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REQUIREMENTS FOR OBSERVATIONS FOR REGIONAL NWP

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Position Paper – Requirements of observations for Regional NWP

Nils Gustafsson, SMHI, Massimo Capaldo, CNMCA,
Bartolomé Orfila Estrada, INM and Jean Quiby, MeteoSwiss

EXECUTIVE SUMMARY

Regional Numerical Weather Prediction (NWP) systems are used operationally by almost all national weather services in Europe for short-range weather forecasting (up to 3 days) and for regional target areas. The regional NWP is either carried out by Limited Area Models, applied over specific regional integration areas and with lateral boundary conditions originating from global NWP models, or by global NWP models, possibly with an increased horizontal resolution in the target area. Due to their complexity, development efforts have been co-ordinated over the years in joint projects. This paper formulates requirements of observations for Regional NWP in a medium term perspective (2001-2015) as well as in a longer perspective (2015-2025).

Improvements in products from regional NWP

There is, first of all, a general demand for more reliable and accurate analyses and forecasts for the main meteorological variables as well as for an increased focus on the warning and forecasting of low probability extreme weather events and for probabilistic forecasting. There are strong requirements in Europe for improved forecasting of rapid and severe phenomena coming from Atlantic and the Mediterranean Sea and for improved forecasting of clouds, precipitation type, precipitation amount, low level winds and fog. More recently strong interest has grown for forecasting of concentrations of low and high level ozone, as well as air pollution and air quality incidents, electric discharges and aerosols.

Frequency and timeliness of operational forecast production

It is expected that regional high resolution NWP models will all have dedicated data assimilation procedures, most of them based on 4D-Var or nudging schemes. The very high resolution expected for the NWP regional models, the requirements for forecasting extreme weather events and the forecasting of phenomena with reduced space and time scales suggest the need of what might be called a *forecasting engine* to be triggered on demand both to assimilate additional observations and to produce forecasts better tailored to specific users.

Requirement on Regional NWP products for nowcasting purposes.

Nowcasting (NWC) and Very Short Range Forecasting (VSRF) are concerned with the weather monitoring and forecasting of weather for the shortest time scales, ranging from 0 to 6 hours. NWC and VSRF methods are expected to shift from the traditional specialised techniques to an utilisation of more general NWP output

products (Golding et al., 2001). This will be made possible through access to future more powerful computers, through the application of mesoscale NWP models at grid resolutions of the order of 1 km or less and through application of mesoscale assimilation techniques. The expected shift in the NWC and VSRF techniques toward NWP modelling will certainly also involve a shift in the need of observed data from observation of the particular phenomena to be forecasted to observation of variables directly or approximately related to the model state variables.

Improvements in regional NWP systems

The background scenario for development of Regional NWP systems during the period 2001 – 2015 foresees the steady increase of computer power, the operational availability of global models with a 10-km mesh run, regional models with mesh sizes of 1 km concentrated on high impact weather and regional ensemble systems providing an estimate of the uncertainty of short range forecasts. More advanced physical parameterisation schemes and more advanced data assimilation system will simultaneously be introduced step by step. The new data assimilation schemes will improve the efficiency of using remote sensing observations from radar and satellites.

Current status and medium term development of regional NWP (2001-2015)

The review of the ideas and plans for the development of regional NWP systems during the period 2001 – 2015 provided a rather homogeneous view (vision) on the expected operational Regional NWP systems to be used by the end of the period. Non-hydrostatic models will gradually be replacing current systems and the computing power will probably allow operational application of these models at a model grid resolution of the order of 1 km and with around 100 levels in the vertical. These non-hydrostatic models will include several new model variables, in particular with regard to a more detailed description of processes related to clouds and precipitations. It seems also reasonable to believe that 4-dimensional variational data assimilation schemes (4D-Var) will be run operationally and will include the assimilation of several cloud variables by year 2015. The data assimilation schemes are expected to be able to utilise more remote sensing information, in particular satellite sounding data. Satellite and radar image information will gradually become more important for the direct use of cloudiness and precipitation information, and for the indirect determination of wind information via 4D-Var. Surface variable assimilation schemes are also likely to become more developed, and possibly also directly linked to the atmospheric assimilation. We also expect to introduce a more probabilistic approach to regional operational NWP during the period, for example based on ensemble forecasting techniques.

However, looking back to the achieved development during 1985–2000, the development sketched above for the period during 2001–2015 may seem quite optimistic. Therefore, it may be reasonable to believe that delays will occur and that the operational introduction of some of the new model system components will occur later during 2015-2025.

Longer term view (2015-2025)

Non-hydrostatic forecast models will be applied operationally with a horizontal grid resolution of 0.2-0.3 km and with 100-200 vertical levels. The models will include several new 3-dimensional variables (e.g. cloud ice particle spectra, precipitation water, ozone, aerosols and possibly several further chemical constitutes).

Regional 4D-Var data assimilation schemes will be further developed, in particular to be in line with the modelling emphasis on moist processes and on environmental and chemical model variables. The utilisation of regional NWP models for nowcasting and very short range forecasting, will put strong demands on the dynamical-physical consistency of the data assimilation. It is furthermore likely that also the data assimilation for Regional NWP will develop in a more probabilistic direction, with the emphasis on data assimilation for extreme weather events and an increased interest on targeted observations also for operational weather forecasting.

There will probably be an increase in coupled models for the total earth system also for Regional NWP. Candidates for such models to be two-way coupled to the atmospheric models are ocean wave, ocean storm-surge, ocean mixed layer/deep ocean models, hydrological models, air pollution dispersion and air chemistry models. These models will also need data assimilation schemes, possibly coupled to the atmospheric data assimilation.

Requirements and use of observations

Operational regional forecast models will be applied with a horizontal grid distance of the order of 1 km (or less) in 2015-2025. This means that atmospheric waves of horizontal scales of 3 km will be correctly resolved by these models. Thus, optimally, we would require a horizontal density of observations corresponding to this horizontally resolved scale. However, considerations of scales of mesoscale phenomena and mesoscale forecast error statistics has motivated the selection of a breakthrough level for horizontal resolution of 30 km for vertical profiles of wind, humidity and temperature. Furthermore it is considered very useful if the density of upper-air data over Europe would be extended to the Mediterranean, the Atlantic and the Arctic, areas for which observations are crucial for regional short range forecasting over Europe. This has defined the threshold level of 200 km for the horizontal resolution of vertical profiles.

For regional numerical weather prediction, the area of influence of initial data is generally more restricted than for global numerical weather prediction, where the influence area, by definition, is global. Considering the group velocity for the horizontal dispersion of forecast errors, the area of influence for regional +24 h forecasts for Europe includes the North Atlantic and the Arctic to the west and to the north and the Mediterranean and North Africa to the south.

Many mesoscale phenomena are strongly forced from in-homogeneities and sharp gradients in the lower boundary conditions. It is therefore considered that a breakthrough level of 10 km and an optimum level of 1 km for the horizontal resolution of surface variables, such as sea and lake surface temperature, soil temperature and soil moisture, is adequate.

