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REQUIREMENTS FOR OBSERVATIONS FOR GLOBAL NWP

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POSITION PAPER:
REQUIREMENTS FOR OBSERVATIONS FOR GLOBAL NWP

EXECUTIVE SUMMARY

The purpose of this paper is to set out the requirements for observations for use in global numerical weather prediction (NWP) in the medium term (up to 2015), to indicate how they are likely to evolve in the longer term (2015-2025) and to identify areas where developments in observing capability are needed to address these requirements. The paper reviews probable trends in global NWP and related activities. It considers how the uses of NWP products are likely to develop and how requirements for the quality and scope of these products will increase. It considers probable developments in global NWP systems, which are needed to respond to the projected evolution in products: developments in the NWP models themselves, in the techniques and systems for assimilating observations, and in their requirements for observations. It summarises the requirements for observational information on specific geophysical variables in the medium term and outlines how these requirements are likely to develop in the longer term. The paper also reviews contributions made by present and planned observing systems to meeting these observational requirements, and it discusses specifically the contributions expected from the MSG and EPS programmes. Finally, the paper identifies the most important areas of deficiency, in which further improvements in observing capability would lead to substantial improvements in global NWP performance.

Improvements in the performance and scope of global NWP systems will be driven by user requirements, which can be categorised as trends under 5 headings:

- improvements in the quality of global NWP products for their main task of forecasting the weather,
- new/extended application areas for global NWP products,
- use of global NWP systems for forecasts beyond the medium-range – for operational monthly, seasonal and inter-annual forecasts,
- use of global NWP models as components of advanced Earth system models for climate change prediction,
- extension of NWP systems to address a wider range of environmental prediction, such as forecasting of pollution, monitoring atmospheric minor constituents, and monitoring biogeochemical cycles in the ocean.

Advances in global NWP systems to meet these user requirements will involve improvements:

- in the NWP models themselves,
  - to become more comprehensive and integrated representations of the Earth-system,
  - to improve the physical realism of specific components of the models, and
  - to increase the models' horizontal and vertical resolutions,
- in their data assimilation systems,
  - to become more comprehensive, including improvements and extensions in their use of observations, particularly satellite observations, and

- to improve data assimilation science,
- and in their observational base.

Developments in observational requirements can be summarised in terms of the geophysical variables to be analysed within the NWP systems:

- variables already analysed, for which observations need to be maintained and, in most cases, improved: 3D wind (horizontal component), 3D temperature, surface pressure, surface wind, 3D humidity, surface temperature (air), surface humidity (air), sea surface temperature, sea ice cover, snow cover, soil moisture, 3D ozone, significant wave height, wave direction, wave period,
- additional variables, to be analysed in the medium term: cloud cover, cloud top height, cloud base height, 3D cloud water/ice, precipitation, land surface temperature, sea-ice surface temperature, snow water equivalent, vegetation index and/or leaf area index,
- additional variables, to be analysed in the longer term: sea-ice thickness, 3D aerosol, cloud drop size (cloud-top), 3D cloud drop size, 3D wind (vertical component), aerodynamic roughness length,
- important additional variables for which observations are required for model validation: outgoing longwave radiation, outgoing shortwave radiation, surface emissivity spectrum, albedo, accumulated precipitation,
- extended requirements or additional variables to be analysed in support of seasonal and inter-annual forecasting: sea surface temperature (with higher accuracy), vegetation type, fraction of photo-synthetically active radiation, ocean topography (surface height), ocean salinity, ocean chlorophyll, ocean suspended sediment, ocean yellow substance.

Requirements for all these variables have been analysed in terms of: horizontal resolution, vertical resolution (where appropriate), frequency (temporal resolution), accuracy and timeliness. Each requirement is presented as a range from “maximum” to “threshold”. The “maximum” requirement is the value beyond which there would be no significant additional improvements in global NWP performance. The “threshold” requirement is the value below which the observation would not yield any significant benefit (for this application). The most cost-effective system will lie somewhere within this range.

Additional variables will be analysed in support of applications requiring a detailed treatment of atmospheric chemistry and based on extensions of global NWP models. These variables will include a range of chemical species - those important for modelling ozone chemistry in the stratosphere, and those needed for forecasting the evolution and transport of pollutants in the lower troposphere. Observational requirements have not yet been analysed in detail, but they will be constrained by the space/timescales represented by the models and by the timescales of relevant chemical reactions. In addition, in support of monitoring and prediction of the dispersion of volcanic ash and gases, observations of the extent and concentration of volcanic ash and sulphur dioxide will be needed.

An assessment has been made, for the geophysical variables of interest, of how well observational requirements are met by existing observing systems or will be met by planned observing systems. The specific contributions of data from the MSG and EPS systems have been analysed in more detail.

Based on the assessment of gaps between the capabilities of present/planned observing systems and the evolving user requirements of the global NWP community, the following are

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REQUIREMENTS FOR OBSERVATIONS FOR GLOBAL NWP

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1. INTRODUCTION

1.1 Objectives and scope

The purpose of this paper is to set out the requirements for observations for use in global numerical weather prediction (NWP) in the medium term (up to 2015), to indicate how they are likely to evolve in the longer term (2015-2025) and to identify areas where developments in observing capability are needed in order to address these requirements.

Before considering the observational requirements, the paper reviews probable trends in global NWP and related activities. Section 2.1 considers how the uses of NWP products are likely to develop and how requirements for the quality and scope of these products will increase. Section 2.2 then considers the developments in the NWP systems themselves, which are needed to respond to the projected evolution in products. These developments will include improvements both in the NWP models and in the techniques and systems for assimilating observations. Section 3.3 discusses the associated developments in requirements for observations. Section 3.4 summarises the requirement for observational information on specific geophysical variables in the medium term and outlines how these requirements are likely to develop in the longer term.

Section 4 reviews contributions made by present and planned observing systems to meeting the observational requirements set out in Section 3.4. It discussed specifically the contributions expected from the MSG and EPS programmes. It then identifies the most important areas of deficiency, in which further improvements in observing capability would lead to substantial improvements in global NWP performance.

