consider the advantages of the cascading forecast process over the building of in-house high end computing infrastructure and staffing required for NWP. The cascading forecasting process explicitly supports the defining of national requirements and therefore helps ensure optimum national investment that avoids duplication of capabilities provided by the GPCs. NMHSs must consider the tradeoff between investment in national NWP capacity and investment in service delivery. As such, the cascading forecasting process appears to be the most cost efficient approach to ensure that GPC products can be fully utilized by even the most capacity limited NMHSs. With this approach NMHSs can focus on optimally using this information in their alerting and warning services (GFDRR & WMO 2013).

## 5.1 Current realities

At present there are a limited number of options to sustain operational funding for the cascading forecast system. NMHSs, while potentially benefiting from donor funded capital investments, must resource their operations and maintenance through their own budgets, which most LICs find challenging to secure. The problem is also complex for RSMCs, where a stable source of operational support needs to be identified. Seen in the broader context of weather and climate resilience, they should be candidates for support from climate investment funds or a specially created multi-donor trust fund (GFDRR & WMO 2013). This assumes reliable delivery and therefore financing for GPCs to provide the global products to drive the cascading process.

The financing structures of the Met Office and ECMWF provide indicative insights into how GPCs are currently resourced. The Met Office is the United Kingdom's national meteorological service, but also fulfills the tasks of a GPC. The international activities of the Met Office include consultancy services, training, observations management and support, as well as provision of model products to assist forecasters. The majority of these services and products are free for LICs (Met Office 2015a & 2015b).

The Met Office receives 80 percent of its budget from the UK government. A part of this budget is dedicated to science research and development and can be used to develop NWP models for different regions. The remaining 20 percent of the budget stems from commercial activity associated with services to the private sector, for example utilities, tourism, renewable energy etc. Met Office international development receives funds from development agencies and national governments in developing countries through competitive tenders; the Met Office is rarely single sourced (non-competitive procurement) to deliver services to development agencies. Further, the UK government's contribution to the Voluntary Cooperation Programme fund (VCP) of the WMO provides an important baseline of international activity for both the UK government and the Met Office. This UK government grant funding is then used by the Met Office to provide products and services to LICs (Met Office 2015).

The ECMWF is financed by its 34 member states, providing all of its outputs to its members and extending this by providing various free forecasting products to many LICs. ECMWF is also awarded specific service contracts, for example from the European Union Copernicus program which aims to deliver environmental operational data and information services. However, the provision of products under the NMHS' non-commercial full and web-only licenses is self-funded. ECMWF focuses on the generation of forecast products (numerical data and processing) but stops short of providing direct

services to non-NMHS entities. Several ECMWF member NMHSs do invest in the complete end-to-end process including NWP development through to providing bespoke services to users.

In summary and at least partially reflecting the situation of most GPCs that are part of higher income country NMHSs, the Met Office provides important services to LICs, funded mainly by its ordinary budget via the UK contribution to WMO VCP. This ensures a certain degree of sustainability and has been a successful model since 2006. Beyond this baseline provision, provision of additional support, expertise and trainings for international development by the Met Office, in partnership with LICs, depends on the success of Met Office in securing funds from development agencies or national governments and is purely limited to development of national institutions. This does not address the continual challenge to find funds to develop the Met Office's own science to better serve the global meteorological community. Currently, the ECMWF is only mandated and financed by its members to provide some limited products directly to LIC NMHSs.

As such, financing the provision of GPCs' forecasting products to LICs through their regular budgets can be considered plausible, but with great limitations regarding sufficiency and sustainability. Direct contracting by development agencies is also plausible, but even less sustainable as the provision depends on a specific project and is therefore temporally limited.

## 5.2 Official Development Assistance (ODA)

Current investment in components of the cascading forecast approach include: specialized donor supported programs, such as the Climate Investment Fund's (CIF) Pilot Program for Climate Resilience (PPCR); countries accessing loans, credits and grants from international financial institutions (e.g. World Bank) and UN agencies (e.g. UNDP) to support NMHSs' modernization; regional and bilateral donor driven initiatives that can incorporate both regional and national activities; donor support directly to SWFDP; and the WMO supported voluntary cooperation program (VCP) which provides support for training, capacity building and minor investments (GFDRR & WMO 2013). None of these currently provide financial support for the GPCs' critical role in the system. If the provision of forecasting products from GPCs to LICs is to be fostered, it is crucial to find a more sustainable mechanism of funding. ODA is explored as a potential solution.

While not legally binding, through the Sendai Framework for Disaster Risk Reduction 2015-2030 (SFDRR) agreed in March 2015, countries recognized the need to strengthen early warning, especially by enhancing hydrometeorological warning services combined with improving emergency preparedness and response plans and operations. The seventh global target of the SFDRR specifically calls to "Substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to the people by 2030." SFDRR further calls for continued and strengthened support and cooperation between countries to strengthen disaster risk reduction, highlighting at the global and regional levels "...technology transfer, access to and the sharing and use of non-sensitive data, information..." to support the priority of understanding risk and "...facilitate the sharing and exchange of information across all countries..." to support the priority of enhancing disaster preparedness (UNISDR 2015). This indicates some global commitment for financing the strengthening of the cascading forecasting system through international cooperation.

