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OBSERVING SYSTEM STUDIES

COST-BENEFIT STUDIES FOR OBSERVING SYSTEMS

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SUMMARY AND PURPOSE OF DOCUMENT

The document proposes a strategy for assessing the cost-effectiveness of observing systems. The elements of the "cost-benefit chain" are described. Two elements of this chain are the assessment of costs of observing systems and the assessment of the impact of observations on a given application. Together they allow the impact per cost of observations for this application to be assessed. This process is illustrated using an example in which impact per cost is evaluated for global numerical weather prediction. The extensions of this general approach to other applications areas and to other elements of the cost-benefit chain are discussed.

ACTION PROPOSED

The Meeting is invited to note the information contained in this document when discussing how it organises its work and formulates its recommendations.

DISCUSSION

1. Introduction

1.1 Meteorological, hydrological and climatological services are dependent on observations; without observations none of these services is possible. Moreover, the observing components are amongst the most costly parts of the total service provision, and it is therefore important that investment in observing systems delivers observations well suited to the intended applications and in a cost-effective manner. It is a central aim of WIGOS to promote and facilitate the development of observing systems that deliver improved products to users in a more cost-effective way.

1.2 In pursuit of this goal, it is important that we develop strategies and techniques for assessing the cost-effectiveness of observing systems, ideally across the full range of applications for which observations are used and the full range of end-user services to which they contribute. This will not be an easy task! However, it is appropriate that OPAG IOS in general and IPET-OSDE in particular, make a strong contribution to this aspect of WIGOS.

1.3 Observing systems have been developed over several decades and for historical reasons, some of which remain valid and some of which do not. With rapid changes in the range and scope of applications, in their requirements for observations and in the observing technologies (and hence costs), it is increasingly important that we assess the cost-effectiveness of observing systems when considering the continuation or extension of existing systems or the implementation of new ones.

1.4 In this paper, we propose a strategy for assessing the cost-effectiveness of observing systems. In section 2, we describe the elements of the “cost-benefit chain”. Two elements of this chain are the assessment of costs of observing systems and the assessment of the impact of observations on a given application. Together they allow the impact per cost of observations for this application to be assessed. In section 3, we illustrate this process with an example in which impact per cost is evaluated for global numerical weather prediction (NWP). In section 4, we discuss the extension of this general approach to other application areas and to other elements of the cost-benefit chain. In section 5, we suggest issues that would need to be addressed when refining and extending the work illustrated in this paper.

2. The cost-benefit chain

The assessment of the cost-effectiveness of an observing system requires consideration of the chain of processes involved in making and exploiting the observation.

2.1 The observing system

2.1.1 Each observing system incurs costs: capital cost in implementing the observing system (which may also include the costs of developing the system), the costs of running and maintaining the system, and the costs of disseminating the observations to primary users. Some of these elements may be negligible compared with others, but all should be considered in principle. Benefits will tend to be quantified in annual, financial terms, e.g. M$ per year, and so it is helpful to convert observing systems costs into similar units. This involves converting capital and development costs into annualised costs over the lifetime of the system, so that the total costs of the observing system are also expressed in M$ per year. "Observing system" is used here in a very general sense; it can refer to a whole system (e.g. a whole satellite programme, or the global radiosonde network), or a sub-system (e.g. a single instrument on one satellite, or a single radiosonde station), or to smaller sub-divisions (e.g. wind observations from a single radiosonde station). From these cost data, together with a measure of the total number of observations per year, it is possible to calculate "cost per observation" data. Note, however, that it is necessary to distinguish between the total number of observations generated and the total number that it is possible for a given application to use effectively. From the perspective of observation impact, and hence benefit, the latter measure will usually be more appropriate.