Operational regional forecast models will be applied with 100-200 vertical levels, and with a vertical grid distance of 10 – 50 meters in the lower part of the atmosphere. This would require, optimally, a vertical resolution of 100 meter for the vertical profile observations. With similar arguments as given for the horizontal scales above, we may argue for a breakthrough level of 1 km and a threshold level of 3 km for the vertical resolution of vertical profile measurements.

Requirements for the frequency of the observations are influenced by (1) the time-scale of the phenomena we want to forecast, (2) the frequency of regional forecast production and (3) the time-windows of four dimensional data assimilation. The time-scales of the fastest of the phenomena we want to forecast are of the order of one hour or a few hours. From this we may consider the optimum for the time resolution of the observations to be 0.5 hours in general. For the fast variables, an appropriate breakthrough time resolution level should be to have at least 1 observation for each standard observation hour, thus every 3 hour.

Targeted observations

Strongly related to the requirement of running forecasts on demand is the possibility to get access to observations on demand. Becoming able to tell in advance where and when observations are needed, it is considered that targeted observations will become a standard tool also for operational regional NWP, and this might also contribute to make the strong requirements on spatial resolution and time frequency more feasible.

Priorities

The basic dynamic variables of the NWP models will remain the most important to be observed. Thus, we will require surface pressure over sea and profiles of horizontal wind, temperature and water vapour everywhere inside, outside and below clouds with highest priority. Due to the increased importance of moist model processes, very high priority should also be given to surface precipitation intensity. Very high priority should also be given to soil moisture, snow coverage, sea/lake surface temperatures, sea/lake ice coverage and profiles of aerosols. Some of these additional variables are required with a lower frequency in time.

Contributions from present and planned satellite observing systems

Present and planned operational satellite observing systems will give substantial contributions to meet several of the observation requirements for regional NWP in 2015-2025. With regard to the 3-dimensional horizontal wind field, of very high priority, planned operational imaging instruments, such as SEVIRI on MSG, will increase the data availability because of the more frequent repeat cycles of imaging and because of the improved horizontal resolution. Scatterometers, for example the Advanced Scatterometer (ASCAT) on EPS will provide significantly improved information on the wind field near the sea surface. Doppler lidars deployed aboard polar research satellites will provide additional experimental wind observations with improved vertical resolution.

Current polar satellite instruments (HIRS and AMSU) provide the basic information to retrieve temperature and humidity profiles in clear and cloudy (non-precipitating) skies, albeit with an insufficient vertical resolution. Advanced radiometers or interferometers are planned for future operational satellites. They will be capable of improving spatial resolution and accuracy, at least in cloud-free areas and above clouds. As an example, IASI on EPS will provide temperature profiles at roughly 25 km horizontal resolution, having a 1.5 K accuracy and a 1 km vertical resolution in the lower troposphere. A 1 km vertical resolution is believed to be achievable by radio-occultation techniques as well for temperature profiles in the upper troposphere and stratosphere, although this is less significant from the regional NWP point of view.

Cloud cover and cloud-top height can be inferred from infrared imagers and sounders providing good horizontal and temporal resolution. SEVIRI in particular should be close to the optimum threshold level for horizontal resolution and accuracy of these variables. Information on cloud liquid water and cloud ice can be retrieved from microwave imagers and sounders, offering good horizontal resolution and acceptable temporal resolution. At present, the primary problem is not so much with the cloud related observations themselves, however, but rather with their assimilation into regional NWP models.

The surface parameter currently better retrievable from satellite measurements is the sea and lake surface temperature available with extensive coverage everywhere except in persistently cloudy areas. Skin sea-surface temperature is inferred with acceptable horizontal resolution from polar satellites, while geostationary satellites complement information with better temporal resolution. Visible/Infrared/Microwave imagery provide information on snow cover in day time and clear sky. Snow water content is experimentally retrieved by microwave imagery.

Much attention has been devoted in the recent NWP development to ozone. Ozone profile observations are known to be very beneficial both for estimating winds and for improving model radiation calculations and therefore also for assimilation of infrared 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 infrared sounders and more accurate solar back-scatter instruments.

Improvements in observations needed for critical improvements in regional NWP performance

We have discussed and established prioritised observation requirements for regional NWP during the period 2015-2025. In particular, we have arrived at breakthrough levels with regard to the spatial and temporal resolutions of variables considered of very high priority to achieve a critical improvement of regional NWP performance. We have also reviewed expected contributions of present and planned satellite observations to meet these requirements. Considering these observation requirements and taking the expected contributions from present and planned observing systems into account, we may briefly summarise needs for further extensions and improvements of the observing systems in order to achieve the required improvements of regional NWP performance:

- There is a clear and very high priority need to get access to more wind profile measurements, in particular over ocean/sea areas and over the Arctic. Wind profile measurements will be provided over land from radiosonde stations in a sparse network, from doppler weather radars and from aircraft (AMDAR) reports in the vicinity of airports. Over ocean/sea and the Arctic areas, only single (or a few) level wind observations will be available, for example from Atmospheric Motion Vectors (AMV), from aircraft reports and from satellite scatterometer data close to the sea surface only. From a theoretical point of view, geostrophic adjustment theory tells us that wind profile information becomes relatively more important for the future regional NWP models with a horizontal resolution of the order of 1 km, as compared to the present situation with regional models having a more modest horizontal resolutions.

- There is also a very high priority need for improved temperature and humidity profile measurements inside and below clouds. Planned infrared satellite sounding instruments like IASI are expected to provide the needed resolution and accuracy in cloud-free areas and above clouds, while the microwave sounders do not meet the required breakthrough levels for vertical resolution and accuracy to achieve the critical improvement of regional NWP performance.

- There is a high priority need for surface pressure observations over the sea with a horizontal resolution of 30 km and with a temporal resolution of 3 hours. On one hand, it is unclear whether such observations are physically feasible with satellite techniques or whether one has to rely on in situ measurements from ships and buoys. On the other hand, we may again refer to geostrophic adjustment theory, the direct measurement of surface pressure may be of less relative importance for the smaller horizontal scales of regional NWP models since, for example, scatterometer data will provide us with high resolution low level wind data.

- There is a very high priority need for improved precipitation intensity observations with a spatial resolution of 10 km and with a temporal resolution of 1 h, in particular for initialisation of mesoscale regional NWP models to be applied operationally for nowcasting purposes.

- There is need for soil moisture observations with a horizontal resolution of 10 km and with a temporal resolution of 6 h.

- There is a need for aerosole profile observations with a horizontal resolution of 30 km, with a vertical resolution of 2 km and with a temporal resolution of 6 h.

1. Introduction

1.1 The scope and the structure of this paper

The purpose of this position paper is to formulate requirements of observations for Regional Numerical Weather Prediction (NWP) in a medium term perspective (2001-2015) and in a longer perspective (2015-2025). The medium term requirements are based on a review of existing plans and on the assumption that current research efforts will result in operational implementation of new Regional NWP forecasting systems. The longer perspective requirements are more tentative, since they have been formulated by projection of trends from the medium term perspective.