1.2 What is global NWP?

Global NWP models are used to produce short- and medium-range weather forecasts (out to 10 days) of the state of the troposphere and lower stratosphere, currently with a horizontal resolution of typically 50-100 km and a vertical resolution of ~1km. Forecasters use NWP model output as guidance to issue forecasts of important weather parameters for their areas of interest.

To initialise these models, an accurate estimate of the complete atmospheric state is required. Observations from surface-based, airborne and space-based platforms are all used to define this initial state. The observational requirements for global NWP are based on the need to provide an accurate analysis of the complete atmospheric state at regular intervals (typically, at present, every 6 hours). Through a "data assimilation" system, new observations are used to update and improve an initial estimate of the atmospheric state provided by a short-range forecast.

Most benefit is derived from data available within 3 hours of measurement time, although most centres can get benefit from data up to 9 hours old. At present, the key model variables for which observations are needed are: 3D fields of wind, temperature and humidity, and the 2D field of surface pressure. Also important are boundary variables, particularly sea surface temperature, and ice and snow cover. Of increasing importance in new NWP systems will be observations of cloud and precipitation. These requirements, and their expected future developments, and discussed in more detail in Section 3.4.

Modern data assimilation systems are able to make effective use of asynoptic observations. Observations are most easily used when they are direct measurements of the model variables (temperature, wind, etc.), but recent advances in data assimilation have facilitated the effective use of indirect measurements (e.g. satellite radiances, which are linked in a complex but known way to the model fields of temperature, humidity, etc.) and also the extraction of dynamical information from frequent (e.g. hourly) time series of observations.

2. IMPROVEMENT IN PRODUCTS FROM GLOBAL NWP

The aim of this section is to establish a list of performance improvements in the products from global NWP systems in the timeframe 2015-2025. It addresses the questions:

- What improvements in the output of global NWP systems do users want, or do we wish to offer them?
- What aspects of global weather forecasting do we expect to improve?
- What extensions to global NWP systems, beyond their current roles in weather forecasting, do we expect to see?

The following list has been established through review of several documents concerning strategic developments in global NWP and associated activities. These documents are referenced for each item on the list, to aid traceability of the requirements.

The first group of trends concerns improvements in the quality of global NWP products for the task of forecasting the weather, which is the main role of these systems today and will remain their main role.

- Basic forecasting of key weather elements (chiefly wind, temperature, precipitation) in the range 1-10 days, with improved resolution and accuracy, and with understanding and quantification of associated uncertainties. [1] [2] [4] [5] [6] [7]

- Improved forecasting of extreme events (of wind, precipitation and temperature) and of their probabilities [1] [2] [5] [6] [7]

- Improved forecasting of occurrence and timing of major changes in the weather [2]

In some cases these general objectives have also been translated into specific targets, e.g.

- 5-day hurricane track prediction to +/- 30 km [4]

The next group of trends concerns:

- New/extended application areas for global NWP products: [1]
  - Stratospheric forecasting
  - Ozone monitoring and forecasting
  - Ocean: ship routeing, pollution control, coastal protection, sea-ice monitoring and forecasting, fisheries
  - Land hydrosphere: flood forecasting, water resource management
  - Land biosphere: forecasts of crop stress and agricultural yield

The third group of trends concerns the operational use of global NWP systems beyond their current range for short/medium-range forecasts (1-10 days) to:

- Operational monthly, seasonal and inter-annual forecasts of increasing skill. [1]

In this area, some specific targets are given:

- 15-20 month El Nino prediction [4]

- 12-month regional rain rate forecasts [4]

- Seasonal forecasts of ocean currents and mixed layer depth [1]

A fourth area of trends concerns the use of advanced Earth system models in climate changes on longer timescales and recognises the important role that advances in NWP systems play in this area:

- 10-year climate forecasts [4]

- evaluation of regional impacts of climate changes [6]

- multi-year atmospheric re-analyses in support of climate research [1]

The final group of trends concerns the extension of NWP systems beyond their current capabilities to address a wider range of environmental prediction:

- Monitoring of atmospheric minor constituents (e.g. CO_2, O_3, CH_4, N_2O) in support of climate monitoring and prediction [1]

- Monitoring of biogeochemical cycles in the ocean, especially in coastal areas [6]

- Improved advice on the movement of materials suspended in the atmosphere (pollutants) [2]

with, for the last item, an example of a specific target:

- 7-day air quality notification [4]

3. Improvements in global NWP systems

This section reviews how the same strategic documents provide some vision on the medium-term and long-term evolution of NWP systems needed to provide the improvements and extensions in products outlined above. It addresses the questions:

- What improvements do we expect/hope to see in NWP systems to meet the objectives of Section 2:
  - in the NWP models themselves (dynamics, physics, resolution, etc.),
  - in their data assimilation systems, and
  - in the observational base?
- Which additional geophysical models are likely to become part of, or closely coupled to, NWP models?
  - and what are their additional observational requirements?

3.1 Developments in NWP models

The first group of trends concerns developments through which models become more comprehensive and integrated. It is summarised in the ECMWF strategy as follows:

- Suitably comprehensive and integrated high-resolution Earth-system modelling facility, covering atmosphere, ocean, land surface, cryosphere and biosphere [1]

Specific aspects of this include:

- AGCMs improved and coupled to other models (ocean GCM, ocean/ice process model, ocean surface wave dynamics model) [1]; coupled ocean-atmosphere model (particularly for monthly, seasonal, inter-annual forecasting) [1]

- land surface modelling improved and extended – improved treatment of surface exchanges (energy and momentum); improved parametrisation of land surface, soil, hydrology, snow [1]

- extensions to include modelling of atmospheric chemistry, particularly to support the monitoring and forecasting of ozone. [1]

- improved modelling of atmospheric dispersion, in support of pollution forecasts [2]

The second set of trends concerns improvements in the physical realism of specific components of the models:

- improved representation of atmospheric processes – cloud physics, radiative transfer, convection, boundary layer, orography - leading to improved cloud and precipitation forecasts [2]

- improved description of boundary-layer turbulence, clouds and shallow convention [1]

- turbulent kinetic energy as prognostic variable [3]

- improved modelling of the structure of the tropopause and of the transport of atmospheric constituents across it [6]

- improved modelling and analysis of the stratosphere, which become significant in tropospheric forecast skill in the late-medium to extended range (7-10 days) [1]

- improved representation of the interactive role of clouds and aerosol [6]

- improved representation of aerosols, to improve forecasting of precipitation and visibility [2]

The third trend is:

- Increased horizontal and vertical resolution is anticipated [1] [2]; extrapolation of recent trends suggests:
  - horizontal grid spacing: 8-15 km by 2015, 3-5 km by 2025
  - vertical grid spacing:
    - boundary layer: 70 m by 2015, 40 m by 2025,
    - free troposphere: 300 m by 2015, 200 m by 2025,
    - stratosphere: 500 m by 2015, 200 m by 2025.

