A systematic approach to delivering socio-economic benefits from Earth-system observations by using Earth-system models and data-assimilation systems

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Abstract

The Group on Earth Observations - GEO - is a coordinated initiative by many nations to address the needs for Earth-system information expressed by the 2002 World Summit on Sustainable Development. We introduce the GEO initiative and discuss the role in GEO of Earth-system observations, modeling and assimilation in delivering the 'predictive products' and 'current status assessments' required by GEO, where the predictions are required on time scales of days to several seasons. A review of recent gains in predictive skill across these time scales, with operational systems in Europe, indicates that the gains in operational predictive skill depend on observational availability, on new science developed in modeling and assimilation of observations, and on developments in computing. We discuss recent progress in Europe in developing end-user applications of the operational predictions which will meet GEO requirements in identified areas of socio-economic benefit is discussed; examples include forecasts of storm-surges, river floods in large basins, health issues, and crop yields. The need to extend current operational Earth-system modeling and assimilation capabilities to atmospheric composition has motivated the European Union to fund a recently initiated four year project - GEMS: Global Earth-system Monitoring using Satellite and in-situ data. This project will build a new operational system to extend current weather operational capabilities in order to exploit a wide range of satellite data to monitor and forecast a range of atmospheric trace constituents including greenhouse gases, reactive gases and aerosols. The plans for the new system, which is expected to be operational in 2009, are reviewed. The GEO observational requirements for the period 2015-2025 and aspects of the associated costs are reviewed. We conclude with some reflections on the value of past investments in Earth observations and in Earth-system modeling systems.

1. Introduction

In response to the Johannesburg Plan of Implementation adopted at the 2002 World Summit on Sustainable Development ministers from thirty-three nations plus the European Commission met in Washington in July 2003 and adopted a Declaration of political commitment to move toward development of a comprehensive, coordinated, and sustained Earth observation system and affirmed the need for timely, quality, long-term, global information as a basis for sound decision making. In order to monitor continuously the state of the Earth, to increase understanding of dynamic Earth processes, to enhance prediction of the Earth system, and to further implement environmental treaty obligations, the adherents to the declaration recognized the need to support the creation of a comprehensive, coordinated, and sustained Earth observing system or systems. To further this goal, they launched the intergovernmental ad hoc Group on Earth Observations (ad-hoc GEO) to develop a 10-Year Implementation Plan. The Group, co-chaired by the United States, the European Commission, Japan, and South Africa and joined by more than 21 international organizations, began preparatory work immediately. The GEO observation system will be built as a System of Systems to be known as GEOSS.

Ministers met again in Tokyo in April 2004, where they adopted the Framework Document for a 10-Year Implementation Plan for GEO. Meeting again in Brussels in February 2005 ministers from some sixty countries adopted the GEOSS Implementation Plan and created a new international entity, the Group on Earth Observations (GEO) to execute the plan. They are supported in this undertaking by about forty international organisations with a mandate in Earth Observations. The GEO Framework Document, the GEO Implementation Plan and the Resolution creating GEO may be found at http://earthobservations.org.

In the words of the GEO Framework Document *'Understanding the Earth system—its weather, climate, oceans, land, geology, natural resources, ecosystems, and natural and human-induced hazards—is crucial to enhancing human health, safety and welfare, alleviating human suffering including poverty, protecting the global environment, and achieving sustainable development. Data collected and information created from Earth observations constitute critical input for advancing this understanding. Comprehensive, Coordinated and Sustained Earth Observations for understanding the Earth system more completely and comprehensively will expand worldwide capacity and means to achieve sustainable development and will yield advances in many specific areas of socio-economic benefit, including:*

- *Reducing loss of life and property from natural and human-induced disasters;*
- *Understanding environmental factors affecting human health and well being;*
- *Improving management of energy resources;*
- *Understanding, assessing, predicting, mitigating, and adapting to climate variability and change;*
- *Improving water resource management through better understanding of the water cycle;*
- *Improving weather information, forecasting, and warning;*
- *Improving the management and protection of terrestrial, coastal, and marine ecosystems;*
- *Supporting sustainable agriculture and combating desertification;*
- *Understanding, monitoring, and conserving biodiversity.*

Globally, these benefits will be realized by a broad range of user communities, including (1) national, regional, and local decision-makers, (2) relevant international organizations responsible for the implementation of international conventions, (3) business, industry, and service sectors,(4) scientists and educators, and (5) the general public. Realizing the benefits of coordinated, comprehensive, and sustained Earth observations (i.e. the improvement of decision-making and prediction abilities) represents a fundamental step toward addressing the challenges articulated in the declarations of the 2002 World Summit on Sustainable Development and fulfilling the Millennium Development Goals agreed at the Millennium Summit in 2000'.

The European initiative on "Global Monitoring for Environment and Security" (GMES, www.gmes.info) will be the main European contribution to GEO. Within Europe, it has been difficult to access new observations of the environment, and advanced products derived from the observations - it has been difficult to synthesise and consolidate information from many disparate sources. In addition the lack of sustained environmental monitoring leads to gaps and incompatibilities in time series of observations; a data collection effort often ends with the research programme which initiated it, leaving no heritage. The challenge for Europe is to secure sustainable, coherent and efficient information for environment and security policies. The GMES initiative has been in preparation since 1998 and currently represents a four-year investment of about 190 million Euro by its joint sponsors, the EU and ESA. The GMES initiative aims to make environmental information more readily available to both providers and users. In addition it will lead to the creation of a "European Shared Information System" for exchanging a wide range of information.

The GEO (and GMES) agendas have substantial implications for the development of modeling and data assimilation systems. In this introductory paper we discuss, the role of Earth-system modeling, assimilation and observations in delivering the 'predictive products' and 'current status assessments' required by GEO and GMES (section 2). Recent gains in predictive skill in European operational systems, and on time scales of a few days to several seasons, are reviewed section 3; the evidence is that the gains in operational predictive skill depend on observational availability, on new science developed in modeling and assimilation of observations, and on developments in computing. We also discuss recent progress in Europe in developing applications of the operational predictions which will meet GEO and GMES requirements in identified areas of socio-economic benefit. The need to extend current operational Earth-system modeling and assimilation capabilities to atmospheric composition is reviewed in section 4. These needs have motivated the European Union to fund a recently initiated four year project - GEMS: Global Earth-system monitoring using Satellite and in-situ data - to build a new operational system to extend current weather operational capabilities in modeling and assimilation in order to exploit a wide range of satellite data to monitor and forecast a range of atmospheric trace constituents including greenhouse gases, reactive gases and aerosols. The plans for the new system, which is expected to be operational in 2009, are reviewed. GEO observational requirements for the period 2015-2025 and aspects of the associated costs are discussed in section 5. We conclude with some reflections on the value of past investments in the observations an in the modeling systems.