The historical development of Regional NWP in Europe is briefly reviewed in section 1 of this paper. Plans, ideas and requirements for the future development of Regional NWP were collected by distribution of a questionnaire. The requirements on the development of regional NWP, formulated mainly from the users point of view are summarised in section 2 of this paper. Then, a vision (or scenarios) for the medium term development of Regional NWP is first presented in section 3. This vision includes development of regional NWP models, regional data assimilation and additional (coupled) models, as well as requirements and use of observations. The projected long perspective vision is also presented in section 3. The contributions from present and planned satellite observing systems to meet the observation requirements for regional NWP are reviewed in section 4 together with a summary of observations required for critical improvements in regional NWP performance.

1.2 Development of Regional NWP in Europe

Regional Numerical Weather Prediction (NWP) is applied for short-range weather forecasting (up to 3 days) and for regional target areas. Regional NWP may be carried out by Limited Area Models, applied over specific regional integration areas and with lateral boundary conditions originating from global NWP models. Regional NWP may also be applied with global NWP models, possibly with an increased horizontal resolution in the target area for the short range forecasting. Regional NWP models in Europe are currently applied with a horizontal resolution in the range 5 – 50 km and with 20 – 50 levels in the vertical.

Most regional NWP systems utilise current observations to create initial data through application of data assimilation. Due to operational requirements on the availability of short-range forecasts, regional NWP systems are generally applied with an observation data cut-off time of less than 2 hours. Some regional NWP systems are applied operationally with initial data taken from global NWP models. The main purpose of the regional NWP model is then to add details to the global model providing initial and lateral boundary data, through improved model resolution and, in particular, through details in the lower surface boundary conditions like orography.

Traditionally, regional NWP systems have been developed, maintained and applied operationally by national weather services. During almost 50 years of NWP development we have seen an increased complexity in such regional NWP systems. This has caused the weather services in Europe to realise the usefulness of co-ordinating their development efforts in joint projects. During the last 15 years, four modelling development groups have emerged from this co-ordinating process among the national weather services in Europe:

1. The HIRLAM group with participation of the weather services of the Nordic countries, Ireland, the Netherlands and Spain.

2. The ALADIN group with participation of the weather services of Austria, Belgium, Bulgaria, Croatia, Czech Republic, France, Hungary, Poland, Portugal, Romania, Slovakia and Slovenia.

3. The COSMO group with participation of the weather services of Germany, Greece, Italy and Switzerland.

4. The UK Met Office modelling group.

The development of regional short-range NWP in Europe is further co-ordinated within the EUMETNET C-SRNWP (Short-range numerical weather prediction) Programme, with participation of the weather services belonging to any of the four modelling groups.

The co-ordination of Regional NWP developments is not only occurring in Europe. Universities, atmospheric research institutes and the National Weather Service in the USA have embarked on the development of a next-generation regional Weather Research and Forecast (WRF) model, see [2] and http://wrf-model.org. The WRF co-operation includes a complete and advanced 4-dimensional variational (4D-Var) data assimilation. There are plans within the National Weather Service in the USA to apply this community model system also for local-scale NWP at Weather Forecast Offices [3].

1.3 A questionnaire on the development of Regional NWP

Regional NWP systems are applied operationally by most national weather services in Europe. The forecasting problems and the corresponding user demands are naturally different in the various European regions and so are the plans and the visions of the modelling groups. Plans for the development of regional NWP, if they exist, only cover the nearest 5-year period 2001 – 2005. This motivated us to distribute a Questionnaire on the development of regional NWP [1]. This questionnaire was distributed to EUMETSAT member states via the participants in the EUMETSAT Applications Expert Groups (AEG) on Numerical Weather Prediction (NWP) and Nowcasting (NWC), as well as to all the national representatives within the EUMETNET C-SRNWP Programme. A very limited distribution of the questionnaire to modelling groups in USA and Canada was additionally done.

Answers to the questionnaire have been received from the weather services of Canada (Ca), Germany (D), United Kingdom (UK), Spain (ES), Sweden (SE), France (F), the Netherlands (NL), Austria (A), Italy (I) and Switzerland (CH). Some personal comments from Fedor Mesinger, NCEP, have been received in addition. These answers to the questionnaire have formed the basis for the content of this position paper. References to the different answers are included, as appropriate.

Some of questions of the Questionnaire were directed toward the operational producers and users of NWP data and not so much toward the scientific community developing Regional NWP systems. This approach was questioned in some of the answers to the questionnaire:

- It is the models general evolution and their higher resolution (horizontal as well as vertical), together with other improvements that will provide the basis for better forecasts – not the user requirements! (SE)

- Most of your questions are aimed at users of regional NWP, or interaction between users and producers, and thus are not in the centre of my interest as I do not talk much to producers, what they want I mean. They get what they want, if they only make it known and try hard enough!! Thus, some of the questions seem to me too detailed -- that is, not something people plan, and if they do, their plans are not much relevant. (Fedor Mesinger)

2. Improvements in products from regional NWP

2.1 Improvements and extensions requested by users of Regional NWP products.

The first question of the issued questionnaire on development of Regional NWP was mainly directed to the producers and users of regional NWP products concerning their requirements and needs, and not so much toward the NWP model system developers concerning their plans and wishes. This section summarises the stated requests for improvement and extension of regional NWP. There is, first of all, a general demand for more reliable and accurate forecasts. The general meteorological variables, i.e. wind, temperature, humidity and precipitation, remain the main variables that need to be accurately analysed and forecasted on the mesoscale (SE, Ca, NL, etc). There is also a general demand for a slower decrease of the forecast quality as the range increases, in particular for the second and the third day (A). Another general demand is an increased focus on the warning and forecasting of low probability extreme weather events (SE, UK, A) and probabilistic forecasting (SE, UK). Such warnings should be issued for areas also outside the direct national areas of responsibility, e.g. the Atlantic (UK).

With regard to the improvement of the forecasting of particular weather phenomena, the answers to the questionnaire reflected relatively similar requests from the different weather services spread over Europe:

- Improved forecasting of rapid and severe phenomena coming from Atlantic and the Mediterranean Sea (F).
- Improved forecasting of clouds, precipitation type and precipitation amount (SE, F, NL). In particular, improved flooding forecasts related to extreme rainfall and state of ground (e.g. soil moisture and snow cover) forecasts (UK, ES)
- Improved forecast for fog and low cloud (NL), specially stratus forecasts associated with wintertime inversion situations (A, CH)
- Improved forecasting of low level winds (SE), in particular forecasting of detailed wind fields, turbulence (and severe weather) near airports (UK)

- Detailed fog forecast (F), specifically of its temporal and spatial evolution (UK, ES). Freezing fog forecast is requested in the inner part of Spain mainly at the region north of the plateau. (ES).
- Boundary layer phenomena, with pollution applications (F)
- Turbulence and visibility forecasting for aviation (I).
- Improved winds in coastal zones because of importance for storm surges and for the coastal management authorities (NL).

There is a convergence that the general meteorological variables will be computed with a resolution of 1 km (I, NL, CH, A), still higher for some applications like air quality models (I) or some variables like wind (NL)

There is also a general agreement that the frequency of forecast outputs will be significantly enhanced: hourly seems to be the minimum (I, CH), more than hourly is also foreseen (NL).