Some aspects of these trends are justified not only by the expectation that advances in computing power will support them but also by the assertion that they will be necessary to obtain desired improvements in forecast accuracy. For example:

- a limiting factor on the accuracy of prediction of mid-latitude cyclones is the rapid growth of small errors in the initial conditions with scales of 10-20 km. Increased model resolution is needed to capture these. [1]

3.2 Developments in data assimilation

A more comprehensive Earth-system model is expected to be matched by:

- comprehensive Earth-system assimilation capability [1]

This will include:

- general improvement and extension in the use of observations, particularly satellite observations, including over land [1] [2] [7]

- assimilation of ozone and possibly other minor constituents [1]

Developments in the science of data assimilation are expected to include:

- a focus on the quantification of uncertainties [7]

- improved methods for analysis of humidity and related variables [1] [2] [7]

- development of strategies for targetted observing systems [7]

3.3 Developments in observational requirements

The details of observational requirements are discussed in the following section. In this section, we consider only key issues concerning requirements arising directly from the strategy documents.

As discussed in section 3.1, a limiting factor on the accuracy of prediction of mid-latitude cyclones (and other phenomena?) is the rapid growth of small errors in the initial conditions with scales of 10-20 km. To capture these,

- increased observation resolution, particularly in the vertical, and accuracy are needed [1]

It is also noted that the areas in which these small errors are important are predominantly cloudy, leading to a requirement for observations of temperature and wind (in particular) of high vertical resolution in cloudy areas.

The extension of NWP to monthly, seasonal and inter-annual timescales leads to some additional observational requirements. Although many are the same as for medium-range NWP, there a few others:

- sub-surface measurements of ocean temperature and salinity,
- more accurate observations of ocean surface wind stress,
- observations of the diurnal cycle of SST,
- more complete description of sea-ice (thickness, in addition to coverage),
- observations of additional variables – see 3.4 for details.

The foreseen extension of systems based on NWP into more diverse application areas discussed in 3.1 would lead to additional observational requirements as follows:

- observations of a range of chemical species in support of modelling the evolution of stratospheric ozone and of pollutants in the lower troposphere,
- observations of variables required for modelling biogeochemical processes in the ocean,
- improved observations of the atmospheric aerosols, in support of modelling of pollution (in addition to their role in improving forecasting of visibility and modelling of cloud and radiation processes).

3.4 Requirements for observation of specific geophysical variables for global NWP

The basis for the analysis presented here is the global NWP section of the WMO user requirements database [8], reviewed by AEG/NWP, and amended and extended where necessary.

The following geophysical variables are already analysed by advanced global NWP systems:

- 3D wind (horizontal component)
- 3D temperature

- surface pressure
- surface wind
- 3D humidity
- surface temperature (air)
- surface humidity (air)
- sea surface temperature
- sea ice cover
- snow cover
- soil moisture
- 3D ozone
- significant wave height
- wave direction
- wave period

It is anticipated that the following additional variables will also be analysed in future, in the medium term:
- cloud cover
- cloud top height
- cloud base height
- 3D cloud water/ice
- precipitation
- land surface temperature
- sea-ice surface temperature
- snow water equivalent
- vegetation index and/or leaf area index

It is anticipated that the following additional variables will also be analysed in future, in the longer term:
- sea-ice thickness
- 3D aerosol
- cloud drop size (cloud-top)
- 3D cloud drop size
- 3D wind (vertical component)
- aerodynamic roughness length

Important additional variables for which observations are required for model validation, rather than for assimilation, are:
- outgoing longwave radiation
- outgoing shortwave radiation
- surface emissivity spectrum
- albedo
- accumulated precipitation

Extended requirements or additional variables to be analysed in support of seasonal and inter-annual forecasting are:
- sea surface temperature, with higher accuracy
- vegetation type
- fraction of photo-synthetically active radiation

- ocean topography (surface height)
- ocean salinity
- ocean chlorophyll
- ocean suspended sediment
- ocean yellow substance

The observation requirements for each variable are presented in Appendix A. They are expressed in terms of “maximum” and “threshold” requirements for the following performance measures: horizontal resolution, vertical resolution, frequency (temporal resolution), accuracy and timeliness. Maximum and threshold requirements are stated consistently with the WMO definitions:

- The "maximum" requirement is the value which, if exceeded, does not yield significant improvements in performance for the application in question. Therefore, the cost of improving the observations beyond this requirement would not be matched by a significantly increased benefit. Maximum requirements are likely to evolve; as applications progress, they develop a capacity to make use of better observations.
- The "minimum" or “threshold” requirement is the value below which the observation does not yield any significant benefit for the application in question. As a system that meets only minimum requirements is unlikely to be cost-effective, it should not be used as a minimum target level for an acceptable system.

Observational requirements are stated, in general, as values appropriate to “Level 2” products, i.e. measured or retrieved geophysical variables at the position and time of measurement. It is recognised that some requirements can best be met using “Level 3” products, through space/time averaging of Level 2 products, with consequential impact on product accuracy.

In addition to the variable listed above, Appendix A includes some “total column” variables. These are vertically integrated equivalents for some of the 3D variables, in cases where the measurement may be practicable and it could be used effectively in global NWP.