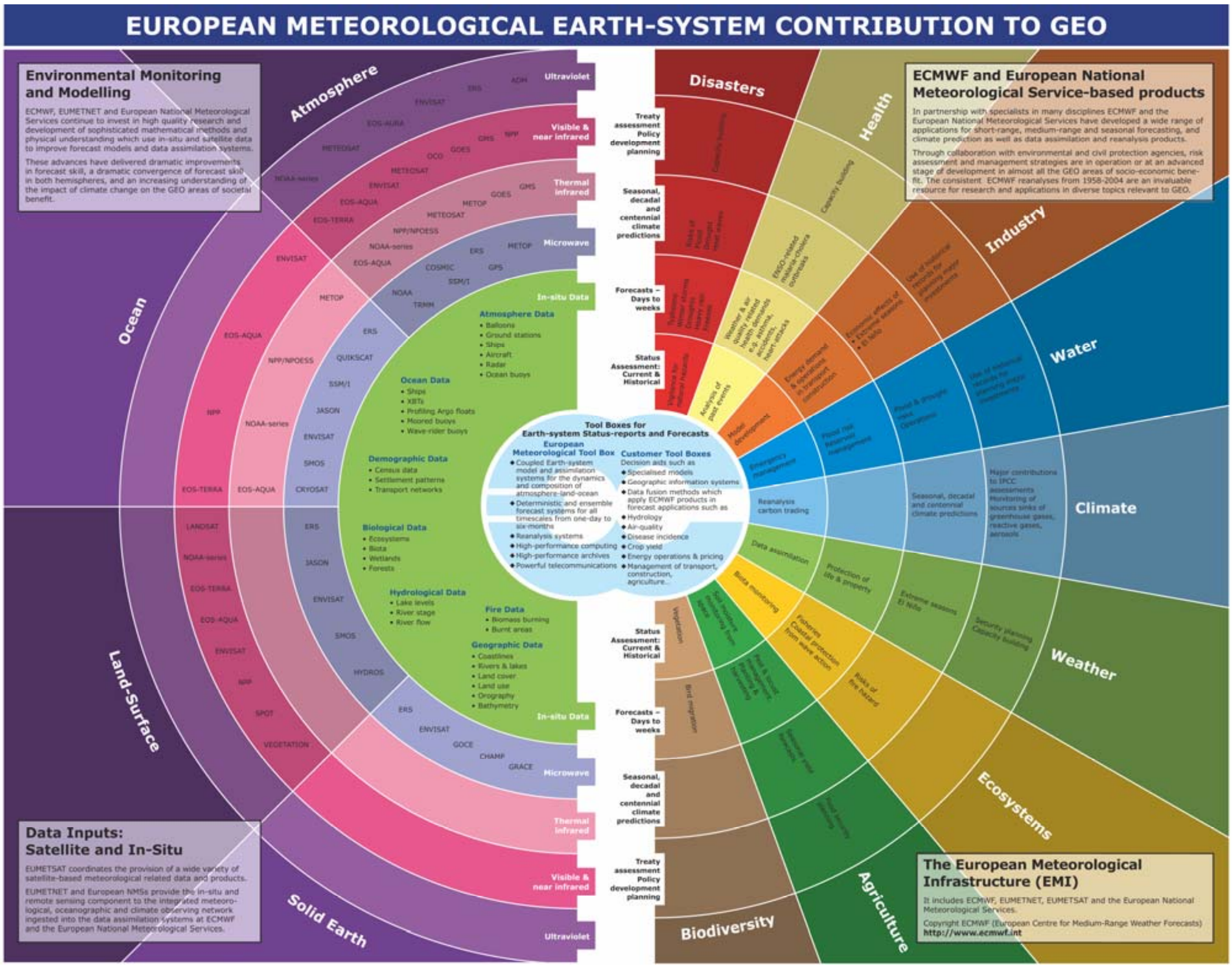
2. GEO Requirements for Observations and for Earth-system Predictions and Assimilations

The GEO Implementation Plan (GEO, 2005) aims to deliver socio-economic benefits across a wide variety of domains, and across a wide range of time scales through improved exchange and exploitation of a wide range of in-situ and space-based observations of the Earth-system. The GEO deliverables may be categorised in two broad groups (i) current status assessments and (ii) predictions. Earth-system modeling and data assimilation methods will play a central role in delivering both categories of products.

Through the GEO initiative governments are demanding much more than science alone from their investments in Earth-system observations and in the scientists who use those observations. Governments realise that with better organisation and coordination of effort one can realise a wide range of socio-economic benefits in the management and development of weather-sensitive and environmentally- sensitive sectors of society including disasters, health, industry, water resources, weather, climate, agriculture, ecology and biodiversity, the key areas of socio-economic benefit identified by GEO.

GEO has high ambitions in terms of the range of products to be delivered, and the range of satellite data needed to create those products. Figure 1 was prepared to illustrate the ambition, the complexity and the feasibility of the GEO objectives, viewed from the perspective of practicing meteorologists. Although geo-hazards such as volcanoes, earthquakes tsunamis and magnetic storms are concerns of GEO they have not been included in the diagram for reasons of space and simplicity, and because they are outside the authors' professional experience; they could be easily included in a more comprehensive and complex diagram.

The left hand side of Figure 1 illustrates the diverse in-situ (green) and satellite data sources (arranged by electromagnetic frequency used) needed to achieve the diverse GEO goals. The in-situ physical and socio-economic observations are categorised in several domains including the categories of the GCOS requirements; the satellite missions are stratified by four main domains of application (Atmosphere, Ocean, Land surface, Solid Earth). The satellite missions listed include current and planned operational and research missions. The right hand side of the figure illustrates the diversity of the GEO deliverables, organised by the areas of socio-economic benefit identified by GEO, and stratified by the time-scale for which the deliverables are relevant. The centre of the diagram illustrates the means used to transform the measurements on the left into the deliverables on the right, including current status descriptions and forecasts. Broadly speaking the means used are of two kinds, complex Earth-system models and data assimilation systems (in the left semi-circle), and specialised application models and decision aids (such as GIS) in the right semi-circle.



Environmental Monitoring and Modelling

ECMWF, EUMETNET and European National Meteorological Services continue to invest in high quality research and development of sophisticated mathematical methods and physical understanding which use in-situ and satellite data to improve forecast models and data assimilation systems.

These advances have delivered dramatic improvements in forecast skill, a dramatic convergence of forecast skill in both hemispheres, and an increasing understanding of the impact of climate change on the GEO areas of societal benefit.

ECMWF and European National Meteorological Service-based products

In partnership with specialists in many disciplines ECMWF and the European National Meteorological Services have developed a wide range of applications for short-range, medium-range and seasonal forecasting, and climate prediction as well as data assimilation and reanalysis products.

Through collaboration with environmental and civil protection agencies, risk assessment and management strategies are in operation or at an advanced stage of development in almost all the GEO areas of socio-economic benefit. The consistent ECMWF reanalyses from 1958-2004 are an invaluable resource for research and applications in diverse topics relevant to GEO.

Tool Boxes for Earth-system Status-reports and Forecasts

European Meteorological Tool Box

- Coupled Earth-system model and assimilation systems for the dynamics and composition of atmosphere-land-ocean
- Deterministic and ensemble forecast systems for all timescales from one-day to six-months
- Reanalysis systems
- High-performance computing
- High-performance archives
- Powerful telecommunications

Customer Tool Boxes

Decision aids such as

- Specialised models
- Geographic information systems
- Data fusion methods which apply ECMWF products in forecast applications such as
- Hydrology
- Air-quality
- Disease incidence
- Crop yield
- Energy operations & pricing
- Management of transport, construction, agriculture...

Data Inputs: Satellite and In-Situ

EUMETSAT coordinates the provision of a wide variety of satellite-based meteorological related data and products.

EUMETNET and European NMSs provide the in-situ and remote sensing component to the integrated meteorological, oceanographic and climate observing network ingested into the data assimilation systems at ECMWF and the European National Meteorological Services.

The European Meteorological Infrastructure (EMI)

It includes ECMWF, EUMETNET, EUMETSAT and the European National Meteorological Services.

Copyright ECMWF (European Centre for Medium-Range Weather Forecasts)
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Figure 1 Based on the GEO Implementation Plan, the figure illustrates

-(right) Deliverables from an Earth_system forecasting system and associated specialized models (e.g ECMWF and its associates) organised in the GEO categories of socio-economic benefits, and stratified by timescale (current status assessments, forecast time-range, long-term studies of reanalysis). The main text indicates how to access information available on the web concerning the specific entries in the array of GEO socio-economic benefits.
-(left) observational requirements to a comprehensive Earth-system model, including in-situ data plus current and projected satellite data (both operational and research satellites). The missions identified in the plot are expected to be used by ECMWF and its customers/associates in the coming 4-5 years. For reasons of legibility we do not specify individual instruments on a mission. The satellite missions are categorised by the geophysical domain observed (Atmosphere, Ocean, Land-surface, solid Earth) and by the electromagnetic frequency used by the missions.
-(centre) Tool-boxes needed at an Earth_system forecasting centre (e.g. ECMWF) and at Customer/Associate sites, to achieve the transformation from observations to information.

The entries on the right of Figure 1 correspond to known current development activities around the world which are of relevance to GEO and which use the ERA-40 datasets (Uppala et al., 2005) in their developments. To provide a preliminary assessment of the current status of development of GEO-relevant applications, we made a web survey of current and future applications of the ERA-40 re-analysis data (http://www.ecmwf.int/research/era/index.html). The ERA-40 datasets are reanalysed gridded global meteorological and surface fields available four-times daily for the period September 1957 to August 2002 (Uppala et al. 2005). In November 2004 we performed an Internet search for projects involving ERA-40 data. Google was employed as search engine using a large number of keywords like "flood" or "greenhouse gases" in conjunction with the "ERA40" keyword. The web hits were categorised into research areas and timescales of forecasts according to the overview given on the right hand side of Figure 1. We found at least one application for each topic, and identified a large number of users in the sections on climate and weather. A clickable image-map of the right half of Figure 1 was linked to a table containing all the information retrieved in the course of the Internet survey. These data are published on the ECMWF webpage (http://www.ecmwf.int/research/era/era40survey/) and provide an overview of research areas of ERA-40 applications relevant to GEO, and incidentally facilitate communication between ERA-40 users. The survey shows that there is a wide range of activity underway around the world that can be harnessed to meet the GEO deliverables.