Some output product needs were particularly stressed for use in Southern Europe:

- Heavy precipitation with an increasing demand of accuracy in spatial and temporal distribution and probability of occurrence. This is critical for the Spanish zones of the Mediterranean area where it would be necessary to distinguish between precipitation from deep convection and from warm clouds, as well as the coexistence of both types of precipitation (ES). Storm activity with the highest spatial and temporal location and probability of occurrence. Hail type and probability of occurrence is a demand common to many Spanish regions. (ES)
- Deep convection organised in clusters or squall lines (thunderstorms) causing significant weather (F). The occurrence of these systems is mainly over South Germany, especially near the Alps (D)
- Precipitation (stratiform, convective) over high complex orography (D, F).

A more detailed discussion on particular regional forecasting problems for the Mediterranean area is included in section 2.2 below.

Other special output product needs were more related to conditions in Northern Europe:

- Icing on high constructions (SE).
- Meso-scale lows over the Western Baltic Sea causing heavy snow fall in the coastal area (D).
- All meteorological variables influencing road conditions, including visibility (NL).

Also with regard to the requested extensions of regional NWP to include new model variables and new output products, the answers to the questionnaire indicated similar needs from the different European regions:

- Chemical and environmental variables need to be added to the dynamical and physical model variables (SE). In particular forecasting of concentrations of low level as well as high level ozone (SE, ES), as well as air pollution and air quality incidents (UK), were mentioned.

- Forecasting of electrical discharge, e.g. thunder, needs to be added (SE).
- Modelling of the 3D distribution of aerosols is needed for the forecasting of visibility, or more generally wave transmission in different electromagnetic frequencies (SE).
- New output products are needed for aviation: cloud parameters (spectrum of droplets, icing conditions in clouds), turbulence conditions, profile of vertical velocity including lee waves, 3D visibility, wake forecasts at airports. (DWD, Ca)
- Forecasting of calm winds lasting several days and wave forecast close to the coast, taking into account interactions between the coast and the sea bottom are widely requested (ES). Frequency of extremes coming from a maritime climatology produced by hindcasting using regional NWP models (ES).
- Increasing demand exists for daily evolution of global solar illumination. (ES)

The large increase in spatial resolution that will be experienced in the future will be very welcome by countries with important mountainous areas, particularly by the Alpine countries because it will become possible to explicitly forecast the weather in the valleys. For a good representation of the main valleys, a resolution of one km is necessary as a characteristic of the Alpine valleys is their narrowness.

2.2 Particular forecasting problems in the Mediterranean area

Since many years the Mediterranean region has been identified as an area subject to relatively frequent developments and deepening of cyclone perturbations. These occur for a number of concurrent reasons. Much literature has been dedicated to describe the main mechanisms. Either the Alpine barrier or other mountain complexes, as well as thermodynamical processes due to the Mediterranean Sea, are capable of triggering the baroclinic conversions. This occurs within the atmospheric flow and makes available the required energy either to create or to enhance meteorological phenomena occurring in the whole Mediterranean basin.

Many past cases of extreme weather events could be highlighted. Typical examples of such cases have been fully studied and reported also recently (e.g. COST 78):

- severe cold air outbreaks which typically occur over the Eastern part of the Mediterranean Sea and more specifically over Southern Balkans and Greece;

- heavy rain events in the Western Mediterranean often affecting many countries during the very same episode (Spain, France, Italy).

The first kind of event is associated with the transit of a fast moving baroclinic wave and a corresponding cold front moving in a North-South direction, the so called "Balkan front". This causes very strong winds, sharp temperature drop (easily up to 10 C) and remarkable temperature gradients (e.g. 10 deg over 50 km). Surface pressure increase associated to the cold air trapped along the slopes of the mountain ridge and a mesoscale pressure ridge is formed along the mountains (pressure rising in excess of 15 hPa within a 12-hour period has been observed). This fast changing surface pressure results in a substantial isallobaric wind component that explains the characteristic gustiness of winds. Persistence of perturbed conditions can cause severe damages both as a result of heavy snowfall causing road blockage as well as dangerous sea conditions over the northern Aegean Sea where wind gusts in excess of 25 m/s are observed.

Heavy rain events, with a few hundreds of mm in a few hours are the phenomena addressed in the second event mentioned above. These may be associated with known phenomena such as Genoa cyclones and other intense synoptic-scale perturbations occurring in the Western Mediterranean, low level jet streams associated with shallow cyclones as well as with warm and humid air layers favouring convective instability.
A typical example may be taken with reference to the Piedmont flood in November 1994. This event lasted four days and produced damaging floods and human losses in the Piedmont region in northern Italy (see picture). Precipitation in excess of 300 mm/24h was reported. However, the severe weather was not limited to Italy but heavy rain was observed in Southern France (95mm/24h) and in Corsica (86 mm/24h) as well as in Catalonia (158 mm/24). The maxima reported over Italy were mainly caused by strong southerly and south-easterly flow ahead of the frontal perturbations subject to up-slope forcing by local orography (the Appenine, the Maritime Alps and the main Alpine barrier) combined with convective instability within the maritime area and reduced stability inland. However, at the same time, the relevant influence over the main atmospheric trough, associated to the Spanish mountain ridges and the Pyrenees, has been identified as the concurrent effect for intensifying the precipitation rate.

2.3 Frequency and timeliness of operational forecast production

It is expected that regional high resolution NWP models will all have dedicated data assimilation procedures, most of them based on 4D-Var techniques or nudging schemes, directly coupled with the models.

Currently limited area models are run 4 times a day with hourly products and dedicated post-processing depending on user applications. However, it seems too conservative to foresee assimilation/forecasting systems based on 3-hourly schedules producing weather parameters and fields on demand in a 20-year perspective. In a more advanced perspective, the very high resolution expected for the NWP regional models and the requirements for forecasting extreme weather events or phenomena with reduced space and time scales suggest the need of what might be called a “forecasting engine”. Such a forecasting engine is to be triggered on demand both to assimilate additional observations significant for the meteorological situation to be monitored and to produce forecasts better tailored to specific users.

2.4 Requirement on Regional NWP products for nowcasting purposes.

Nowcasting (NWC) and Very Short Range Forecasting (VSRF) are concerned with the weather monitoring and forecasting for the shortest time scales, ranging from 0 to 6 hours. The development of NWC and VSRF, including requirements of observations, is the subject of an accompanying position paper (Golding et al., 2001). Traditionally NWC and VSRF have been based on a wide range of forecasting techniques, very often tailored for each specific forecasting problem. For several reasons, one may expect a shift of these NWC and VSRF forecasting techniques from the traditional specialised techniques to an utilisation of more general NWP techniques. This will be possible through the application of mesoscale NWP models at grid resolutions of the order of 1 km or less, through application of mesoscale assimilation techniques and through access to future more powerful computers.

Additional requirements of mesoscale (storm-scale) NWP for NWC and VSRF purposes, on top of the regional scale NWP requirements, are provided by Golding et al. (2001):

- Finer time and space scale winds and humidity;
- Detailed surface forcing;
- Detailed boundary layer winds;
- Detailed height and strength of stable layers;
- Detailed precipitation distribution.