The Sustainable Development Goals (SDGs) further provide a strong argument that the provision of GPC products to LICs should count as ODA. In general, improving weather and climate forecasting is a crosscutting issue that has the potential to reduce poverty, diseases and fatalities as well as increase economic growth and food security. It can directly impact SDG delivery, explicitly mentioned in several SDG sub-goals, listed in Box 5.1.

**Box 5.1: SDG Sub-Goals Relevant to Weather Forecasting**

1.5: By 2030, build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters.

11.5: By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations.

11.b: By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015-2030, holistic disaster risk management at all levels.

13.1: Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries.

The recently concluded 21st Conference of Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC) adopted the Paris Agreement, which includes a number of relevant commitments as listed in Box 5.2.

**Box 5.2: Most relevant commitments from the UNFCCC COP21 Paris Agreement**

Article 7

1. Parties hereby establish the global goal on adaptation of enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change, with a view to contributing to sustainable development and ensuring an adequate adaptation response in the context of the temperature goal referred to in Article 2.
6. Parties recognize the importance of support for and international cooperation on adaptation efforts and the importance of taking into account the needs of developing country Parties, especially those that are particularly vulnerable to the adverse effects of climate change.
7. Parties should strengthen their cooperation on enhancing action on adaptation, taking into account the Cancun Adaptation Framework, including with regard to:
  - a. Sharing information, good practices, experiences and lessons learned, including, as appropriate, as these relate to science, planning, policies and implementation in relation to adaptation actions;
  - b. Strengthening institutional arrangements, including those under the Convention that serve this Agreement, to support the synthesis of relevant information and knowledge, and the provision of technical support and guidance to Parties;

- c. Strengthening scientific knowledge on climate, including research, systematic observation of the climate system and early warning systems, in a manner that informs climate services and supports decision-making;

#### Article 8

1. Parties recognize the importance of averting, minimizing and addressing loss and damage associated with the adverse effects of climate change, including extreme weather events and slow onset events, and the role of sustainable development in reducing the risk of loss and damage.
3. Parties should enhance understanding, action and support, including through the Warsaw International Mechanism, as appropriate, on a cooperative and facilitative basis with respect to loss and damage associated with the adverse effects of climate change.
4. Accordingly, areas of cooperation and facilitation to enhance understanding, action and support may include:
  - a. Early warning systems;
  - b. Emergency preparedness;
  - e. Comprehensive risk assessment and management;

While the goal of improving weather and climate forecasting in LICs certainly is in line with the SFDRR, SDGs and UNFCCC agreements, the approach of achieving this by financing GPCs to provide forecasting products for NMHS in LICs is less clear: The Organization for Economic Cooperation and Development's (OECD) Development Assistance Committee (DAC) defines ODA as follows (OECD 2015a):

*“those flows to countries and territories on the DAC List of ODA Recipients and to multilateral institutions which are:*

- i. provided by official agencies, including state and local governments, or by their executive agencies; and*
- ii. each transaction of which:*
  - a) is administered with the promotion of the economic development and welfare of LICs as its main objective; and*
  - b) is concessional in character and conveys a grant element of at least 25 percent (calculated at a rate of discount of 10 percent).”*

According to this definition, funds given to a GPC to enable the provision of forecasting products to LICs would not count as ODA as the funds would go to an organization that is located in a developed country. If this kind of funding has to be defined as development aid, it would be considered “tied aid” - money that does not directly flow into LICs but is given to entities in the donor country that then provide products or services to the recipient country. This kind of aid is increasingly criticized as inefficient, principally serving the interests of the donor countries (see for example Oxfam America 2009). The 2005 Paris Declaration on Aid effectiveness, endorsed by more than 130 countries, argues in the same vein: LICs should set their own strategies for poverty reduction, aid should be untied and local systems and infrastructure should be used (OECD 2008).

International agreements appear therefore to work against the proposition to use ODA to finance the provision of GPC products to LICs. However, despite the valid argumentation against tied aid, the case at hand might not be comparable to usual ODA. Due to the involved resource requirements and

economies of scale, the production of global forecasting products clearly is not something that is ideally done by each NMHS separately. It would not be efficient to use large volumes of ODA to empower all NMHSs in LICs and MICs to operate their own global models if there are already several global centers that can deliver such products. Furthermore, while tied aid is often justifiably seen as inefficient, it has been shown to be economically efficient for providing global weather forecasting products. However, due to the negative outlook on tied aid, other financing mechanisms might be more politically astute to consider.

### 5.3 Special funds

A new or existing special fund may be an alternative option to finance the provision of GPC products to LICs. While it could be argued that paying GPCs to provide products to LICs through a fund is a kind of indirect tied aid, generally multi-donor trust funds are entrusted to invest optimally to achieve certain results agreed by the contributing donors. Support to a GPC could therefore potentially be accepted if a sound business case is presented. Further, a fund is a more reliable and sustainable financial source than a single state or a temporary project.