2.1. The transformation of measurements into predictive information

The transformation of the measurements on the left of Figure 1 into the information products on the right (both predictive products and status-assessment products) is mediated by the models, procedures and facilities described in the central disc of the figure. Prominent among the engines for transformation of measurements into information are the operational comprehensive global Earth-system models for atmosphere, ocean and land-surface, including representations of the biosphere and cryosphere. The output of these models in the form of forecasts and outlooks on daily, weekly, monthly, multi-seasonal and decadal time-scales will be used directly for many GEO purposes. In addition, the outputs of the global models will be used to drive a range of specialised application models such as distributed hydrological models, storm-surge / coastal zone models, air-quality models, health and socio-economic models, crop-yield models, all linked to decision aids such as GIS, in order to provide regional forecast information in a form directly applicable to real-world problems.

3. Recent developments in predictive skill with Earth-system models

Most of the initial effort in GEO will be devoted to extending current well-established capabilities in Earth-system forecasting on a range of time scales to wider groups of users in domains such as disaster management, health management, water-resource management and other GEO domains. Here we review the recent progress in improving predictive skill on medium-range time scales (3-10 days), on weekly-monthly time scale, and on multi-seasonal time scales. No useful forecasts are possible without observations. The evidence is clear that the sustained availability of Earth-system observations has stimulated the substantial scientific developments which were needed to understand and simulate the observations. The scientific developments in turn led to substantial improvements in the socio-economic benefits of the forecasts. As a result, Earth-system models and assimilations are essential to deliver the most accurate and most useful forecast products, and are frequently essential to deliver the most accurate and most useful ‘current status’ assessments. Indeed an important development in recent decades has been the growing contribution of Earth-system assimilation systems to maintenance and interpretation of observing systems.

3.1. Contribution of data assimilation systems to maintenance and interpretation of observation systems

The capability of data assimilation systems to provide effective long-term monitoring of the quality and availability of observations has been well-established for several decades (Hollingsworth et al., 1986) and is now an important part of the routine work of numerical weather prediction (NWP) centres. More recently, NWP assimilation systems have played a substantial role in the calibration and validation of new instruments, because of their ability to provide an ‘expected value’ for every measurement from a new system. Provided the biases in the NWP system can be estimated from other information, statistical analysis of the ‘observation minus expected’ values can provide rapid identification of anomalies in instrument performance or algorithm performance. The first demonstrations of the value of such diagnostic capabilities were with the scatterometer and altimeter on ERS-1. Recent examples include the scatterometers and altimeters on ERS-2, ENVISAT and QuickScat, the chemistry instruments on ERS-2 and ENVISAT , the SEVIRI imager on MSG and the AIRS sounder on AQUA. A new application in geodesy has recently emerged.

The GRACE mission is aimed at studying temporal changes in the Earth's gravity field. High-precision geodetic measurements from the GRACE mission can be interpreted, inter alia, as continental-scale fluctuations of soil moisture, a quantity which is of great practical significance and which is otherwise difficult to measure. Indeed Rodell et al. (2004) show successful comparisons of inter-annual changes in European summer soil moisture estimated by the GRACE geodetic mission, and by the operational ECMWF soil-moisture analysis.

A novel aspect of these results is the contribution of NWP analyses of weak tides in atmospheric surface pressure to the processing of the GRACE data. As noted by Tapley et al. (2004) success in interpreting GRACE data on secular variations in the gravity field requires great precision in calculating tidal effects in the ocean, and then removing those effects from the GRACE measurements. The ocean models used in these calculations are forced by ECMWF operational wind stresses and surface pressure fields. The wind stresses have long been used in ocean studies, but the use of the pressure fields to represent atmospheric tidal pressure forcing of ocean tides is new. Rui et al. (2003), Ray and Ponte (2003), and Richard et al (2004) indicate that the NWP analyses contain useful representations of the prominent S2 and S1 (solar semi-diurnal and diurnal) atmospheric surface pressure tides, as well as useful representations of weak atmospheric tides such as the M2 (lunar semi-diurnal) tide and the P1 & K1 declinational tides. The S1 tide is small in the ocean and is forced primarily by diurnal atmospheric pressure loading. As a demonstration of the utility of the NWP analyses, Richard et al (2004) report a simulation of the global S1 ocean tide using the S1 atmospheric pressure tide extracted from the ECMWF analyses; the S1 ocean-tide simulation was successfully verified against Topex /Poseidon radar altimeter data, and against tide-gauge data. A difficulty affecting the use of ECMWF analyses for work of this kind is the need for a good time interpolation of the semi-diurnal S2 tide, when using 6-hourly archived data. Dobslaw & Thomas (2005) demonstrate that 3-hour forecasts can be used to address the problem, and go so far as to suggest that '(ECMWF) forecasts allow one to account for atmospheric variability and corresponding oceanic responses down to semidiurnal timescales, dispensing with any additional model of atmospheric tides'. A general result noted by these authors is the benefit for ocean-tide studies (and thus geodetic studies) of the faithful representation in the NWP pressure analyses of substantial seasonal and other low-frequency variations in the atmospheric tides.

3.2. Developments in Medium-range Forecasting Models and Ensemble Methods

The 1980-2005 record of annual-average operational forecast skill for the northern and southern hemispheres is shown in Fig 2a, where skill is measured by the anomaly correlation of the 500hPa forecasts at 3-day, 5-day and 7-day lead times; the figure is an updated version of Fig 4 in Simmons and Hollingsworth, (2002) and of Fig 14 of Uppala et al. (2005). The operational scores show sustained gains of about one day per decade in forecast skill in both hemispheres since 1980. Since about 1999 the skill for the southern hemisphere is almost as high as that for the northern hemisphere. Simmons and Hollingsworth (loc.cit.) showed that the gains could be attributed to improvements in the science of modeling and data assimilation, in observations, and in the computing resources which determine model resolution .

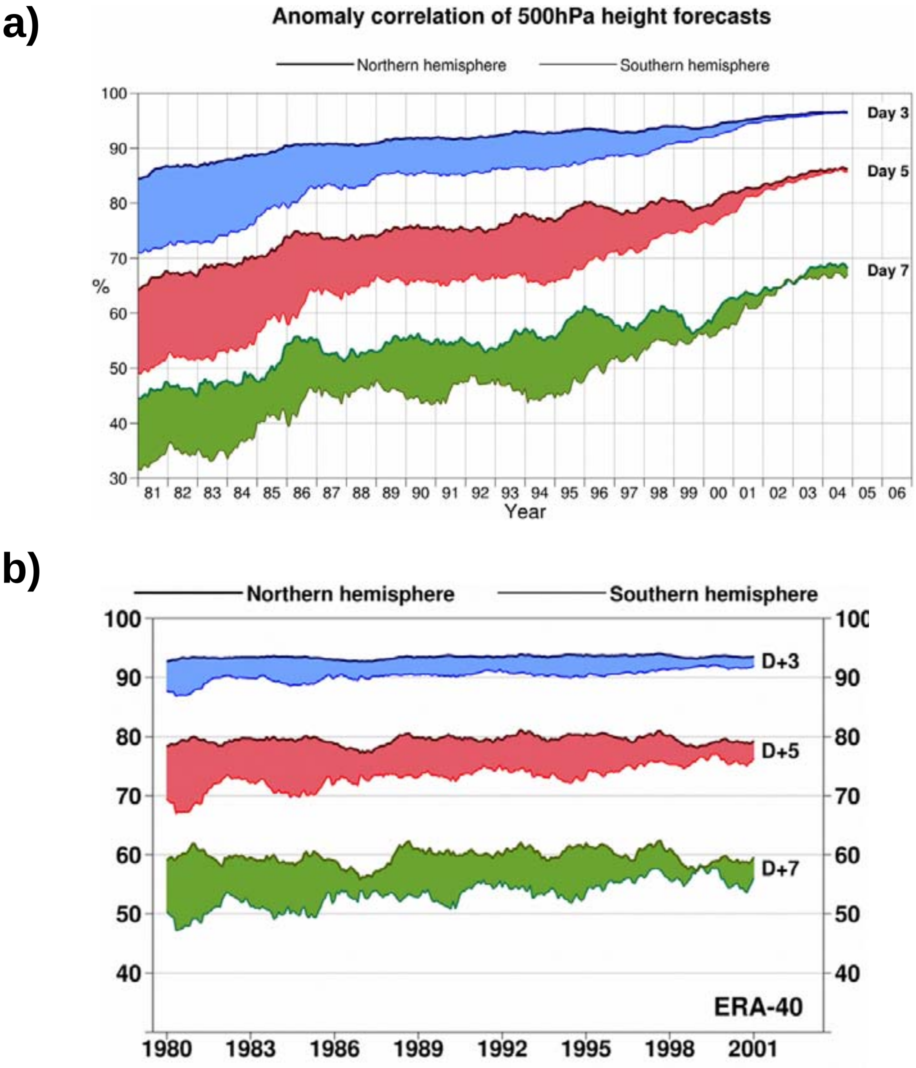

Figure 2 Twelve-month running mean anomaly correlations (%) of 3-, 5- and 7-day 500hPa height forecasts for the extratropical northern and southern hemispheres. (a) Operational 12UTC ECMWF forecasts from January 1980 to April 2005. (b) 12UTC ERA-40 forecasts from January 1980 to August 2002. The shading shows the difference in scores between the two hemispheres at the forecast ranges indicated. [From Uppala et al. (2005)].