The detailed values given in Appendix A represent requirements for the medium term. In the longer term requirements will evolve in the following general ways. Firstly, observations of a greater range of geophysical variables will be needed; this aspect is already addressed in Appendix A. Secondly, the maximum requirements, principally for spatial and temporal resolution, will increase in line with evolution in resolutions of models. Note, however, that the maximum requirement for observations does not in general represent the most cost-effective system (see definition above); the degree to which it is desirable for improvements in observing systems to track developments in model resolution will need to be considered an a case-by-case basis, informed by the marginal costs of the available technology.

Additional variables will be analysed in support of applications requiring a detailed treatment of atmospheric chemistry and based on extensions of global NWP models. These variables will include a range of chemical species - those important for modelling ozone chemistry in the stratosphere, and those needed for forecasting the evolution and transport of pollutants in the lower troposphere. Observational requirements have not yet been analysed in detail, but they will be constrained by the space/timescales represented by the models and by the timescales of relevant chemical reactions. In addition, in support of monitoring and prediction of the dispersion of volcanic ash and gases, observations of the extent and concentration of volcanic ash and sulphur dioxide will be needed.

4. CONTRIBUTIONS OF SATELLITE OBSERVING SYSTEMS TO MEETING FUTURE OBSERVATIONAL REQUIREMENTS

4.1 Contributions of present and planned observing systems

This section provides an assessment, for the geophysical variables of interest, of how well the observational requirements are met by existing observing systems or will be met by planned observing systems. The analysis follows that provided by the WMO Statement of Guidance [8], reviewed and updated by AEG/NWP, and extended to cover geophysical variables not yet considered by WMO.

In conformance with [8], the following terminology has been adopted:

- "marginal" indicates threshold user requirements are being met,
- "acceptable" indicates greater than threshold but less than maximum requirements (in the useful range) are being met, and
- "good" means close to maximum requirements are being met.

3D wind field (horizontal component)

Wind profiles are available from radiosondes over populated land areas and from aircraft (ascent/descent profiles) and wind profilers over some of these areas. In these areas, horizontal and temporal coverage is acceptable and vertical resolution is good. Over most of the Earth – ocean and sparsely-inhabited land – coverage is marginal or absent. Profile data are supplemented by single-level data from aircraft along main air routes only, and by single-level satellite winds (motion vectors from cloud or humidity tracers in geostationary imagery) over low and mid-latitudes. In these areas, horizontal and temporal resolution is acceptable or good, but vertical coverage is marginal. There is almost no wind coverage in polar regions. In the lower stratosphere, only radiosondes provide information. Accuracy is good/acceptable for in situ systems and acceptable/marginal for satellite winds. The geostrophic component of the wind can be deduced from temperature information in the extra-tropics.

Extension of AMDAR technology (principally for ascent/descent profiles but also for flight level information) offers the best short-term opportunity for increasing observations of wind, although large areas of the world would still remain uncovered. From satellites, Doppler wind lidar technology is being developed to provide 3D winds of acceptable coverage and vertical resolution, but there are significant technical problems and thick cloud will provide limitations. Advanced geostationary imager-sounders (e.g. GIFTS) offer wind profile information in cloud-free areas through tracking of highly-resolved features in water vapour channels. In the lower stratosphere, coverage may be supplemented in future by tracking ozone features in satellite imagery (see *Ozone* below).

Surface pressure and surface wind

Over ocean, ships and buoys provide observations of acceptable frequency. Accuracy is good for pressure and acceptable/marginal for wind. Coverage is marginal or absent over large areas of the Earth. Polar satellites provide information on surface wind - with global coverage, good horizontal resolution and acceptable accuracy - in two ways. Scatterometers give information on wind speed and direction but, because of their narrow measurement swaths, of marginal temporal resolution. Recently launched and planned scatterometers will provide acceptable coverage via broader swaths. In addition, seasonal and inter-annual forecasting requires accurate fields of sea-surface wind stress, which scatterometers will contribute to providing. Passive microwave imagers already provide information of acceptable temporal resolution but on wind speed (only). Several NWP centres have noted the positive impact from both data types, including the analysis and prediction of tropical cyclones. Passive polarimetric radiometers, to be tested in the near future, represent another possible way of providing wind speed and direction information.

Over land, surface stations measure pressure and wind with horizontal and temporal resolution which is good in some areas and marginal in others. Measurement accuracy is generally good, though this can be difficult to use (particularly for wind) where surface terrain is not flat, because of the sensitivity of the measurements to small scale circulations that global NWP models do not resolve.

Surface pressure is not observed by present or planned satellite systems, with the exception of some contribution from radio occultation data (which has been demonstrated theoretically and merits further study).

3D temperature field

Temperature profiles are available from radiosondes over populated land areas and from aircraft (ascent/descent profiles) over some of these areas. In these areas, horizontal and temporal resolution is acceptable and vertical resolution and accuracy are good. Over most of the Earth – ocean and sparsely-inhabited land – coverage is marginal or absent. Profile data are supplemented by single-level data from aircraft along main air routes, where horizontal and temporal resolution and accuracy are acceptable or good.

Polar satellites provide information on temperature with global coverage, good horizontal resolution and acceptable accuracy. However, vertical resolution is currently marginal. Until recently performance in cloudy areas was poor, but the new microwave measurements from AMSU have provided substantial improvements here, and strong positive impact has been demonstrated by several NWP centres. Geostationary infra-red soundings (GOES) are also helping to expand coverage in some regions by making measurements hourly and thus creating more opportunities for finding cloud-free areas. Vertical resolution will be substantially improved in cloud-free areas with the launch of high resolution infra-red sounders planned for METOP, NPOESS, and EOS-Aqua. Satellite sounding data are currently under-utilised over land, but progress in this area is anticipated in the near future. Radio-occultation measurements for planned satellites will complement other systems through high accuracy and vertical resolution in the stratosphere and upper troposphere (thus helping to improve analyses around the tropopause).

3D humidity field

Tropospheric humidity profiles are available from radiosondes over populated land areas. In these areas, horizontal and temporal resolution is usually acceptable (but sometimes marginal, due to the high horizontal variability of the field), vertical resolution is good and accuracy is good/acceptable. Over most of the Earth – ocean and sparsely-inhabited land – coverage is marginal or absent.