Reflecting their donors' desire to provide direct financing to climate vulnerable developing countries, most adaptation funds would however most likely not finance GPCs hosted by high-income countries. The Adaptation Fund (AF), established by the Conference of Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) in 1997, finances "concrete climate change adaptation projects and programmes in developing countries" (AF 2016). To date, no GPCs have received formal AF accreditation nor have any RSMCs been formally accredited as AF Regional Implementing Entities, while WMO, the World Bank Group, and a number of other UN agencies and international financial institutions have been accredited as AF Multilateral Implementing Entities (AF 2016). While one of these could in theory develop a proposal that includes financing for GPC product provision to LICs, considering past and current prioritization of financing, it is doubtful to be approved. Most adaptation funds follow a similar model.

The Green Climate Fund (GCF) is accountable to the UNFCCC and was established in 2010. Its goal is "to respond to climate change by investing in low-emission and climate-resilient development." (GCF 2015). As of November 2015, pledges to the GCF amounted to USD 10 billion. This should increase dramatically as advanced economies agreed to make USD 100 billion per year available for the GCF by 2020 (GCF 2015). While increasing the quality of weather forecasting in LICs is not the main task of this fund, one can still make a reasonable case that it might well be part of its mandate as improved weather forecasting abilities must be seen as a measure to increase resilience to climate change. This potential source of funding to GPCs providing forecasting products to LICs should be evaluated in more detail in further research.

ECMWF was recently awarded a European Union (EU) contract, under the Copernicus program of the European Commission's (EC) Directorate-General (DG) for Internal Market, Industry, Entrepreneurship and SMEs, to manage climate change and atmosphere monitoring services in Europe (Copernicus 2016). While the financed activities focus on Europe as the primary client, they will also yield benefits to global users. These kinds of global service investments that reach beyond regional or national clients may provide further financing opportunities for GPCs, but so far have been provided only infrequently.

In summary, the provision of GPC products to LICs' NMHS is in line with the SFDRR, SDGs and UNFCCC Paris Agreement. Nevertheless, it is unrealistic that this provision would be financed using ODA, mainly due to the controversial nature of tied aid. However, international funds like the UNFCCC's GCF might well be options to finance GPCs to provide forecasting products to LICs in a more sustainable way than the current practice, where funding depends on the regular budget of the GPCs or on temporary project funding. Further evaluation is needed on the potential of the GCF and other specialized funds as potential resources for GPCs to provide products to LICs' NMHS.

## 6 Conclusions

From 1970 to 2012, weather-related disasters caused two million deaths and US\$ 2.4 trillion of economic losses (WMO et al 2014). Better forecasting in developing countries could save 23,000 lives and avoid up to US\$ 2 billion in economic losses per year (Hallegatte 2012). These statements alone justify the goal of increasing weather forecasting quality around the globe, but especially in LICs, where forecasting and disaster preparedness capacity is generally limited. However, the objective of this research was to produce pragmatic evidence and guidance regarding the costs, socioeconomic benefits, public service imperatives and potential financing modalities to facilitate LICs' access to the full suite of products delivered by GPCs.

The potential socioeconomic benefits of providing global forecasting products to LICs outweigh the associated costs by at least a factor of four, with a more probable benefit/cost ratio of more than 80:1. The associated net present benefits over a period of 15 years amount to more than US\$ 5 billion. These numbers show the immense potential of investing in LICs' access to global forecasting products, which however can only be realized by concurrently investing in RSMC, NMHS and national risk management actors' capacities to leverage this increased access to global NWP. While the analysis required a number of assumptions due to limited availability of quantitative data, resulting in large ranges in the results, the conclusion is robust within its order of magnitude: it pays to invest in the provision of GPC products to LICs.

Existing capacities for the production of global NWP products and the extent of their potential benefits for LICs is one of many convincing arguments encouraging higher income countries to foster the provision of open and unrestricted data on a moral basis and therefore facilitate full access of LICs to GPC products. Global NWP should be treated as a global public service.

The role of RSMCs also merits further analysis. There are sensitivities around establishing a network of regional centers that operate as part of the cascading process. Many NMHS in LICs have concerns that they will be subsumed by such entities, but generally under-capacitated RSMCs are a missing link and there could be great value in working towards a better resourced cascading arrangement.

While the SFDRR, SDGs and UNFCCC Paris Agreement clearly suggest that improving weather forecasting quality in LICs should be targeted by ODA, providing finance to GPCs to enable them to provide forecasting products to LICs is reminiscent of tied aid. While in this case potentially justifiable, tied aid is not politically feasible, such that the provision of global forecasting products by GPCs to LICs' is therefore difficult to finance through direct ODA. However specialized funds such as the Green Climate Fund could provide mechanisms to legitimately finance GPC operations in support of LICs.

While we are confident that our results are valid, the various limitations and omissions in this research field - notably the assumption of sufficient regional and national forecasting and disaster management capacity as well as a lack of comprehensive benefit data – must be acknowledged. Macro-scale research pieces like this one have to be complemented by detailed case studies - both qualitative and quantitative. Therefore, considering the importance of improving weather forecasting in LICs, further research in this field is strongly encouraged.

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