The operational system that produced the forecasts in Fig 2a was in continuous evolution throughout the period. Uppala et al (2005) describe the development of the ERA-40 reanalysis system and the reanalysed products covering the period September 1957 - August 2002; the ERA-40 system corresponds qualitatively to the operational systems used in the second half of the 1990s. Using the invariant ERA-40 forecast system on the daily data between 1957 and 2002, Uppala et al. show that a fundamental improvement in the observing system was made in the late 1970s, almost certainly from the introduction of the TOVS and geostationary satellite observing systems, although there were changes in the in-situ observing system at the same time. Figure 2b, reproduced from Uppala et al. shows that for the period 1980-2002, the forecast performance with the invariant ERA-40 system (strictly, one should speak of the hindcast performance) is much more uniform in time than the performance of the real-time operational system. The implication is that the substantial improvements in operational skill since 1979 are only due in part to improvement of the satellite observing system since 1979. The ERA-40 results in Fig 2b indicate that operational forecasts have improved substantially since 1979 mainly because of steady development in the science of modeling and data assimilation, although caveats are noted by Uppala et al.

The fact that since 1999 the operational southern hemisphere forecasts have been almost as good as those for the northern hemisphere could not have been achieved without the satellite data, but it took 20 years to develop the science and the computer technology to exploit effectively the observing systems put in place in the late 1970s. In short, the availability of the satellite observations stimulated sustained improvements in the science, so that the improved forecasts are due to the combination of the observations and the improved science stimulated by the availability of the observations.

The improved models and variational assimilation systems developed over the last two decades are used today to improve the use of currently available data. A central challenge in numerical weather prediction is the modeling and assimilation of the hydrological cycle especially by using remotely sensed data affected by rain and clouds. This challenge poses formidable research problems - the 2005 extension of ECMWF's operational 4D-Var system to assimilation of rain-affected microwave radiances, Andersson et al. (2005), required a substantial and sustained research effort over eight years. Given the central role of the hydrological cycle in the atmosphere, there is every reason to expect that improved models and assimilation systems together with a sustained flow of new high-quality observations will yield steadily improving forecasts.

Ensemble forecasts as a means to estimate forecast uncertainty

The last decade has seen important developments in the use of ensemble forecasts to estimate forecast uncertainty, Buizza et al. (2005). Generally, the model used to generate the ensembles has lower resolution (and less cost per single forecast) than the headline resolution of the model used for the deterministic forecasts. The initial data for the ensemble forecasts are perturbed to sample the uncertainties in the starting data, and the forecast model includes a stochastic element to represent the inevitable stochastic events on the sub-grid scale. A further development has been the linking of weather model output to end-user models to generate ensembles which estimate the uncertainty in forecasts of end-user variables.

Hindcasts of extreme weather events: The Dutch storm-surge of 1 Feb 1953

Because of the cost of observations, weather forecasters are continually pressed to demonstrate the value of their observations in terms understandable to the general public. On 31 Jan and 1 Feb. 1953 an intense storm traversed the Irish Sea, Great Britain, and the North Sea creating severe devastation - the ferry Princess Victoria foundered in the Irish Sea with the loss of about 150 lives, and the storm surge in the North Sea overwhelmed coastal defences in England and the Netherlands, killing some 300 persons along the English coast and some 2000 persons along the coast of the Netherlands. No effective warnings could be provided in either country to the civil population. The proceedings of a commemorative symposium provides much more detail (http://www.knmi.nl/kenniscentrum/ watersnood_symposium.html). Figure 3 shows two sets of hindcasts of the sea-level at the port of Vlissingen, as well as the observations of sea-level at Vlissingen; the hindcasts have lead times of 36 hours and 108 hours before 0000UTC on 1 Feb 1953, the peak of the storm. The starting data for the forecasts were created by assimilating the observations for the relevant period using the ERA-40 system. Deterministic weather forecasts were made at a resolution of ~40 km (T511), and 51-member ensemble weather forecasts were made at a resolution of ~120km (T159). The weather forecasts were then used to drive the KNMI storm surge model, generating the storm-surge hindcasts shown in the figure. The critical water level for the sea defences at Vlissingen was 3.8m, and the observations show the surge peaking at about 4.3m. Had these hindcasts been available in 1953, it is clear that there would have been alerts for a severe event at 4-5 days lead, and the accuracy of the alerts improved as the lead time shortened. The observations used in the hindcasts were those available in 1953. The quality of the hindcasts is attributable to the observations available in 1953 and to scientific and computing capabilities developed since 1953.

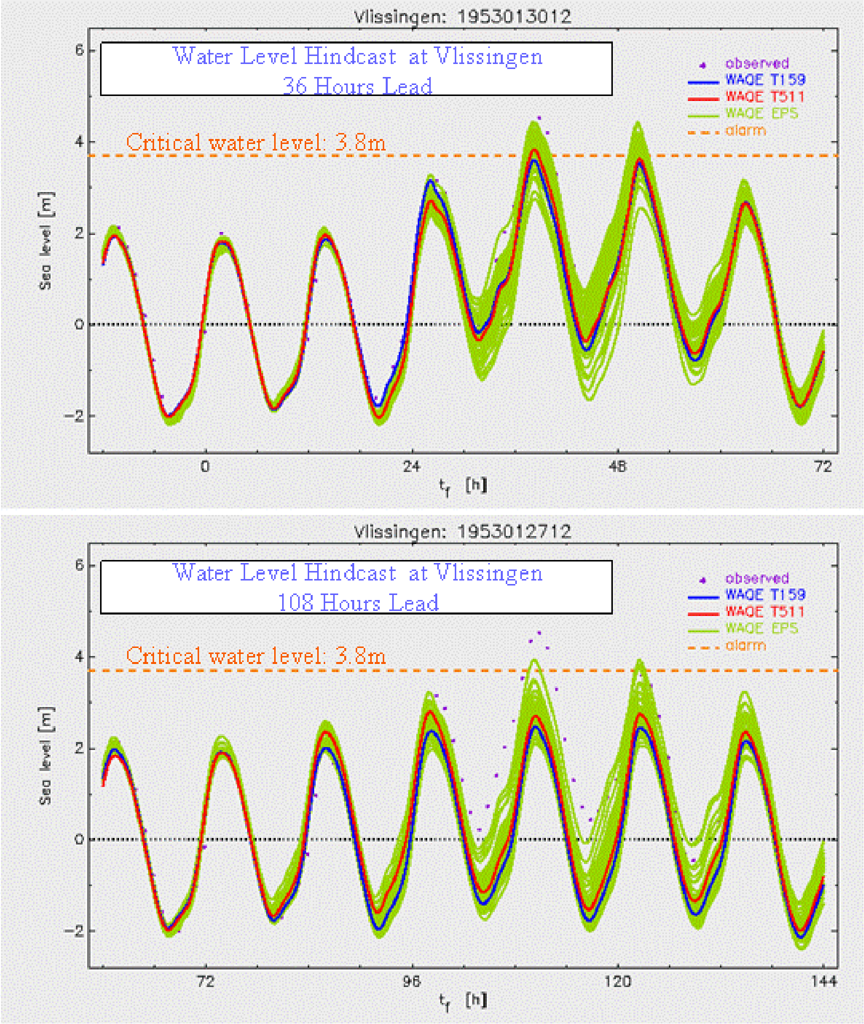

Figure 3 The plots show the observed hourly sea-levels at Vlissingen (dots), peaking at 0000UTC on 1 Feb 1953 together with a series of sea-level forecasts made with the KNMI storm-surge model, forced by ECMWF weather forecasts run at T159 (125km) resolution (blue), T511 (40km) resolution (red), and in ensemble mode (N=51, T159, green), all starting from reanalyses with the ERA-40 system. The critical sea-level for over-topping of the dykes at Vlissingen was 3.8m (orange) The forecasts were started 108hours (4.5 days, bottom) before the peak of the storm-surge, and 36 hours (1.5 days, top) before the peak of the surge . The forecasts started from reanalyses made with the ERA-40 system.