Polar satellites provide information on tropospheric humidity with global coverage, good horizontal resolution and acceptable accuracy. However, vertical resolution is currently marginal. Until recently performance in cloudy areas was poor, but the new microwave measurements from AMSU offer substantial improvements. Geostationary infra-red soundings (GOES) are also helping to expand coverage in some regions by making measurements hourly and thus creating more opportunities for finding cloud-free areas. Over ocean, coverage is currently supplemented by information on total column water vapour from microwave imagers.

Vertical resolution will be substantially improved in cloud-free areas with the launch of high resolution infra-red sounders planned for METOP, NPOESS and EOS-Aqua. Satellite sounding data are currently under-utilised over land, but progress in this area is anticipated in the near future. Radio-occultation measurements from planned satellites will complement other systems by providing information on the humidity profile in the lower troposphere. Over populated land areas, growth is expected in the availability of total column water vapour data from ground-based GPS measurements. Very few aircraft currently provide humidity measurements, and these data are not generally available, but technical advances in this area are anticipated in the next decade.

Sea surface temperature

Ships and buoys provide observations of sea surface temperature of good temporal frequency and accuracy. Coverage is marginal or absent over large areas of the Earth. Instruments on polar satellites provide information with global coverage, good horizontal resolution and accuracy, except in areas that are persistently cloud-covered. Temporal coverage is adequate for short-medium range NWP but, for seasonal/inter-annual forecasting, observation of the diurnal cycle is required, for which planned geostationary satellites offer a capability.

Sea-ice

Sea ice cover is observed by microwave instruments on polar satellite with good horizontal and temporal resolution and acceptable accuracy. Operational ice thickness monitoring will be required in the longer term, but is not currently planned.

Snow

Over land, surface stations measure snow cover with good temporal resolution but marginal horizontal resolution and accuracy (primarily because of spatial sampling problems). Visible/near-infrared satellite imagery provides information of good horizontal and temporal resolution and accuracy on snow cover (but not on its equivalent water content) in the day-time in cloud-free areas. Microwave imagery offers the potential of more information on snow water content (at lower but still good resolution) but data interpretation is difficult and products are not yet operational.

Soil moisture

Microwave imagery is sensitive to surface wetness, but no present or planned operational missions meet minimum requirements for measurement of soil moisture (i.e. below the surface). Research instruments such as SMOS offer some progress here. Some land surface stations report soil moisture routinely with marginal accuracy, but most do not report.

Surface air temperature and humidity

Over ocean, ships and buoys provide observations of acceptable frequency and good accuracy. Coverage is marginal or absent over large areas of the Earth. Over land, surface stations measure with horizontal and temporal resolution which is good in some areas and marginal in others. Measurement accuracy is generally good, though this can be difficult to use where surface terrain is not flat, because of the sensitivity of the measurements to local variability that global NWP models does not resolve. Satellite instruments do not observe these variables, or do so only to the extent that they are correlated with atmospheric variables that significantly affect the measured radiation (i.e. skin temperature and atmospheric layer-mean temperature and humidity).

Land and sea-ice surface skin temperature

Satellite infra-red and microwave imagers and sounders provide data containing information on these variables, although retrieval accuracy is affected by cloud detection problems and surface emissivity uncertainties, and interpretation is difficult because of the heterogeneous nature of the emitting surface for many surface types. Otherwise, planned instruments offer data of good resolution and frequency.

Vegetation type and cover

Present-day operational satellite imagery from visible / near infra-red channels offers good resolution and frequency, and marginal accuracy. Research instruments, such as MODIS, offer considerably improved accuracy.

Clouds

Surface stations measure cloud cover and cloud base with a temporal resolution and accuracy that is acceptable but a horizontal resolution that is marginal in some areas and missing over most of the Earth.

Satellite instruments offer a wealth of information on cloud. Infra-red imagers and sounders can provide information on cloud cover and cloud-top height of good horizontal and temporal resolution and good/acceptable accuracy. Microwave imagers and sounders offer information on cloud liquid water of good horizontal resolution and acceptable temporal resolution, with an accuracy that is probably acceptable (though validation is difficult).

At present the primary problem is not with the cloud observations themselves but with their assimilation, arising from weaknesses in data assimilation methods and in the parameterisation of clouds and other aspects of the hydrological cycle within NWP models. Substantial improvements in these areas will be needed in order to make more use of the available observations over the next decade.

Current and planned visible/infra-red imagers offer some information on cloud drop-size at cloud top. Active microwave instruments are required to give more information on the 3D distribution of cloud water/ice amounts and cloud-drop size; research instruments are planned.

Precipitation

Surface stations measure accumulated precipitation with a temporal resolution and accuracy that is acceptable but a horizontal resolution that is marginal in some areas and missing over most of the Earth. Ground-based radars measure instantaneous precipitation with good horizontal and temporal resolution and acceptable accuracy, but over a few land areas only.

Microwave imagers and sounders offer information on precipitation of marginal horizontal and temporal resolution, and acceptable/marginal accuracy (though validation is difficult). Satellite-borne rain radars, together with plans for constellations of microwave imagers, offer the potential for improved observations.

Ozone

Developments are under way to add ozone as a new NWP model variable, primarily to allow ozone observations to be used to provide information on wind. In addition, more accurate model ozone fields will improve model radiation calculations and the assimilation of infra-red temperature sounding data. The accuracy of total column ozone obtained from satellite instruments is acceptable and will be improved with the launch of high resolution infra-red sounders and more accurate solar backscatter instruments. However, to maintain realistic vertical distributions of ozone in NWP models, some observations of ozone profiles are also needed at lower horizontal and temporal resolution.

Wave height, direction and period

Ships and buoys provide observations of acceptable frequency and acceptable/marginal accuracy. Coverage is marginal or absent over large areas of the Earth.

Altimeters on polar satellites provide information on significant wave height with global coverage and good accuracy. However, horizontal/temporal coverage is marginal. Information on the 2D wave spectrum is provided by SAR instruments with good accuracy but marginal horizontal/temporal resolution. Moreover, future continuity of satellite coverage is not assured.