2.2 The "Applications"

2.2.1 For these observations to provide benefit, they must be delivered in an operational or quasi-operational manner to direct users of observations, i.e. to activities corresponding to the Application Areas of the WMO RRR process or to analogous activities. To assess the benefit of an observation, it is necessary (though not sufficient) to be able to assess its impact on the target Application. This is not straightforward; an example of how it can be done for one Application is given in section 3, and the possible extension of this approach to other Applications Areas is discussed in section 4. If it is possible to assess "impact per observation" for a given Application, then this may be combined with "cost per observation" data to yield "impact per cost" estimates. Whilst "impact" is not the same as quantitative benefit, it should be noted that "impact per cost" is very useful for assessing the relative benefit of different observation types for a single Application.

2.2.2 A complete assessment of the benefits of an observing system should cover its impact on all the Applications to which it contributes. It is normal to find that a given observation type may only have a small impact of Application A, which would not justify the investment in this observing system. However, in such circumstances this is normally because Application A was not the primary Application for which the observing system was implemented; there normally exists an Application B in which the impact of this observation type is more important.

2.3 The "services"

2.3.1 Meteorological, hydrological and climatological services (MHCSs) tend to be the direct users of the outputs of the "Applications" described above. For example, weather forecasts and warnings are the services delivered to downstream users, but the forecast and warning services are themselves the primary users of the output of NWP systems, and it is NWP that, in this example, is the primary user of observations. In some cases, the processes delivering the services are themselves primary users of observations, but nowadays this tends to be the exception rather than the norm.

2.4 The "users"

2.4.1 For the purposes of this discussion we define "users" as agents, downstream of the MHCSs, who are users (or customers) of the services that the MHCSs provide. It is the users who see "benefit" to which a financial value might be attached.

2.5 Summary

2.5.1 A complete cost-benefit chain will link the benefits to users (quantified where possible in M$ per year) back to the services provided by the MHCSs, which in turn are linked back to the Application Areas that directly use and benefit from observations, which in turn are linked back to the observations and their costs. A complete cost-benefit calculation will therefore assess annualised observing system costs, impacts of observations on each Application, impacts on services from observation impacts on Applications, and benefits to users attributable to impacts on services.

3. An example: impact per cost for observations in global NWP

3.1 Quantitative assessment of impact per observation, and hence impact per cost, is only possible when metrics can be developed to quantify impact. In NWP, and particularly in global NWP, such metrics are available. For many years it has been possible to run a type of Observing System Experiment (OSE), usually referred to as Data Denial Experiment (DDE), in which the skill of forecasts from the full observing system is compared with the skill of forecast when a specific observation type is withheld. By systematically withholding all the principle observations types, their relative impacts can be assessed. Whilst such systematic experiments are important and continue to be needed, they are expensive.

3.2 In recent years, as a by-product of the development of four-dimensional variational data assimilation (4D-Var) systems, adjoint-based techniques, often called "Forecast Sensitivity to Observations" (FSO), have been developed. These allow the impact of observations to be assessed in a more economical way, with increased flexibility to look at the impact of different sub-groupings of observations, or even of individual stations or individual observations. With this technique the impact of observations is assessed in a subtly different way: the technique measures the amount by which the reduction of forecast error due to observations may be apportioned between the different observation types assimilated, i.e. in the context of the full observing system (rather than when one observation type is withheld).

3.3 It should be noted that, for both OSE/DDE and FSO, these techniques are only well suited to examining the impact of observations that play a role through the data assimilation cycle; the impacts of observations used outside this framework (e.g. for setting fixed fields such as sea surface temperature, sea ice or vegetation, or for verifying NWP outputs such as precipitation) are not measured but are nevertheless important.

3.4 In this study we illustrate "impact per cost" assessment through FSO calculations in the framework of the Met Office's operational global NWP system, as it was during the period April-July 2013, i.e. using the version of the NWP system and the observations that were used operationally at that time.

3.5 Illustrative results are given in Table 1. **It must be emphasised that these results are illustrative and preliminary – all the costs in this table are, at best, estimates and, at worst, guesses.** The author intends to seek the help of international colleagues to improve these data.