The expected shift in the NWC and VSRF techniques toward NWP modelling will also involve a shift in the need of observations from observation of the particular phenomena to be forecasted to observation of variables directly or approximately related to the model state variables. Furthermore, the NWC and VSRF needs will put stronger requirements on access to more frequent NWP runs (more often than 1/hour) and access to observations with very short time delays to be used for early cutoff (less than 30 minutes) NWP runs.

3. Improvements in regional NWP systems

As a background to a scenario for development of Regional NWP systems during the period 2001 – 2015, we may cite the assumptions of the strategy for NWP developments of the German Weather Service (DWD):

- Moore's law (doubling of computer power every 18 months) is valid for the whole period,
- at the end of the planning period (2015), global models with a 10-km mesh run operationally,
- regional models with mesh sizes of 1 km concentrate on high impact weather,
- regional ensemble systems provide an estimate of the uncertainty of short range forecasts.

Plans for development within all four Regional NWP groups in Europe are in general agreement with these assumptions. Regional non-hydrostatic NWP models with grid resolutions of a few km will gradually be introduced during the period 2001 – 2015. Simultaneously more advanced physical parameterisation schemes and more advanced data assimilation systems will be introduced step by step. The new data assimilation schemes will make it possible to make more efficient use of remote sensing observations from radar and satellites.

3.1 Current status and medium term development of regional NWP

3.1.1 Regional forecast models

Model strategy, dynamics and numerical techniques

Some general dynamical and numerical characteristics of planned Regional NWP models have been extracted from the answers of the Regional NWP questionnaire and entered into the Table below. In addition to the four European modelling groups, the plans for Environment Canada have been introduced in the Table as a non-European reference.

First of all, it should be mentioned that the Regional NWP modelling strategy varies between the different modelling groups. Weather services belonging to the ALADIN, COSMO and UKMO groups have access to "fresh" lateral boundary data from global model runs, integrated prior to the regional model run with data from the same initial time. Due to the availability of fresh lateral boundary data, these weather services generally apply a single regional model run at meso-scale resolution. The weather services in HIRLAM community, on the other hand, only have access to lateral boundary from a (6 hours) "old" global model run. For this reason, these weather services normally apply a chain of nested regional models with decreasing model areas and with improved spatial resolutions in order to compensate for the lack of fresh boundaries.

The plans of Environment Canada for the period 2001-2010 are for a gradual evolution toward a regional-continental model at a resolution of 8-10 km, integrated up to 3 days, four times per day. This model will be used to drive a number of high-resolution LAM windows (resolution of a few km) covering Canada; these could be used to drive still higher-resolution LAMs (order of a few hundreds meters) focusing on regions of high potential for severe weather, in a quasi-automatic manner.

Model group	2001	2005	2010
HIRLAM (SE as an example)	Hydrostatic 44 and 22 km grid 31 levels	Hydrostatic 22 and 11 km grid > 40 levels	Non-hydrostatic 11 and 2.5 km grid > 50 levels
UKMO	Hydrostatic 12 km 38 levels	Non-hydrostatic 3km grid > 70 levels	
COSMO (D as an example)	Non-hydrostatic 7 km grid 35 levels	Non-hydrostatic 2.8 km grid 45 levels	Non-hydrostatic 1 km grid > 50 levels
ALADIN (F as an example)	Hydrostatic 9 km 31 levels		Non-hydrostatic 2-3 km
Environment Canada			Non-Hydrostatic 10, 2 and 0.2 km grid 70 levels

Physical parameterisations

Significant resources will be devoted to the development of improved physical parameterisation schemes during the period 2001–2015. These developments will involve most of the processes covered by parameterisations in models of today. Particular emphasis will be devoted to processes involving moisture, such as cloudiness, fog, haze and the different forms of precipitation. Due to the increased importance of the forcing from the lower boundary condition at the mesoscale, high priority will also be given to the improved description of surface and soil processes.

Taking the gradual decrease of model resolution towards the order of 1 km into account, present implicit parameterisations will be replaced by complex explicit parameterisations for, e.g., convection and condensation (UK, D, Ca). This also means that several new micro-physical cloud variables, in addition to cloud liquid water and cloud ice, have to be included in the model and provided with initial data (for example cloud ice , droplet spectra, aerosol concentration). Closely related to the improved description of cloud parameterisation, improved parameterisations for cloud-radiation-interaction are also planned (D). With a gradual decrease of the model resolution toward the cloud-resolving scale, a few km or less, it will furthermore be necessary to move away from the present 1-dimensional vertical representation for physical processes like radiation and boundary layer turbulence, and to introduce more realistic models with a 3-dimensional perspective.

Improved surface parameterisation schemes are not only needed for the direct improvement of the accuracy of Regional NWP products for their forecasting usage. The new generation of satellite sounders (e.g. IASI, AIRS, MODIS) will provide the most important opportunity for profile information at high horizontal and vertical resolution. In order to use these profile data also over land, more accurate surface parameterisation schemes and more efficient use of surface observations in the data assimilation will be needed for the lower boundary condition of these sounding data [4].

Probabilistic forecasting

As already mentioned above, there are ideas and plans to extend the present deterministic Regional NWP towards probabilistic regional NWP. The intention by several model groups is to develop ensemble prediction system (COSMO, HIRLAM, F) based on multi-model, multi-analyses and multi-lateral-boundary data. There exist also ideas to develop such probabilistic forecasting systems within a joint European framework, either as EU Project or in the frame of the EUMETNET SRNWP Programme. There are also considerations, however, that the probabilistic representation may not necessarily be based on ensembles (UK).

3.1.2 Regional data assimilation

Some characteristics of plans for Regional NWP data assimilation have been extracted from the answers to the Regional NWP questionnaire and entered into the Table below. A majority of the modelling groups have recently made significant investments into the development of new data assimilation schemes based on variational techniques. 3-dimensional versions of these variational assimilation schemes (3D-Var) are now being introduced into operational use, and the aim is to introduce 4-dimensional versions (4D-Var) within a few years. The are two main motivations for the development of the variational assimilation schemes:

- The possibility to utilise flow-dependent assimilation structure functions through the use of the time-dimension and model integration in 4D-Var
- The increased possibility to utilise remote sensing data in 3D-Var and 4D-Var as compared to previously utilised techniques (statistical interpolation)

The COSMO modelling group has chosen to introduce a data assimilation scheme based on nudging in order to take advantage of the time dimension of the model during the data assimilation. In order to utilise also the advantages of variational methods for assimilation of indirect (mainly remote sensing) measurements, there are plans within the COSMO group to combine the nudging approach first with a 1D-Var for the assimilation of the satellite radiances, then with a 3D-Var scheme.