EFAS: A pre-operational system for medium-range river flood alerts in Europe

Europe has been much affected by devastating large scale river floods in recent years. The benefits of coupling weather models to end-user distributed hydrological models to generate medium-range ensemble flood alerts has been explored by De Roo et al (2003). Fig 4 shows an example of such an ensemble hindcast for the Meuse flood in Jan 1995, made by coupling a meteorological model (ECMWF) to a distributed hydrological model (LISFLOOD). The figure shows the observed discharge at the Borgharen gauging station on the River Meuse, Netherlands, for 0000 UTC on 21st January 1995 (labeled hour 48 on the time axis) and for a period of 20 days thereafter, together with 10-day forecasts of the discharge where the distributed hydrological model is driven by different meteorological forecasts including forecasts from the 40km (TL511 / L60) and 80km (TL255 / L40) versions of the model, as well as the 50-member ensemble of discharge forecasts. The simulations show that the coupled hydro-meteorological system provides a good forecast of discharge up to 5 days ahead and a probabilistic assessment of extreme flooding for forecast lead times in the range 5-10 days. Further examples of successful medium-range forecasts for extensive floods in the Po valley may be found in Hollingsworth et al. (2004).

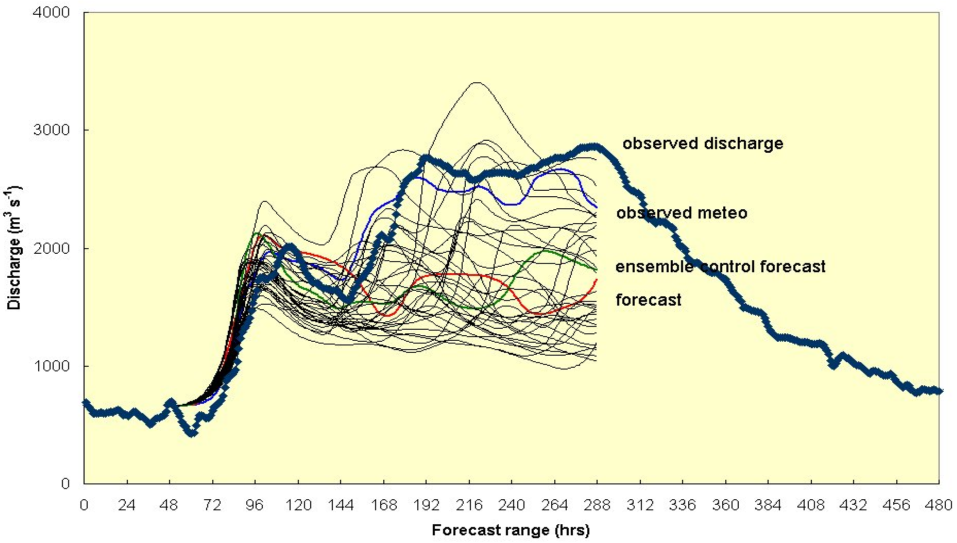

Figure 4 shows the observed discharge (thick blue line) for a 20-day period (0000 UTC on 19 January 1995 to 0000UTC on 8 Feb 1995) for the Borgharen gauging station on the River Meuse, in the Netherlands; during the period there was a major flood on the Meuse. The plot also shows forecast simulations (hindcasts) of discharge at Borgharen, made with a distributed hydrological model (LISFLOOD) driven by different versions of the ECMWF forecast system. The simulation driven by observed meteorological data is shown as a thin blue line, the simulation driven by the 40km(T511 L60) ECMWF deterministic forecast is shown in red, the simulation driven by the ECMWF 80 km (TL255 L40) ensemble control forecast is shown in green and the simulations driven by the 50 ECMWF TL255L40 ensemble forecast members are shown in black. All the forecasts started from 0000UTC on 21 Jan 1995 (labeled hour 48), and were run for 10 days. Most of the discharge forecasts are quite good for 5 days, capturing the initial rise and small decline of the discharge. In addition many of the ensemble members provide an alert for a further rise in the discharge with a lead of 5-7 days. [from de Roo et al. (2003)].

These and related studies have led to the implementation of a pre-operational system for medium-range river flood alerts in large trans-national river basins in Europe, known as the European Flood Alert System (EFAS: http://efas.jrc.it/.). The pre-operational EFAS system involves extensive collaboration between meteorological institutes (ECMWF, DWD) providing meteorological forecasts, the EU’s Joint Research Centre in Italy responsible for the distributed hydrological model, and National Hydrological Services in a growing number of large European basins. The pre-operational phase is expected to run for several years to assess real-time experience on a variety of hydrometeorological situations.

3.3. Developments in forecasting and applications on the weekly-monthly time scale

The encouraging progress seen in medium-range forecasting (previous section), together with the development of successful coupled Atmosphere-Ocean-Land models for multi-seasonal forecasting (next section) prompted an evaluation of the value of monthly forecasting using such models, Vitart (2003). As a result of the success of the experimental tests, ECMWF implemented the monthly forecasts as an operational product in October 2004. The new system was discussed by Vitart (pers.comm 2005) at a user workshop in June 2005; the workshop presentations, including user evaluations and workshop conclusions, are accessible at http://www.ecmwf.int/newsevents/meetings/forecast_products_user/presentations.html

The new forecast system creates once a week (starting from 0000UTC each Thursday) a monthly ensemble forecast (ensemble size 51) with the same ocean model as the seasonal forecast system discussed in section 3.3 and with a higher resolution atmospheric model (T159 v T95). The monthly forecasts are run for 32 days. In Vitart's presentation and in the user presentations the following definitions are used:

- Week 1 is day 5-11 (Monday to Sunday)
- Week 2 is day 12-18 (Monday to Sunday)
- Week 3 is day 19-25 (Monday to Sunday)
- Week 4 is day 26-32 (Monday to Sunday)

As an example of the monthly forecasts Fig 5 shows the weekly-mean forecasts of the anomaly in two-metre temperature (T2m) for the 21-27 Feb 2005 which was anomalously cold over much of western Europe, together with the observed anomaly. The forecasts at week-2 and week-3 for this event look very encouraging. The summary conclusions of the user workshop (available on the same web-site) indicate that

- During winter 2004-5 the system provided good predictions of transition between flow regimes last winter;
- The forecasts for weekly-mean two-metre temperature (T2m) for week-2 (days 12-18) show skill over persistence of the probabilities of the previous week and, using a similar criterion, show skill to a lesser extent for week-3 and week-4 (days 19-32), treated jointly;
- Meteo France finds moderate skill in T2m forecasts for week-3 over France;
- In the UK, the Met Office finds that the outer quintiles of the forecast probability distributions for T2m are skilful.

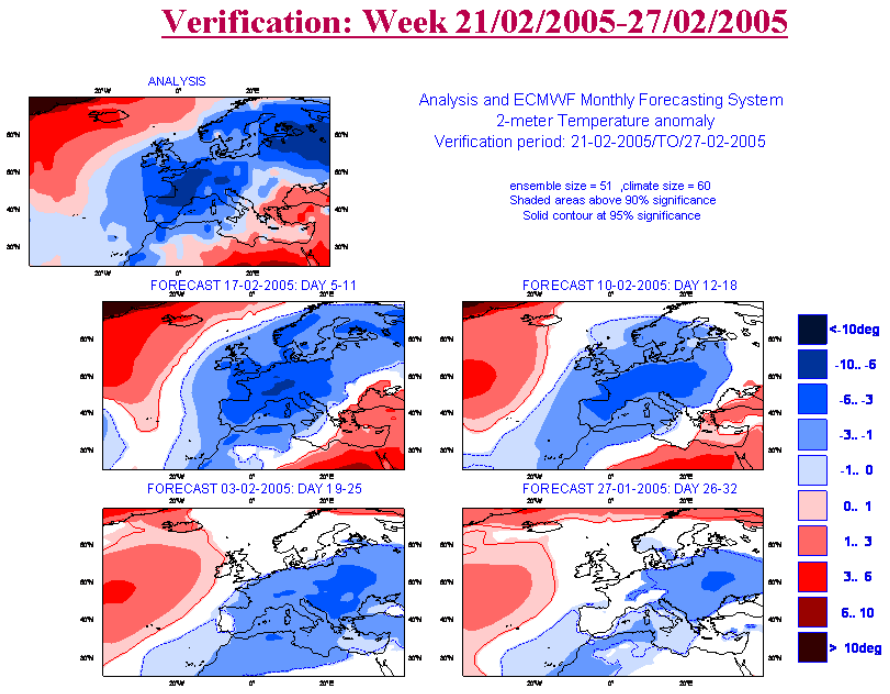

Figure 5 The plot shows the observed weekly-mean screen-temperature (T2m) anomaly over Europe for the week Mon 21 Feb to Sun 27 Feb 2005 (top) together with the corresponding week-1 (day 5-11) forecast made from 17 Feb (middle row left), the week-2 (day 12-19) forecast made from 10 Feb (middle row right), the week-3 forecast made from 3 Feb (bottom row left), and the week-4 forecast made from 27 Jan (bottom row right).