3D aerosol

Operational visible / near infra-red satellite imagery is used to provide estimates of total column amounts over the ocean with good horizontal resolution and acceptable temporal resolution but marginal accuracy. Advanced imagers such as MODIS are expected to improve accuracy for total column amounts and to provide information on aerosol particle size and type. However, retrieved quantities will be of column totals and means only. Lidar measurements will be required to provide vertically resolved information. Research demonstrations of lidars are planned.

3D wind – vertical component

No present or planned capability. Research required on indirect observation via sequences of geostationary infra-red imagery.

Aerodynamic roughness length

No present or planned capability.

Additional observations for model validation

Outgoing longwave and shortwave radiation fluxes can be estimated, with varying degrees of accuracy, from several broadband or multi-spectral infra-red and visible satellite radiometers designed primarily for other purposes. Specialised instruments designed to measure accurately some component(s) of the Earth's radiation budget include CERES on TRMM, TERRA and Aqua, and GERB on MSG. Horizontal resolution is good. Accuracy is acceptable and depends on the accuracy of the absolute calibration and of the radiance to flux conversions.

Advanced infra-red sounders (e.g. AIRS, IASI, CrIS), providing complete or near-complete spectral coverage of the thermal infra-red at high spectral resolution, should offer the opportunity to monitor the infra-red spectrum of surface emissivity with good horizontal resolution and accuracy, although further research is required.

Surface albedo can be estimated from shortwave broadband or multi-spectral radiometer measurements with good horizontal resolution. Clouds, aerosols and atmospheric gases affect the accuracy achievable, which is currently marginal/acceptable but should become good as progress is made in interpreting data from high-resolution, multi-spectral instruments.

Additional observations for seasonal and inter-annual forecasting

A full assessment of the observational data requirements for seasonal and inter-annual forecasting, and the extent to which they are met by present and planned observing systems is given in [8]. We summarise here the key aspects.

Many of the variables important to the accuracy of the seasonal to inter-annual forecasts are the same as for global NWP. However, oceanic variables (e.g. sea surface temperature, subsurface ocean temperature and salinity profiles, ocean surface topography, as well as wind-stress over the oceans) play a major role in the process of forecasting the seasonal variability of weather using coupled models. In addition, variations in some land and atmosphere variables assume greater importance in seasonal forecasting. Examples are: snow and ice cover, snow water-equivalent depth, soil moisture, vegetation cover and type, and atmospheric liquid water and cloudiness.

Seasonal and inter-annual forecasts:

- have benefited substantially from the input of sub-surface ocean measurements in the tropics (e.g. from the TOGA buoys), and require continued sampling of temperature and salinity profiles on an operational basis,
- will benefit from improved accuracy of sea surface temperature measurement in the tropics,
- would benefit from the use of available satellite data on vegetation type and cover (instead of climatology), and on wind stress,
- would benefit from continued topography measurements by altimetry, and by improved knowledge of the geoid (leading to sea-surface heights interpretable in absolute terms rather than, as at present, anomalies only).

In addition to those variables listed in sub-sections above, observations of the following variables are likely to be improved through planned observing systems:

- upper oceanic profiles of temperature and salinity, through new in situ observing systems (e.g. ARGO),
- ocean surface topography, via satellite altimeters, although continuity of missions is not yet assured.

4.2 **Contributions from EPS and MSG**

Satellites of the EPS and MSG series form part of the planned satellite component of the Global Observing System and, as such, their contributions to meeting observational data requirements has already been outlined in Section 4.1. In this section, we described in more detail the specific contributions of the EPS and MSG systems.

3D wind field (horizontal component)

Satellite atmospheric motion vectors (AMVs) from present geostationary satellites are already an important part of the observing system for global NWP. AMVs generated from MSG SEVIRI imagery are expected to be improved in terms of coverage, spatial and temporal resolution, and accuracy of both wind vectors and height assignment, as a result of SEVIRI's improved spatial resolution, image frequency and spectral information. Tracking of features in ozone imagery may also provide new wind information in the lower stratosphere.

At present there is no AMV coverage in polar regions. AVHRR on METOP offers the possibility of some coverage using overlapping imagery from successive orbits, but this technique requires more research.

AMVs are valuable because they offer some wind information in areas of the world where there would otherwise be none. However, AMVs are only available where there are suitable image features to be tracked, and each AMV is only a single-level observation. MSG will provide significant improvements on current capabilities but these observations will not meet users' needs for observations of complete profiles of the horizontal wind.

Sea surface wind

ASCAT on METOP will provide information on sea surface wind speed and direction. It will continue the type and quality of winds provided by the scatterometers on the ERS satellites and, through its double-sided swath, will improve the coverage / temporal resolution. ASCAT will also provide information on surface wind stress required for seasonal and inter-annual forecasting.

Surface pressure

Theoretical studies of the information content of radio occultation data show that they contain some information on surface pressure. If this is confirmed by more detailed studies, then GRAS on METOP can be expected to make a contribution here.

3D temperature field

METOP, as part of the NOAA/EUMETSAT joint system of operational polar satellites, will continue to provide information on temperature of present-day quality through data from AMSU-A and HIRS. These instruments currently make a major contribution to the Global Observing System. In particular, the recent introduction of AMSU-A has improved coverage in cloudy areas and has thus led to substantial improvements in global NWP performance. However, the vertical resolution of these instruments is fundamentally limited and does not approach users' maximum requirement. The innovation of IASI on METOP will address this limitation by improving the vertical resolution of temperature information, at least in cloud-free areas.

The GRAS instrument on METOP will provide temperature information of high accuracy and vertical resolution in the stratosphere and upper troposphere (helping to improve analyses around the tropopause). Its information will thus be complementary to that provided by the passive sounding instruments on METOP.

The SEVIRI imager on MSG has only a limited temperature sounding capability, which is expected to contribute useful semi-quantitative stability products for nowcasting but not contribute significantly to precision temperature sounding for NWP.