Model group	2001	2010
HIRLAM	OI and 3D-Var	4D-Var
UKMO	3D-Var	4D-Var Radar and satellite imagery
COSMO	Nudging	Nudging combined with 3D-Var for indirect observations
ALADIN	OI - 3D-Var	3D-Var, 4D-Var mix or more local techniques (OI, Kalman filter)
Environment Canada	3D-Var	4D-Var

The operational variational data assimilation schemes are today only applied for the basic model variables, i.e. surface pressure, temperature, water vapour and wind. Surface model variables and cloud model variables are not included among the initial model variables to be determined by the variational assimilation (the control variables). Separate surface variable assimilation (analysis) schemes are applied for variables like snow cover, snow-depth, sea-surface temperature, fraction of sea ice, soil moisture and soil temperature. For snow cover analysis, ALADIN has developed a OI (optimal interpolation scheme) and COSMO is using the successive correction method.

The application of 4D-Var for a non-hydrostatic model with a horizontal resolution of a few km involves some basic design problems, still to be investigated. We may cite the discussion contained in the questionnaire answer from Environment Canada: Given our current knowledge, the analysis increments would be based on a lower-resolution hydrostatic model with simplified physics. However, a non-incremental 4D-Var remains a possibility in which the full physics is kept in the direct integration and simplifications introduced only for the adjoint model.

For the development of Regional NWP data assimilation over the period 2001 – 2015 we will certainly see stronger emphasis on the assimilation of variables related to the water cycle (water vapour, cloud water/ice/snow, etc.) and to the surface processes. It is likely that model variables related to clouds and surface processes will be introduced among the control variables of variational data assimilation schemes. Observed precipitations, differentiated in rain and snow, will also be assimilated and consequently influence several control variables.

To summarise this section we present a tentative list of model variables that are assimilated in operational data assimilation schemes of today, and another list of variables for which data assimilation is expected to be introduced during the period 2001 – 2015. As pointed out by the DWD in their answer to the Regional NWP questionnaire, profiles need to be assimilated separately outside, inside and below clouds when we are approaching cloud-resolving model spatial resolutions.

Model variables and fields assimilated today:

Surface pressure
Vertical profiles of temperature, water vapour and wind
2m-temperature and humidity
10m wind
Sea surface temperature
Fraction of sea ice
Snow depth
Soil moisture
Soil temperature

Model variables and fields intended for assimilation during 2001 – 2015:

Vertical profiles of cloud liquid water, cloud ice and cloud snow
Vertical profiles of cloud cover
Vertical profiles of drop spectra in clouds

Vertical profiles of precipitation fluxes (rain and snow)
Vertical profiles of turbulent kinetic energy
Vertical profiles of aerosols
Particle spectra in clouds
Vertical profiles of ozone
Boundary layer height
Wave height and spectra in coupled wave models
Lake surface temperature
Land surface, soil and vegetation properties:
- Albedo, surface temperature, water content in soil, surface water (interception reservoir) and emissivity
- Vegetation fraction, leaf area index, vegetation type (from which the roughness length due to vegetation only will be inferred)
- Snow cover, snow depth and snow equivalent water

Sea surface albedo
Fraction of sea ice and ice thickness

Model variables and field intended for assimilation in a longer time perspective:

Soil and vegetation:
- a differentiation of temperature and emissivity between the soil surface and the canopy
- a determination of the two components of the roughness lengths: soil rugosity and vegetation type
- a differentiation between the soil surface temperature (skin temperature) and the temperature in the soil

Chemical substances, including natural and antropogenic sources

3.1.3 Additional (coupled) models

A large number of additional models are applied together with regional NWP forecasting systems. Such additional models that are currently applied operationally, but without any feedback to the atmospheric model, may be summarised as follows:

- High resolution ocean wave models (SE, ES, UK, D), storm surge models (SE, UK), regional deep ocean models (SE, UK, D) and ocean shelf and dispersion models (UK, D). Very high resolution ocean wave models (coastal models, 200 – 400m) to approximate waves for the wind surfing zone and to feed other types of very specific and detailed models.
- Hydrological models (SE, ES, UK, CH). Mesoscale models are particularly used for input of short range precipitation forecasting into the models of the water authorities for water level forecasting. Sophisticated hydrological models also need wind, humidity and temperature from the mesoscale model.
- Road conditions: forecast of the road surface (dry, wet, icy, snow covered) for the general public (UK, D, CH).
- Atmospheric dispersion models (SE, ES), trajectory models (D, CH), lagrangian particle dispersion models (D, CH).

There are plans for extension of the sets of additional models and also plans for coupling of the additional models with feedback also to the atmospheric models:

- Extra tracer variables for pollution applications will be developed (UK, SE, ES). Inclusion of chemical processes, coupled to precipitation and radiation processes, in NWP-models is a long term requirement (SE). For example forecasts of surface ozone and other environmental parameters with input from natural as well as antropogenic sources.
- Wave models with feedback from the ocean to the atmosphere (ES).

3.1.4 Requirements and use of observations

Tentative plans and ideas for use of observations in Regional NWP data assimilation have been extracted from the answers to the Regional NWP questionnaire and entered into the Table below. Table entries for the present time and for the period 2005-2010 have been introduced only. Questionnaire answers from the different groups did not contain great detail.

Model group	2001	2005 – 2010
HIRLAM	Conventional observations Radar VAD winds	Satellite winds Scatterometer winds ATOVS radiances Radar radial winds GPS total delay SSM-I winds and precipitable water IASI radiances Radar reflectivity Satellite imagery
UKMO	Conventional observations Satellite soundings Satellite winds Radar precipitation Satellite cloud imagery	IASI and other sounder radiances Radar and satellite imagery in 4D-Var
DWD	Conventional observations Precipitation (for latent heat nudging)	GPS data Radar data Wind profilers Differential absorption lidars MW and IR radiometers
Aladin- Meteo-France		Most of sounder radiances Doppler wind lidars Space GPS data Satellite imagery data (ozone for winds) Radar data
Environment Canada		AIRS and IASI radiances SSM/I data Geostationary satellite data

3.2 Projected long term evolution of regional NWP to meet the requirements of section 2.

There is very little material in the answers to the Regional NWP questionnaire with regard to ideas and plans for the period 2015 – 2025. Some general comments were provided:

- Things will be highly dependent on how European Meteorology will decide NWP be finally organised (ES).

- My idea, in personal capacity, or forecast, is that once we have after 5-10 years realised that increasing resolution has not brought improvements in accuracy hoped for, emphasis will shift to development of more accurate numerical methods. And/or, different parameterisation schemes, that work on neighbourhood of points as opposed to individual grid-points. Currently, pressure to keep increasing resolution, which includes moving to non-hydrostatic regional models, is taking just about all manpower resources available. No attention is given to the fact that our numerical schemes assume smooth fields while our parameterisation schemes create grid-point-to-grid-point discontinuities. Using finite-volume numerical schemes is one way of avoiding this conflict. Different parameterisation schemes, as mentioned above, another. (Fedor Mesinger)

The review of the ideas and plans for the development of regional NWP systems during the period 2001 – 2015 provided a rather homogeneous view (vision) on the expected operational Regional NWP systems to be used by the end of the period. Non-hydrostatic models will gradually be introduced (some centres have already done so) and the computing power will probably allow operational application of these models with a grid resolution of the order of 1 km and with around 100 levels in the vertical. These non-hydrostatic models will include several new model variables, in particular with regard to a more detailed description of the processes related to clouds and precipitation. It seems also reasonable to believe that we will have introduced operationally 4-dimensional variational data assimilation schemes (4D-Var), including the assimilation of several cloud variables and turbulent kinetic energy by year 2015. The data assimilation schemes are expected to be able to utilise more remote sensing information, in particular satellite sounding data. Satellite and radar image information will gradually become more important for the direct use of cloudiness and precipitation information and for the indirect determination of other control variables via 4D-Var. Surface variable assimilation schemes are also likely to become more developed, and possibly also directly linked to the atmospheric assimilation what would be, from a theoretical point of view, the best solution. We also expect to introduce a more probabilistic approach to regional operational NWP during the period, for example based on ensemble forecasting techniques.