3.6 The data in Table 1 have been organised, compiled and calculated according to the following column headings:

- Observation category. The observations used in global NWP are firstly divided into the categories used in the "Vision for the GOS in 2025":
  - space-based – operational – low earth orbiting
  - space-based – operational – geostationary
  - space-based – other
  - surface-based – land – upper air
  - surface-based – land – surface
  - surface-based – land – weather radar
  - surface-based – land – hydrology
  - surface-based – ocean – upper-air
  - surface-based – ocean – surface
  - surface-based – ocean – sub-surface
  - surface-based – other

- Platform. Within each observation category, the observations are then sub-divided according to the natural sub-types for their use in NWP. For space-based observations, this is firstly by satellite type, and then by instrument on each satellite, and then (if necessary) by observation data type from each instrument. For surface-based observations, this is by observing technology. Observing systems that are important components to the GOS but which do not (currently) contribute to global NWP have been omitted from the table, in the interests of clarity.

- Costs. Observing system costs (in UK£M) have been estimated in various ways:
  - The costs of EUMETSAT programmes have been obtained from data available to the author. However, they do not yet include the costs of associated ESA programmes and they have not yet been referenced to the economic conditions for a fixed year. Costs are total programme costs divided by the years of planned operational life for the programme.
  - The costs of other satellite programmes have been guessed on the basis of similar EUMETSAT programmes.
  - The costs of surface-based observing systems have been estimated from the costs of systems funded or part-funded by the Met Office (UK). Using the numbers of observations delivered to global NWP both by UK-funded systems and by global systems, the UK costs have been scaled up to estimate the global costs.

  These costs are intended as a first attempt; much further refinement is needed! Guesses should be replaced by real estimates. Also, consistent ways need to be found for representing costs of programmes performing beyond their expected lifetime, and for attributing costs of multiple products from the same observing system.

- Instrument and cost-fraction. For satellites carrying multiple instruments, costs have been apportioned in proportion to instrument mass (which is approximate but, in the experience of the author, is probably reasonable). Instruments not currently contributing to global NWP have been omitted from this table for clarity.

However, their masses have been included in the mass fraction calculation. Instrument masses have been obtained from the OSCAR database (WMO, 2014) in most cases. For surface-based observing systems, no such apportionment of costs has been attempted (yet); all cost-fractions have been set to one.

- Data. This column in the table shows the form in which the data are assimilated into the NWP system.

- Impact. The FSO impact of each observation type is given as the fraction of the total observation impact (i.e. their sum is 1.0). The system used to calculate these values is described by Lorenc and Marriott (2014) and Joo et al. (2013). The data presented by Joo et al. are for the period August-September 2010. The data in Table 1 are for a more recent period, April-July 2013, in which new observations types were available and a more recent version of the operational NWP systems was used. Figure 1 illustrates the FSO impacts of the different observation types calculated for this period, both in terms of total impact and of impact per observation.

- Impact per cost. These values are calculated for each observation type by dividing the fractional FSO impact by the estimate of the global cost per year.

3.7 It is interesting to note which observation types are assessed as giving the highest impact per cost. However, it is important to bear in mind the provisional and tentative nature of these data, particularly the costs.

4. Extension to other Application Areas and to services

4.1 The calculations illustrated in section 3 are possible because of the impact metrics available for global NWP. It is probable that similar metrics will soon be developed for high-resolution NWP, although this is a challenging topic. It is also desirable that appropriate metrics be developed for other applications: i.e. nowcasting, climate monitoring, ocean forecasting, and the other Application Areas recognised by the WMO RRR process. It may not be possible in all cases to develop metrics that are as objective as they are for global NWP, but this should not be considered an obstacle to proposing useful metrics.

4.2 Such metrics would allow impact per cost calculations for each Application Area. This would be important for assessing the relative value of different observation types for each Application. Ideally, we would wish to go beyond this and assess the impacts and benefits derived from each observing system when aggregated over all Application Areas. This will involve tracing impacts from the Applications (i.e. the direct users of observations) to the downstream services and from there to the user benefits. There is already much useful work in this area quantifying the benefits of meteorological services, e.g. Riishojgaard (2013), Hallegatte et al. (2013).