These early operational results are consistent with Vitart's pre-operational results, and give grounds for optimism about future developments. It is still early days with the monthly forecast system, but there are already strong indications that one can deliver a useful product on major weather shifts in week 2 and possibly in week 3. There is a huge social and economic demand for such products across almost all the GEO areas of interest.

The available evidence from the multi-seasonal forecast system is that the forecast errors are dominated by errors in the atmospheric model (D.L.T. Anderson, pers.comm. 2005). Since the same is probably true to some extent for the monthly forecast errors, one expects that more and better process-oriented observations will stimulate the improved science needed to realise the full potential of such forecasts.

Applications in the Construction sector

The UK Met Office monthly forecast outlooks are generated by (customer-specific) post-processing of the ECMWF monthly forecast ensembles. The products can be tailored for specific sectors, and one such sector is the Construction industry (http://www.metoffice.gov.uk/monoutlook/index.html)

Potential applications in the Health sector

As noted earlier, governments expect GEO to produce a wide range of products from their investments in Earth observations. An important example of such requirements is Article 7b of the Declaration of the Fourth Ministerial Conference on Environment and Health organised by WHO_Europe in Budapest, June 2004, (see conference paper EUR/RC54/10 which may be downloaded from http://www.euro.who.int/Governance/RC/RC54/20040426_1).

Article 7b of the ministerial declaration reads

> *7b. We recognize that climate is already changing and that the intensity and frequency of extreme weather events, such as floods, heat-waves and cold spells, may change in the future. Recent extreme weather events caused serious health and social problems in Europe, particularly in urban areas. These events will continue to pose additional challenges to health management and to the reliability of the power supply and other infrastructure. This demands a proactive and multidisciplinary approach by governments, agencies and international organizations and improved interaction on all levels from local to international. Based on the working paper 'Public health responses to extreme weather and climate events', we decide to take action to reduce the current burden of disease due to extreme weather and climate events. We invite WHO, through its European Centre for Environment and Health, in collaboration with the World Meteorological Organization, the European Environment Agency (EEA) and other relevant organizations, to support these commitments and to coordinate international activities to this end. We agree to report on progress achieved at the intergovernmental meeting to be held by the end of 2007.*

The ministerial conference devoted much attention to the health impacts of the devastating heat wave of August 2003 in Western Europe, which caused 20,000 - 40,000 excess deaths. A clear implication of the ministerial statement is the continuing demand from governments for better warnings of severe events, and of the associated health impacts. Further investigation of the monthly forecast system will assess the extent to which those requirements can be met.

3.4. Developments in multi-seasonal forecasting models and ensemble methods

The World Climate Research Programme's 1985-1994 TOGA initiative developed the observational basis for scientific insight into the mechanism of the ENSO phenomenon, and inspired the further development of coupled Atmosphere-Land-Ocean models for use in operational multi-seasonal forecasting at a number of centres world-wide. The main physical basis for predictability on these time scales is provided by atmosphere-ocean interactions in the tropical Pacific. The seasonal forecasts use ensemble methods to assess the uncertainties of the forecasts. A consensus of the various forecasts has successfully predicted the major shifts in the ENSO phenomenon over the last decade.

A feature of the seasonal forecasts with coupled models is that time-mean systematic errors in the forecast models can be as large as the signal one is trying to forecast. This has prompted interest in assessing the value of making an ensemble seasonal forecast using several different coupled models. A useful summary of the issues involved may be found in Palmer's (2005) preface to the special volume of Tellus on the results of an EU-funded experiment (DEMETER). The experiment used the ERA-40 datasets and seven European coupled models in a systematic exploration of forecast multi-seasonal skill in the period 1958-2002. One of the main results of the experiment was a clear confirmation of the skill of the multi-seasonal forecasts, and a demonstration of the value of using a multi-model approach to generate the forecasts, Hagedorn et al.(2005), Doblas-Reyes et al. (2005)

End-user applications of seasonal forecasts in Agriculture and Health

Palmer (2005) also notes the 'ground-breaking demonstrations on the benefits of linking the forecast model output to end-user application models, specifically for crop-yield, Cantelaube and Terres(2005) Marletto et al. (2005), Challinor et al. (2005) and for malaria incidence, Morse et al. (2005); in this way, probabilistic forecasts of end-user variables become possible'. The latter paper indicates for instance that 'malaria incidence is predictable a season or more ahead in parts of Africa, thus providing guidance on where preventative efforts should be targeted'.

A new European operational multi-model multi-seasonal forecast system

Prompted by the DEMETER results, a new operational multi-model seasonal forecast system will be launched in Europe in late 2005, based on ensemble forecasts from three coupled forecast systems (ECMWF, UK Met Office, Meteo France) using a common forecast protocol (start dates, duration), and with the results archived, verified and displayed in a common format. Research will continue on methods to combine the individual ensembles; as well as on improving the performance of the individual coupled systems, and on the means to extract from the forecasts information of direct value to end-users.

3.5. Discussion

The literature reviewed here has shown that there has been substantial and sustained progress in improving predictive skill on medium-range time scales (3-10 days), and on weekly-monthly time scales. In addition research has demonstrated the value of multi-model ensembles for multi-seasonal forecasts. The evidence is clear that a virtuous circle operates between the sustained availability of Earth-system observations, the substantial scientific developments needed to understand and simulate those observations, and the substantial improvements in the quality of the resulting forecasts and the socio-economic benefits derived from the improved science in the forecast systems. Observations, models and data assimilation systems are essential to this virtuous circle. Indeed the recent introduction of many more physical parametrizations in the operational assimilation of rain-affected radiances is a further step in strengthening the link between models and the interpretation of observations.

Current reasonable expectations, based on predictability studies and on analysis of forecast errors, are that there is considerable room for improvement in the Earth-system models, and in the starting data for forecasts. Thus, if the observation networks and investments in modeling and data assimilation are sustained, then the trends for improved delivery of Earth-system forecasts will also be sustained. Moreover direct coupling between Earth-system forecasts and end-user application models is increasingly used as an effective means to provide forecasts of quantities of direct relevance to end-users. We noted pre-operational examples in ensemble flood forecasts, crop-yield forecasts, and malaria forecasts. Forthcoming developments will include air-quality forecasts and related services to the health community, as discussed in the next section.

4. Extension of the scope of operational Earth-system models to atmospheric composition

As part to the GMES initiative, the EU has funded a new project to develop a real-time operational assimilation and forecast capability of aerosols, greenhouse gases and reactive gases; the project is known as GEMS (Global Earth-system Monitoring using Satellite and in-situ data) The GEMS operational system will be an extension of current data assimilation and forecast capabilities for Numerical Weather Prediction. It will be used to monitor the composition, dynamics and thermodynamics of the atmosphere and produce medium-range and short-range air-chemistry forecasts.

Satellite data will be a major source of information for the assimilation, and ground-based observations of atmospheric composition will be used initially for validation and evaluation. The inclusion of these new parameters in data assimilation systems will improve the retrieval of temperature and moisture from infrared sounders. Also the explicit representation of ozone and aerosols in the models will have a positive impact on weather forecasts. The GEMS Project should provide a good step towards fulfilling the new environmental monitoring mission of ECMWF. The main beneficiaries of the GEMS Project will be high-level policy users, operational regional air-quality and environmental forecasters, users of the GMES, and the scientific community.

4.1. GEMS Objectives and participants

The GEMS forecast capabilities will require sophisticated operational models. In addition global and regional data assimilation systems will be needed to exploit satellite and in-situ data so as to provide initial data (‘status assessments’) for the forecasts. These operational ‘status assessments’ are also invaluable for documenting sources, sinks and transports of atmospheric trace constituents. The specific objectives of the GEMS Project are to:

- Develop and implement at ECMWF a validated, comprehensive, and operational global data assimilation/forecast system for atmospheric composition and dynamics, which combines all available remotely sensed and in-situ data. Operational deliverables will include current and forecast three-dimensional global distributions (four times daily with a horizontal resolution of 50–100 km, and covering the troposphere and stratosphere) of key atmospheric trace constituents including greenhouse gases, reactive gases and aerosols.
- Provide initial and boundary conditions for operational regional air-quality and ‘chemical weather’ forecast systems across Europe. This will provide a methodology for assessing the impact of global climate changes on regional air quality. It will also provide improved operational real-time air-quality forecasts.
- Provide a retrospective analysis of all accessible remotely sensed data on atmospheric dynamics and composition as validation material for the ENVISAT-EOS era (1999–2007).
- Develop state-of-the-art variational estimates of the sources/sinks, plus inter-continental transports, of many trace gases and aerosols. These estimates will be designed to meet policy-makers' key information requirements relevant to the Kyoto and Montreal Protocols and to the UN Convention on Long-Range Trans-boundary Air Pollution.