Is it reasonable to trust that we will achieve all these developments during the2001-2015 period? In order to compare with something, we may briefly review the progress during the previous 15-year-period, 1985 –2000. In this period we essentially stayed within the same basic model equations, the primitive equations, and we introduced semi-Lagrangian time integration schemes. We moved from model grid resolutions of the order of 100 km and 10 levels to model grid resolutions of the order of 10 km and

30 levels. We introduced cloud liquid water (and possibly cloud ice) as new explicit model variable(s) as well as turbulent kinetic energy. We improved significantly the physical parameterisation schemes and developed multi-layer soil models. Data assimilation based on the 3-dimensional variational technique was introduced, replacing statistical interpolation schemes from the 1970's and we have started to introduce satellite data in these assimilation schemes. Compared to the achieved development during 1985 – 2000, the expected (planned, wished) developments for 2001 – 2015 may seem quite optimistic. It may be reasonable to believe that delays will occur and that the operational introduction of several of the planed components will occur later, during 2015-2025.

In the following, some very rough projections (crystal ball viewing) for the long term evolution of regional NWP during the period 2015 – 2025 are summarised. The given figures are essentially a rather conservative extrapolation of plans, visions and wishes of the development for the period 2001 – 2015.

3.2.1 Regional forecast models

Non-hydrostatic regional forecast models will be applied operationally with a horizontal grid resolution of 0.2-0.3 km and with 100-200 vertical levels. The models will include several new 3-dimensional variables that are explicitly integrated forward in time, for example, cloud water, ice and snow, cloud droplet and cloud ice particle spectra, water, ice and snow precipitations, turbulent kinetic energy, ozone, different types of aerosols and possibly several further chemical constituents. These non-hydrostatic forecast models will also be utilised for probabilistic forecasting, for example by ensemble forecasting techniques.

As already mentioned above for the time period 2001-2015, the role of non-hydrostatic regional NWP models for nowcasting, particularly for issuing warnings, and for very short-range forecasting is expected to increase (Golding et al., 2001).

3.2.2 Regional data assimilation

Regional 4D-Var data assimilation schemes will be further developed, in particular to be in line with the modelling emphasis on moist processes and on environmental and chemical model variables. The utilisation of regional NWP models for nowcasting and very short range forecasting, for example detailed convection and precipitation forecasts with short lead time in the range 0.5 h – 3 h, will put strong demands on the dynamical-physical consistency of the data assimilation. It is furthermore likely that also the data assimilation for Regional NWP will develop in a more probabilistic direction, with the emphasis on data assimilation for extreme weather events. Kalman filter data assimilation schemes and ensemble data assimilation approaches are possible roads of developments if the computer power will be sufficient. It is furthermore likely that the efforts on probabilistic data assimilation and forecasting will put forward an increased interest for targeted observations also for operational weather forecasting.

3.2.3 Additional (coupled) models

It is likely that we will see an increase in integrated or coupled models for the total earth system also for Regional NWP during the period. Candidates for such models to be fully integrated in or two-way coupled to the atmospheric models are ocean wave, ocean storm-surge, ocean mixed layer/deep ocean models, hydrological models, air pollution dispersion and transport models and air chemistry models. These models will need data assimilation schemes, possibly coupled to the atmospheric data assimilation.

Concerning the simulation of the interaction soil/atmosphere, two strategies will be possible. As an alternative to the present fully integrated soil-atmosphere models, the soil models could become independent models that will interact with the atmospheric models through a coupler as it is already the case today in climate modelling between the atmospheric and oceanic models. This strategy would foster the development of very sophisticated soil models by teams of soil physicists, hydrologists and vegetation specialists. These people could, for example, design much more accurate schemes for the plant transpiration than the very bulky formulation we use today. These models would also be fully hydrological models that, by budgeting adequately the run-off waters, would forecast river water levels. This would introduce more modularity in the regional NWP, i.e. more flexibility in the set-up of a regional NWP system.
The main drawback is that this would hinder an integrated data assimilation for the atmosphere-soil models. We would so loose the possibility of influencing the atmosphere when assimilating by 3- or 4D-Var soil data and reciprocally.

3.2.4 Requirements and use of observations

A preliminary list of prioritised observation requirements is given in Appendix 1. This list was constructed based on the following assumptions and reasoning:

Horizontal resolution

Operational regional forecast models will be applied with a horizontal grid distance of the order of 1 km (or less) in 2015-2025. This means that atmospheric waves of horizontal scales of the order of 3 km will be correctly resolved during the time integration of these forecast models. Thus, *optimally*, we would require a horizontal density of observations corresponding to this horizontally resolved scale. However, statistics of forecast errors generally show very little variance (energy) in the shortest resolved scales. The variance (energy) peak of forecast errors is more related to the horizontal scales of the fastest growing disturbances. For synoptic scale forecasting of today, the horizontal scale of the peak variance of the forecast errors is in the range of 100 – 300 km. With the meso-scale models foreseen for 2015-2025 we may expect to have a large variance of forecasts errors also for much smaller horizontal scales, for example 10-30 km corresponding roughly to the horizontal scales of fronts and convective storms. This has motivated our selection of *a breakthrough level for the horizontal resolution of 30 km for vertical profiles* of wind, humidity and temperature, provided the profiles are available inside, below and outside clouds. The present radiosonde network over Europe has an average horizontal density of a few hundred kilometres. It is considered as very useful if this density of upper-air data would be extended to the Mediterranean, the Atlantic and the Arctic areas for which observations are crucial for regional short range forecasting over Europe. This has defined *the threshold level of 200 km for the horizontal resolution of vertical profiles*.

Many meso-scale phenomena are strongly forced from in-homogeneities and sharp gradients in the lower boundary conditions. For nowcasting and very short-range forecasting it is important to have access to the observed state of the lower boundary conditions. This has motivated a *breakthrough level of 10 km and an optimum horizontal resolution of 1 km for the surface variables* such as sea and lake surface temperature, soil temperature and soil moisture.

Vertical resolution

Operational regional forecast models will be applied with 100-200 vertical levels, and with a vertical grid distance of 10 – 50 meters in the lower part of the atmosphere. We may then resolve vertical structures with a vertical scale of 100 meter (or less). Thus, we would *optimally* require a vertical resolution of 100 meter for vertical profiles. With similar arguments as given for the horizontal scales above, we may argue for a *breakthrough level of 1 km and a threshold level of 3 km for the vertical resolution of profile measurements*.