5. Next steps

5.1 IPET-OSDE is invited to consider how the suggestions in this study might be taken forward:

- What actions are needed to improve the estimates/guesses of observing system costs presented in section 3 and to generalise the results to more than one NWP centre?
- What actions are needed to promote the development of appropriate metrics for other Application Areas?
- What actions are needed to extend impact per cost assessments to other parts of the cost-benefit chain, and eventually to an integrated assessment of cost-benefit over many applications and services?

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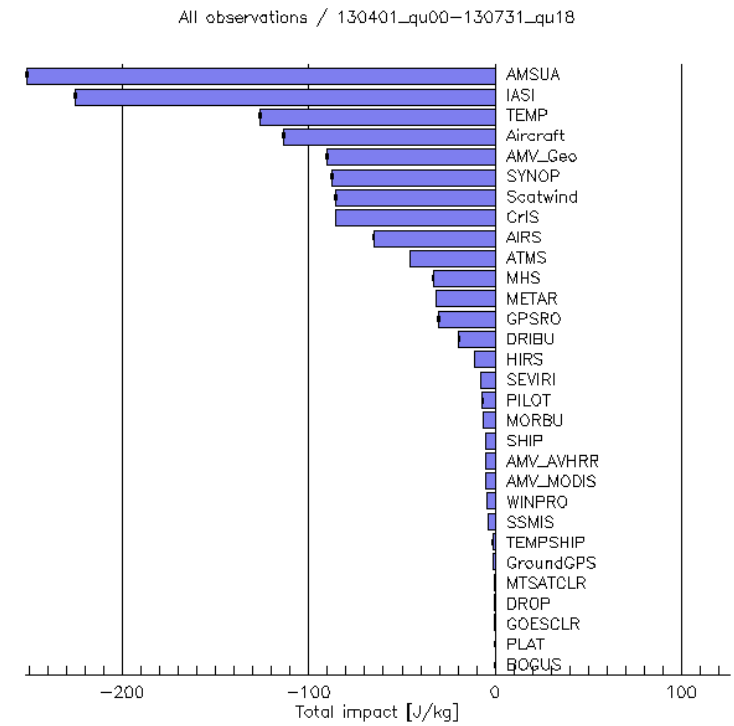
Table 1. **Observing system costs, impacts and impacts per costs for global NWP**
Note: this table is for illustrative purposes – some costs are very approximate.

Obs category	**Platform**	**Cost in UK£M/ year**	**Instru-ment**	**Cost fraction**	**Cost in UK£M/ year**	**Data**	**Impact**	**Impact / cost**
Space								
LEO	Metop-A+B	110	AMSU-A	0.12	13.2	radiances	0.072	**5.5**
			MHS	0.08	8.8	radiances	0.009	**1.0**
			HIRS/4	0.04	4.4	radiances	0.004	**0.91**
			IASI	0.28	30.8	radiances	0.167	**5.4**
			AVHRR/3	0.04	4.4	AMVs	0.002	**0.45**
			ASCAT	0.31	34.1	surface wind	0.038	**1.1**
			GRAS	0.04	4.4	bending angles	0.004	**0.91**
	Suomi-NPP	130	ATMS	0.13	16.9	radiances	0.034	**2.0**
			CrIS	0.26	33.8	radiances	0.63	**1.9**
	NOAA 15-19	120	AMSU-A	0.38	45.6	radiances	0.114	**2.5**
			MHS	0.23	27.6	radiances	0.014	**0.51**
			HIRS/4	0.13	15.6	radiances	0.004	**0.26**
			AVHRR/3	0.12	14.4	AMVs	0.002	**0.14**
	DMSP F16	140	SSMIS	0.50	70.0	radiances	0.003	**0.04**
GEO	Meteosat-10	110	SEVIRI	0.90	99.0	AMVs	0.012	**0.12**
					99.0	radiances	0.006	**0.06**
	Meteosat-7	10	MVIRI	1.00	10.0	AMVs	0.012	**1.2**
	MTSAT-2	100	JAMI	1.00	100.0	AMVs	0.017	**0.17**
					100.0	radiances	0.001	**0.01**
	GOES-W	120	IMAGER	0.50	60.0	AMVs	0.018	**0.30**
					60.0	radiances	0.000	**0.00**
	GOES-E	120	IMAGER	0.50	60.0	AMVs	0.009	**0.15**
					60.0	radiances	0.000	**0.00**
Other	EOS-Aqua	150	AIRS	0.19	28.5	radiances	0.048	**1.7**
			MODIS	0.26	39.0	AMVs	0.001	**0.03**
	EOS-Terra	160	MODIS	0.24	38.4	AMVs	0.002	**0.05**
	COSMIC 1-6	10	IGOR	1.00	10.0	bending angles	0.019	**1.9**
	Oceansat-2	50	OSCAT	0.50	25.0	surface wind	0.019	**0.76**
	Coriolis	60	Windsat	0.90	54.0	surface wind	0.006	**0.11**