The GEMS consortium consists of four categories of participants.

- Sixteen research institutes in seven countries providing expertise in satellite and in-situ observations for assessing/validating models, expertise in developing models and assimilations of tropospheric and stratospheric chemistry and aerosol, and expertise in inversion methods to estimate sources, sinks and transports.
- Ten regional modeling centres in nine countries, most with operational responsibilities for national or regional air-quality forecasts.
- Two environmental protection agencies.
- Two international bodies: ECMWF with extensive experience in exploiting satellite and in-situ data to produce forecasts, and the Institute for Environment and Sustainability of the EU's Joint Research Centre.

The members of the consortium are listed in the Annex.

4.2. GEMS strategy

Figure 6 illustrates the main strands of the GEMS strategy to build an integrated operational system for monitoring and forecasting the atmospheric chemistry environment. The main global elements are the individual modules for assimilation of greenhouse gases, reactive gases and aerosols, each coupled to a common NWP framework, and collectively serving a group of regional air quality forecast and assimilation teams. Many of the building blocks of the global and regional elements of the system already exist. The schematic also illustrates the scientific interactions between the strands of development, which will develop and mature as the integration of the system proceeds. In formulating the strategy, both scientific and practical considerations were taken into account. The primary scientific goal is to create an architecture which will provide a fully integrated treatment of all aspects of atmospheric composition and dynamics when it becomes operational in the first half of 2009. In doing this full use will be made of the existing infrastructure provided WMO's World Weather Watch and European resources in information technology.

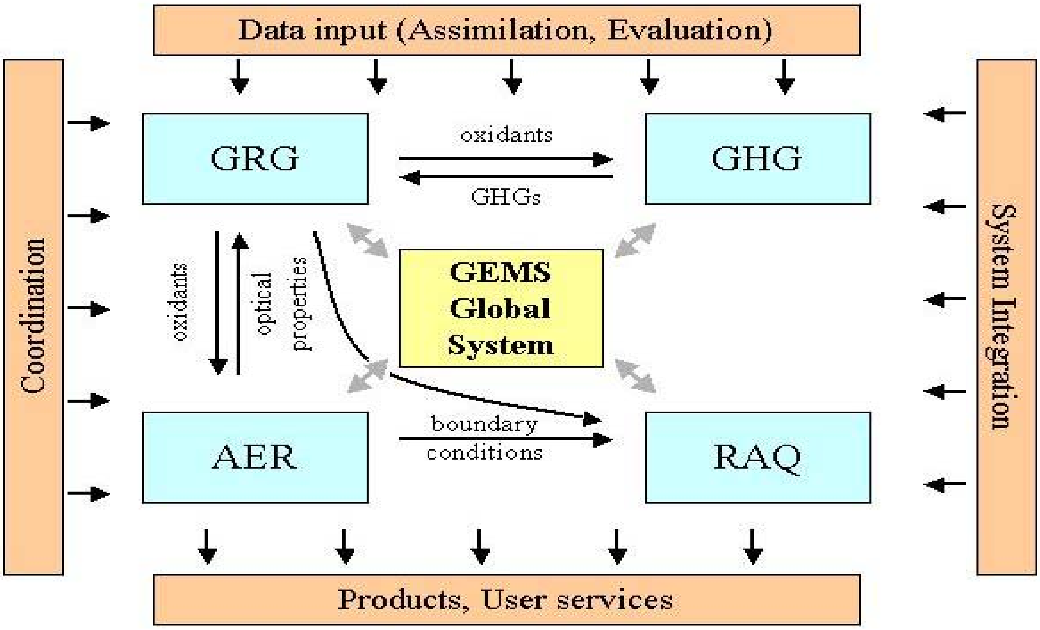

Figure 6 The schematic illustrates the links and the flow of data and information between the main elements of the GEMS system: Greenhouse Gases (GHG), Global Reactive Gases (GRG), Global Aerosol (AER), Regional Air Quality (RAQ) and the GEMS global assimilation system at ECMWF.

The GEMS strategy is based on a step-wise approach.

- Establish in parallel, and validate, individual elements of the system in the first half of the period.
- Merge the individual components in an integrated system, and validate the integrated system.

The operational system for greenhouse gases and for the inference of surface fluxes will be one of the first such operational systems. It will considerably strengthen the already strong European position in international negotiations, because of its transparency and sophistication. Research systems for assimilation of reactive gases and aerosol have been developed in recent years, but none has the comprehensive use of satellite data, the comprehensive validation mechanisms and the high spatial resolution of the system proposed here. The new operational global system will maintain and strengthen European leadership in these areas. The GEMS assessments of the impact of the global composition changes on regional air quality will be based on a range of regional air-quality models using similar assessment protocols. The resulting assessments will be comprehensive and extensive, examining impacts on mean fields and on extreme events.

4.3. GEMS Deliverables

The heat-wave of summer 2003 led to more than 18,000 excess deaths in Europe, partly due to heat-stress and partly due to high ozone levels. The operational GEMS system will provide a major improvement in European capabilities to forecast natural disasters, to monitor the global environment, and to advance the science of atmospheric dynamics and composition. Within the GEMS consortium ECMWF will undertake the global modeling and assimilation tasks. Other partners will use the global fields as boundary conditions for regional air-quality models as part of the regional air-quality forecast tasks. In addition the research partners will address the issues necessary to improve the system, and to assure the quality of the daily global analyses of greenhouse gases, monthly estimates of sources and sinks of carbon dioxide, daily global analyses and forecasts of reactive gases and aerosols, and the provision of boundary conditions for regional air-quality models. The availability of these data will be an important resource for the wider scientific community.

4.4. Institutional aspects of the GEMS operational implementation

The aim of the GEMS project is to be scientifically and technically ready to transition the global and regional GEMS systems to operational status by mid-2009, at the end of the project. To ensure successful transition it will be necessary to create institutional arrangements stepwise in the next four years. The actors will include the following.

- European Commission (e.g. GMES Advisory Committee), European Environment Agency (EEA) and European Space Agency (ESA).
- National Meteorological Services, together with ECMWF, EUMETSAT and EUMETNET.
- National Environment Agencies and Regional Environment Agencies.
- Other scientific and technical partners in GEMS and related GMES activities (see http://www.gse-promote.org/).

The institutional arrangements will address issues such as long-term funding, data sharing, and product dissemination funding. There are further challenges in the availability of satellite data beyond 2010. The current ENVISAT/EOS era provides a wealth of observational capability from space, which GEMS will exploit. Beyond 2010, the operational METOP series will provide upper-troposphere measurements of ozone. In addition information about aerosols, land-surface properties and ocean conditions will come from the operational NPOESS series. The main gap in satellite provision is an effective atmospheric chemistry observing capability from space. No such missions are committed beyond the demise of ENVISAT and

EOS-AURA. ESA's current priority for a chemistry mission is very low. Missions currently under study could not fly before 2015, even in a favourable funding environment.

Individual elements of the GEMS operational suite may be useful for NWP, and so may be incorporated in the NWP assimilating model and/or in the deterministic and ensemble forecast models. Those elements of the GEMS suite not incorporated in the NWP suite will be run operationally as a stand-alone assimilation/forecast suite for the reasons just cited. From the viewpoint of GCOS (Global Climate Observing System) there may be arguments for operational running of all elements of the GEMS suite at a common resolution.

The initial post-2008 operational configuration of the GEMS assimilation system could have a 50–100 km resolution. The operational configuration will evolve thereafter to realise benefits for the NWP system. On the other hand, some elements of the GEMS suite (e.g. aerosol) could prove of sufficient value to justify implementation in the NWP suite by 2008.

5. Operational GEO requirements for observations in 2015-2025

The wide range of current and projected in-situ and satellite observations shown on the left-hand side of Figure 1 illustrate the breadth of the observational challenges posed by the GEO programme. It is a large and arduous task to prepare and maintain a formal statement of observation requirements, such as that provided by WMO’s Rolling Requirements Review. The GEO Implementation plan is built on that continuing work, and on related efforts by the IGOS_P partnership. Here we outline a broad-brush estimate of what the GEO requirements may be in 2015-2025 for the atmosphere and ocean.