3D humidity field

The passive sounding instruments on METOP – HIRS, AMSU-A and MHS – all provide information on humidity to continue the capabilities of present-day NOAA instruments. As with temperature, their vertical resolution is currently marginal. IASI will address this limitation with improved vertical resolution on humidity, at least in cloud-free areas.

GRAS will provide humidity information of high vertical resolution in the lower troposphere.

The SEVIRI imager on MSG has a humidity sounding capability comparable to HIRS, but at higher spatial and temporal resolution. As already demonstrated with similar capabilities on GOES, SEVIRI will help to enhance coverage of humidity observations in some regions; its frequent measurements will create more opportunities for finding cloud-free areas. Although primarily designed to support nowcasting, SEVIRI's humidity sounding capability may prove valuable in global NWP, when used via advanced data assimilation techniques.

Sea surface temperature

AVHRR on NOAA satellites is currently a primary source of sea surface temperature (SST) information for global NWP, and this capability will be continued by AVHRR on METOP.

SEVIRI will also provide SST information, and at high temporal resolution. This will increase opportunities for finding cloud-free areas, and also contribute to the requirement of seasonal/inter-annual forecasting for observations of the diurnal cycle of SST.

Sea-ice

METOP instruments AMSU-A, MHS and ASCAT will provide information on sea-ice to complement the main source of satellite information from current and future USA satellites (SSM/I and SSMIS on DMSP, microwave imagers on NPOESS).

Snow

AVHRR on METOP will provide information on snow cover (but not on its equivalent water content) in the day-time in cloud-free areas. The microwave instruments on METOP offer the potential for some information on snow water content, but data interpretation is difficult and microwave imagers on USA satellites should provide superior information.

Land and sea-ice surface skin temperature

AVHRR, HIRS, IASI and AMSU-A on METOP and SEVIRI on MSG will provide information on these variables, although retrieval accuracy is affected by cloud detection problems and surface emissivity uncertainties, and interpretation is difficult because of the heterogeneous nature of the emitting surface for many surface types.

Vegetation type and cover

AVHRR will provide the capability to continue provision of current products, with good resolution and frequency, and marginal accuracy. However, it is likely that products from more advanced instruments, such as MODIS, will be preferred. SEVIRI may offer complementary information, primarily via its high temporal resolution and hence increased opportunities for finding cloud-free areas.

Clouds

HIRS, AMSU-A, MHS and IASI on METOP and SEVIRI and GERB on MSG offer a wealth of information on cloud. The infra-red imagers and sounders can provide information on cloud cover and cloud-top height, and the microwave sounders information on cloud liquid water. The infra-red imagers and sounders also offer some information on cloud drop-size at cloud top.

Precipitation

The microwave sounders on METOP – AMSU-A and MHS - offer some information on precipitation. SEVIRI offers less direct information, through its ability to monitor high, cold cloud, which is often strongly correlated with precipitation at the surface.

Ozone

IASI and GOME will provide information on ozone - both total column ozone and some information on the vertical profile. HIRS and SEVIRI will offer total column information of lower accuracy. The ozone channel on SEVIRI is expected to be more useful for providing dynamical information (through tracking features in the ozone field) than for ozone information per se.

Aerosol

AVHRR on METOP will continue current (limited) capabilities to provide estimates of total column aerosol amounts over the ocean, and SEVIRI will have similar capabilities but with increased temporal resolution.

Additional observations for model validation

GERB and SEVIRI on METOP will provide new capabilities for measuring the diurnal cycle of top-of-the-atmosphere outgoing longwave and shortwave radiation, and also surface albedo. IASI will provide improved information on the infra-red surface emissivity spectrum.

4.3 Improvements in observations required for critical improvements in global NWP performance

This section summarises key differences between user requirements and capabilities of present/planned observing systems (including MSG and EPS systems), where significant improvements in observing capabilities could result in substantial performance improvements in global NWP.

It is stressed that user requirements in section 3.4 have been stated “technology-free”; it is expected that they will be met by a composite observing system comprising both space-based and ground-based components. Efforts should be made to define the best compromise between the two components, particularly where the long-term capabilities of either component are fundamentally limited.

Observations of the wind 3D field at all levels

Although current satellite winds are very useful and the improvements in coverage and quality expected with MSG will be important, observations of the wind field will still represent a major limiting factor on the progress in global NWP. Observations of the 3D temperature field contribute to analysis of the wind field, but they cannot improve the analysis of important, unbalanced components of the flow. Global wind profile information is required.

3D temperature observations of adequate vertical resolution in cloudy areas

AMSU-A-class instruments provide excellent coverage, particular in important cloudy areas, but their vertical resolution is fundamentally limited. IASI-class instruments will substantially improve vertical resolution, but they will not be able to provide temperature information below cloud-top in heavily clouded areas (which are often the most meteorologically active). GRAS will provide complementary “all-weather” information in the upper troposphere but with limited coverage and horizontal resolution. Therefore, in the METOP/NPOESS era, there will still be a deficiency in the provision of temperature (and wind) information for the lower troposphere in heavily clouded areas.

Precipitation

Precipitation is not well observed except in a few land regions covered by ground-based radar networks. Satellite systems are deficient: in accuracy, because of the indirect link between the radiances measured and the surface precipitation; in temporal resolution from polar orbiters, because of the transient nature of precipitating systems; and in horizontal resolution, because of the small scale size of precipitating cloud cells.

Soil moisture

Current and planned microwave instruments offer information on “surface wetness” only. Microwave imagery at lower frequency would offer greater surface penetration, although both the science and the technology of capabilities in this area remain to be demonstrated.

Surface pressure

Surface pressure is a primary analysis variable for global NWP, but there are no plans to measure surface pressure from space directly. This deficiency is currently addressed using a sparse network of surface ships/buoys to provide a few direct measurements of surface pressure, together with pressure gradient information from sea-surface wind measurements. However, direct measurement of surface pressure over the ocean would be valuable.

Snow equivalent water content

This is an important variable for accurate forecasts at high latitudes in winter. Passive microwave measurements offer some information but interpretation is difficult. No high quality product has yet been demonstrated, and instrumentation improvements may be needed.