Surface								
Land – upper air	synoptic + reference	33.7	radio-sondes	1.00	33.7		0.093	**2.8**
	remote sensing	1.1	wind profilers	1.00	1.1		0.003	**2.7**
	aircraft	7.3	AMDAR+ AIREP	1.00	7.3		0.084	**11.5**
	GNSS	0.8	GNSS	1.00	0.8	ZTD	0.001	**1.3**
Land – surface	synoptic + reference	78.4	SYNOP+ METAR	1.00	78.4		0.088	**1.1**
Land – weather radar								
Land – hydrology								
Ocean – upper air	ship sondes (ASAP)	1.4	radio-sondes	1.00	1.4		0.001	**0.71**
Ocean – surface	ships	3.0	-	1.00	3.0		0.004	**1.3**
	buoys - moored	9.4	-	1.00	9.4		0.005	**0.53**
	buoys - drifting	1.2	-	1.00	1.2		0.015	**12.7**
Other								
TOTALS					2063		0.994	

(a)



(b)

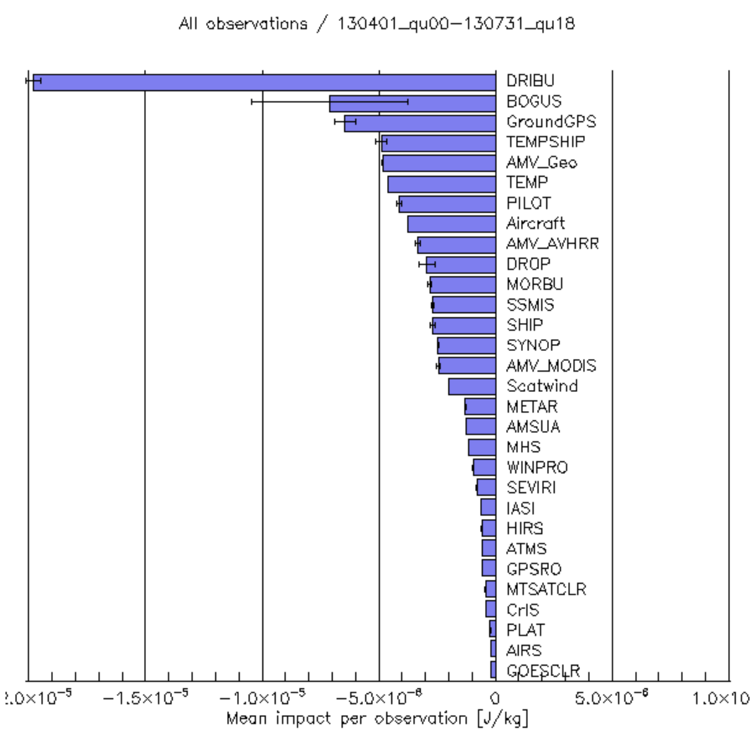


Figure 1. FSO impacts: (a) total impact, (b) impact per observation