> **THE BASIC REQUIREMENT IS AN ALL-WEATHER CAPABILITY TO MEASURE ALL RELEVANT ASPECTS OF THE EARTH-SYSTEM**

where relevant means that the measurements can be used to improve the GEO products. The all-weather requirement poses a particular challenge because a cloudy atmosphere (found over 50% of the planet at any time) is opaque to instruments operating at electromagnetic frequencies shorter than the microwave. The following discussion focuses on observational requirements for medium-term and longer predictions.

For atmospheric dynamics, specifically profiles of winds, the operational requirement will include an operational wind lidar (following the forthcoming Atmospheric Dynamics Mission) to provide vertical profiles of horizontal wind fields, as well as surface all-weather ocean wind measurements from scatterometers on the METOP series. Other than radiosondes, there is no prospect of an all-weather capability to deliver profiles of horizontal wind fields.

For vertically-resolved atmospheric temperature and humidity profiles, the forthcoming operational advanced infra-red sounders (IASI, CrIS) will be valuable in clear sky conditions. However the requirement for an all-weather microwave (55Ghz) capability delivering comparable vertical resolution poses formidable technical challenges in cloudy areas, and in rain areas. The best prospect for improvement in these areas is the use of GPS radio-occultation measurements which operate around 1.4GHz, a frequency range for which a cloudy atmosphere is almost transparent. However one then has the problem of disentangling the temperature and humidity effects in the lower troposphere. A particularly interesting but unexplored aspect of such measurements is the ability of a fleet of GPS receivers in low earth orbit to provide a tomographic profiling capability.

Successful prediction of all elements of the hydrological cycle is a key GEO requirement. The use of profiles of rain-rate and clouds, (through modeling and assimilation of rain-affected and cloud-affected satellite measurements in the visible infra-red and microwave) is still at an early stage of development. In the expectation that the Global Precipitation Mission will fly in the coming decade, it is likely that there will be a requirement in the following decade for an operational follow-on mission. Likewise, successful demonstration of the predictive value of cloud profile data from missions such as CLOUDSAT will surely trigger a requirement for an operational cloud-profiling radar in orbit.

Successful prediction on medium-term and longer time scales requires a variety of data on ocean circulation and on ocean surface conditions. Many instruments can measure sea-surface temperature, but all-weather capability is limited. Microwave imagers, altimeters, scatterometers and synthetic aperture radars provide a great deal of information about ocean surface waves, ocean surface stress and winds, ocean -ice extent age and movement, sea-level height and ocean surface salinity. A sustained comprehensive operational observational capability of ocean surface conditions is a key requirement for the decade 2015-2025. Because of the opacity of water to electromagnetic radiation, measurement of sub-surface ocean conditions depends on in-situ data such as the ARGO floats, and on acoustic remote sensing for ocean tomography. GEO will surely generate operational requirements for such observations.

Accurate observation of land-surface conditions is essential for many GEO predictive purposes. Experience shows that one cannot make a good three-day forecast of near-surface temperature in Europe in most seasons without good observation and a good model representation of land-surface and soil processes, and their interactions with the atmosphere. There is evidence that successful longer term predictions have similar requirements, Ferranti et al. (2005) and references cited therein. There will therefore be operational requirements for land-surface skin-temperature, soil moisture, soil type, vegetation, albedo, roughness-length, extent of snow, lake temperatures and ice-cover, atmospheric sources of trace gas and particulates from biomass burning (as well as information on the associated biomass-fuel availability and state of vegetation). In addition, for hydrological purposes there will be requirements for in-situ and altimeter measurements of the stage of large lakes and rivers.

Use of space-based data for operational assimilation of ozone is already underway at several operational centres. The GEMS project described in section 4 will develop a much more comprehensive operational capability for modeling, monitoring and assimilation of atmospheric composition as well as dynamics and thermodynamics. Operational data requirements for atmospheric composition will therefore include profile measurements of a range of greenhouse gases and reactive gases as well as vertical profiles of a range of aerosol types. In addition it will require most of the observational capabilities just described, because of the profound impact of atmospheric dynamics, and of ocean and land-surface exchanges on atmospheric composition.

5.1. The cost of Earth observations and of the products derived from them

The cost of the observations represents the major cost element in GEO. Current costs, based on WMO members' budgets and space agency budgets for Earth observations, are conservatively estimated to be about $10B annually, including in-situ data and both operational and research satellites. By comparison the cost of an operational forecast centre such as ECMWF is much smaller at about $40M annually. The annual cost of 10 such centres distributed globally is about 5% of the cost of the observations. No estimate of the cost of the diverse specialised regional and applications models is available. However it is unlikely to change the overall result that the cost of observations will dominate the costs of GEO.

Given their $10 billion annual global spend on satellite and in-situ observations governments rightly demand a continually wider range of products derived from their continuing investments in observations. The mission statement from governments to meteorologists and other Earth-system scientists is clear: use every available scientific and technical resource to improve the skill, the scope and the utility of forecasts.

6. Concluding remarks on past investments in observations and science

Over the last 15 years partnerships in Europe, including ECMWF, have been building first versions of an Earth Information System, for the physical, and hydrological elements of the atmosphere-ocean-land surface-ice system, with a view to use in operational forecasting on weekly, and multi-seasonal time scales, and most recently for weekly-monthly forecasting. The record shows that the operational forecast systems have delivered broad socio-economic benefits on these various timescales. The next stage in this phased development will be the GEMS project to extend current capabilities to encompass atmospheric composition.

Delivery and sustained improvement of the socio-economic benefits depends on sustained investment in observations and in the science and computing necessary to transform the observations into useful products. Sustained and comprehensive observations of the Earth-system expose our ignorance of important natural processes and drive improvements in the science of the models and assimilation systems and in the science of the products. The cost of the investments in the science and computing is substantially smaller than the cost of the observations. Thus the costs of GEO will be dominated by the costs of the observations. Governments rightly demand improved value-for-money from their investments in Earth observations by requiring that the mix of observing systems which they fund should be scientifically-efficient and cost-efficient , and secondly by requiring that GEO provide a steadily improving and widening range of predictive and current-status products.

Although we have not discussed the issue here, observing system experiments to help optimise the GEO observing system will probably be a key feature of the GEO scientific activity. There has been a long and sustained history of such research in Europe and world-wide, since the preparations for the global weather experiment in the early- and mid-1970s. Such work will need to continue in order to optimise future observing systems. An important element to note is that spatial resolution is an important limitation on model accuracy, and improvements in resolution make heavy demands on computer resources. One may also remark that given the way technology advances, we can continue to generate better science and products provided GEO can achieve a sustained budget in real economic terms for observations, science and computing..

An integral part of the European developments described here has been active and continuing dialogue with scientists and practitioners in communities such as land-surface experts, hydrologists, ocean wave modellers, oceanographers, geodesists, crop forecasters, and most recently those concerned with environment and health. In some cases this has led to the development of pre-operational ensemble forecast systems where end-user models are coupled to the Earth_system ensemble forecasts, to produce ensemble forecasts of end-user variables. Extension of such capabilities to air-quality forecasting is an integral component of the GEMS project, and should generate new services to the health sector.

In discussions of the costs of observations, it is impossible to do a controlled experiment on the atmosphere and society and see what the difference is between a good forecast and a less-good one. However for major disasters (or series of disasters) of the past, a cost-benefit analysis of the value of the observing system of the time, and of today’s modeling capabilities, can be facilitated by reanalyses and re-forecasts of the disasters, and comparison with the forecasts made at the time. For the re-forecasts of the 1953 Dutch disaster discussed above, it is likely that such a cost-benefit analysis would give a positive outcome Similar positive outcomes are likely for ongoing reforecasts of the 1962 storm which cost 200-300 lives in Hamburg (Klinker, 2004, pers.comm.) and the 1966 storm which caused devastating floods in Florence together with an equally devastating storm surge in Venice (R. Buizza and L.Cavaleri, pers.comm. 2005). An advantage of this approach to value assessment is that the Earth-system models can be coupled to end-user models (e.g. for floods or surges or chealth or crop-yield, etc.) so that end-users can make their assessments of value in terms that are directly meaningful to them.

The benefits of an Earth Observing system are realised in a whole variety of products, not least of which is science. As shown in an earlier section, there is a virtuous circle relating the provision of sustained observations to the development of new science and thus to the delivery of improved forecasts. Sustained observations expose our ignorance of important processes and force improvements in the models and products. A flow of new science and steadily improving forecasts will provide the motivation to sustain and improve the observational programmes, which are the major cost elements of the forecast process. Given reasonable expectations of technological advances in observational instrumentation and in computing, GEO can expect to meet its socio-economic deliverables in a progressive fashion provided governments can sustain, in real economic terms, the current budgets for observations and the necessary science, computing and operational infrastructure.

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