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identified as areas of key deficiency, in which further improvements in observing capabilities could lead to substantial improvements in global NWP performance:

- observations of the wind 3D field at all levels,
- observations of the 3D temperature field of adequate vertical resolution in cloudy areas,
- precipitation – accuracy, and horizontal and temporal resolution,
- soil moisture,
- surface pressure,
- snow equivalent water content.

Appendix A						
Observation requirements for global NWP			Version dated: 4 October 2001			
Observable (direct or proxy)	**Parameter**	**Accuracy (Threshold/ maximum)**	**dx (Threshold/ maximum)**	**dz (Threshold/ maximum)**	**dt (Threshold/ maximum)**	**delay (Threshold/ maximum)**
Global NWP						
analysed now						
	3D wind, horizontal	8 / 1 m/s	500 / 50 km	3 / 0.5 km	24 / 1 h	4 / 1 h
	3D temperature	3 / 0.5 K	500 / 50 km	3 / 0.5 km	24 / 1 h	4 / 1 h
	3D humidity	20 / 5 %	250 / 50 km	3 / 0.5 km	12 / 1 h	4 / 1 h
	humidity - total column	5 / 1 Kg/m^2	250 / 50 km		12 / 1 h	4 / 1 h
	surface pressure	2 / 0.5 hPa	250 / 50 km		12 / 1 h	4 / 1 h
	surface wind	5 / 0.5 m/s	250 / 50 km		12 / 1 h	4 / 1 h
	surface air temperature	2 / 0.5 K	250 / 50 km		12 / 1 h	4 / 1 h
	surface air humidity	15 / 5 %	250 / 50 km		12 / 1 h	4 / 1 h
	sea surface temperature	2 / 0.5 K	250 / 15 km		120 / 3 h	120 / 3 h
	sea ice cover	50 / 5 %	250 / 15 km		120 / 24 h	120 / 3 h
	snow cover	50 / 10 %	250 / 15 km		120 / 3 h	120 / 3 h
	soil moisture	20 / 5 g/Kg	250 / 15 km		120 / 24 h	120 / 3 h
	3D ozone	20 / 5 %	250 / 50 km	10 / 1 km	12 / 1 h	4 / 1 h
	ozone - total column	20 / 5 DU	250 / 50 km		12 / 1 h	4 / 1 h
	significant wave height	0.5 / 0.25 m	250 / 50 km		12 / 1 h	4 / 1 h
	wave direction	20 / 10 deg	250 / 50 km		12 / 1 h	4 / 1 h
	wave period	1 / 0.5 s	250 / 50 km		12 / 1 h	4 / 1 h
to be analysed - medium term						
	cloud cover	20 / 5 %	250 / 50 km		12 / 1 h	4 / 1 h
	cloud top height	1 / 0.2 km	250 / 50 km		12 / 1 h	4 / 1 h
	cloud base height	1 / 0.2 km	250 / 50 km		12 / 1 h	4 / 1 h
	3D cloud water/ice	50 / 5 %	250 / 50 km	5 / 0.2 km	12 / 1 h	4 / 1 h
	cloud water/ice - total column	50 / 10 g /m^2	250 / 50 km		12 / 1 h	4 / 1 h
	precipitation	1 / 0.1 mm/h	100 / 50 km		12 / 1 h	4 / 1 h
	land surface temperature	4 / 0.5 K	250 / 15 km		12 / 1 h	4 / 1 h
	sea-ice surface temperature	20 / 5 %	500 / 50 km	10 / 1 km	12 / 1 h	4 / 1 h
	snow water equivalent	4 / 0.5 K	250 / 15 km		12 / 1 h	4 / 1 h
	vegetation index and/or LAI	20 / 5 mm	250 / 15 km		12 / 1 h	4 / 1 h
to be analysed - long-term						
	sea-ice thickness	1 / 0.5 m	250 / 50 km		720 / 24 h	4 / 1 h
	3D aerosol	50 / 10 %	250 / 50 km	3 / 0.2 km	180 / 1 h	180 / 1 h
	aerosol - total column	50 / 10 %	250 / 50 km		180 / 1 h	180 / 1 h
	cloud drop size (cloud-top)	2 / 0.5 µm	250 / 50 km		12 / 1 h	4 / 1 h
	3D cloud drop size 3D	2 / 0.5 mm	250 / 50 km	3 / 0.2 km	12 / 1 h	4 / 1 h
	3D wind, vertical component	5 / 1 cm/s	500 / 50 km	3 / 0.5 km	12 / 1 h	4 / 1 h
	aerodynamic roughness length	tbd	tbd		tbd	tbd
Additional variable required for model validation						
	outgoing LW radiation	20 / 5 W m^{-2}	250 / 50 km		6 / 1 h	720 / 24 h
	reflected SW radiation	20 / 5 W m^{-2}	250 / 50 km		6 / 1 h	720 / 24 h
	surface emissivity spectrum	5 / 1%	250 / 15 km		720 / 24 h	720 / 24 h
	albedo	5 / 1%	250 / 15 km		720 / 24 h	720 / 24 h
	accumulated precipitation	5 / 0.5 mm/d	250 / 50 km		180 / 24 h	180 / 24 h
Extneded requirements or additional variables to be analysed for seasonal and inter-annual forecasting						
	sea surface temperature	1 / 0.1 K	500 / 50 km		120 / 24 h	120 / 24 h
	vegetation type	18 / 9 classes	250 / 15 km		720 / 180 h	720 / 24 h
	fraction of photosynthetically active radiation	10 / 5 %	250 / 15 km		720 / 180 h	720 / 24 h
	ocean topography	4 / 1 cm	100 / 25 km		360 / 120 h	360 / 48 h
	ocean salinity	0.3 / 0.1 psu	250 / 50 km		720 / 360 h	720 / 360 h
	ocean chlorophyll	0.5 / 0.1 mg/m^3	100 / 25 km		72 / 24 h	72 / 24 h
	ocean suspended sediment	tbd	500 / 50 km		180 / 24 h	1440 / 24 h
	ocean yellow substance	tbd	500 / 50 km		180 / 24 h	1440 / 24 h