Frequency

There are at least three inter-related factors that should influence our requirements for frequency of the observations: (1) The time-scale of the phenomena we want to forecast; (2) The frequency of regional forecasts, including nowcasting, to be issued and (3) The time-windows of 4D-Var. The time-scale of the fastest of the phenomena we want to forecast are of the order of one hour or a few hours. We have argued for running forecasts on demand with shorter intervals than 3 hours and, on the other hand, the time windows of 4D-Var are likely to become 0.5 hour or less. Thus 0.5 hour seems to be an optimum time resolution of the observations, with exceptions for some variables with an obvious slower time scale. For the fast variables, a *breakthrough time resolution* should be at least 1 observation for each standard observation hour, thus every *3 hour*.

Targeted observations

Strongly related to the requirement of running forecasts on demand is the possibility also to get access to observations on demand. With the development of adjoint models and singular vector techniques for regional forecast models, we will most likely be able to tell in advance where and when we need observations. Thus, we expect that targeted observations will become a standard tool also for operational regional NWP. The possibility of targeted observations may also contribute to make some of our rather strong requirements on spatial resolution and time frequency more feasible by relaxing them.

Priorities

The basic dynamic variables of the NWP models will remain the most important to be observed. Thus, we will require *surface pressure over* sea and *profiles of horizontal wind, temperature and water vapour everywhere inside, outside and below clouds* with highest priority. Due to the increased importance of moist model processes, very high priority should also be given to *surface precipitation intensity*. Very high priority should also be given to *soil moisture, snow coverage, sea/lake surface temperatures, sea/lake ice coverage and profiles of aerosols*.

Accuracy

For the accuracy requirements for the different variables to be observed, we have followed the corresponding WMO requirement tables.

3.3 Highlights of differences in the development and requirements of global and regional numerical weather prediction.

There are obviously many similarities in the development of techniques and also in the requirement of observations for global and regional numerical weather prediction. The model equations, the numerical techniques and the basic data assimilation techniques will be very similar. The application of regional NWP, which occurs on a limited integration domain will of course introduce certain specific technical differences, but we will first mention some differences related to the general regional forecasting task, as compared to the general global forecasting task:

- The regional forecast models will in general be run with an increased spatial resolution as compared to the global forecast models. This means that some physical processes, which are parameterised in the global model, will be explicitly resolved by the regional model. If, for example, the regional model has enough resolution to explicitly resolve clouds, this implies a stronger need for specific vertical profiles of the basic model variables outside, inside and below clouds. The increased spatial resolution of the regional forecast model obviously also put stronger requirements on the spatial resolution of the observations. Furthermore, dynamical adjustment theory tells us that the wind field becomes relatively more important than the mass field at higher spatial resolutions. Similarly moist processes and observations of moist variables become more important at increased spatial resolutions.

- Regional numerical weather prediction is applied for short-range forecasting purposes, while global numerical weather prediction is applied also for medium-range forecasting. Short-range numerical weather prediction puts stronger requirements on the timeliness of the observations (today short-range NWP is generally carried out 1-2 hours after observation time, while medium range NWP models are run a few hours later). The application of regional NWP for nowcasting purposes puts further increased requirements on the timeliness and frequency of observations.

- For regional numerical weather prediction, the area of influence of initial data is generally more restricted than for global numerical weather prediction, where the influence area, by definition, is global. Considering the group velocity for the horizontal dispersion of forecast errors, the area of influence for regional +24 h forecasts for Europe includes the North Atlantic and the Arctic to the west and to the north and the Mediterranean and North Africa to the south.

- There is a need for regional NWP model runs on demand in challenging weather situations, and similarly there is a need for observations on demand, i.e. targeted observations. But targeted observations are not thought to be useful only for forecasts on demand.

Regional numerical weather prediction with Limited Area Models (LAMs) involves certain specific issues and problems different from those of the global numerical weather prediction:

- The need for accurate (in particular rather fresh) lateral boundary conditions.
- The need for an accurate technique for coupling to a global model, in particular the need for assimilating those large spatial scales that are not described by observations within the limited model integration area.

4. Contribution of satellite observing systems to meeting future observational requirements

Various national and international space agencies are operating and planning the satellite constellation that currently ensures, and in the future will provide, the meteorological observing systems from space. This constellation includes both polar and geostationary satellites. National and international resources are gathered to achieve the time and space coverage needed for many meteorological observing requirements. In addition, research satellite systems are deployed and are very effective for demonstrating the capabilities of possible future operational systems. Finally application satellites with a limited number of missions also provide significant contributions and, more recently, radio-occultation techniques have been implemented to take advantage of the GPS/GLONASS constellation.

Present and planned operational satellite observing systems contribute significantly to meet the observational requirements for future regional NWP. The EUMETSAT MSG and EPS programs will be important components in the future satellite observing system. However, to achieve the needed improvement in regional NWP performance during 2015-2025, further enhancements in the observing systems are needed.

4.1 The contribution of present and planned satellite systems

Regional NWP take direct or indirect advantage of a number of remote sensing products both from geostationary satellites and from polar satellites. The current and planned space-based observing techniques are summarised in Appendix 1, where observed variables needed for Regional NWP are listed and prioritised. The most important of these variables are discussed in the following paragraphs.

3-D Horizontal wind field

Horizontal wind may be inferred by motion vectors or by humidity tracers in geostationary imagery. It is a consolidated technique, using data from instruments such as the Visible and Infrared Spin Scan Radiometer, since many years aboard on different satellites such as Meteosat, GOES and GMS. A large amount of information is provided, especially in low and middle latitudes, albeit its quality is not homogeneous, as performance of cloud targeting is more reliable when reasonably small non-convective cloud targets are considered. Planned operational instruments such as SEVIRI on MSG and ABS on current GOES successors will increase data availability especially for Regional NWP in Europe because of more frequent repeat cycles of imaging and lower spatial sampling distance. The limited vertical resolution and the height assignment will remain as problems, however.

Doppler lidars deployed aboard polar research satellites will provide additional wind observations with improved vertical resolution.

Temperature profiles

Currently polar satellite instruments provide the basic information to retrieve temperature profiles (HIRS, AMSU) in clear and cloudy (non-precipitating) skies. Their coverage is global and has adequate horizontal resolution (~ 50 km – the estimated breakthrough level for regional NWP is 30 km) but limited vertical resolution, in particular with regard to the microwave measurements (AMSU). The frequency of the current satellite profile information is marginal for Regional NWP. The quality has improved in cloudy areas due to more advanced microwave sounders and positive results have been shown for regional NWP, though the use of radiances over land is still experimental. Infrared sounders cannot be used below clouds and microwave sounders, with the capability to penetrate in cloudy areas, have a broader horizontal field of view. Geostationary infrared soundings increase data availability because of more frequent sampling that gives better possibility of detecting cloud-free areas. However, they suffer shortcomings similar to polar infrared satellite soundings.

Advanced radiometers or interferometers are planned for future operational satellites. They will be capable of further improving spatial resolution and accuracy. As an example, IASI on EPS will be providing profiles at roughly 25 km horizontal resolution, having 1.5 K accuracy and 1 km vertical resolution in the lower troposphere.

Finally, a 1 km vertical resolution is believed to be achievable as well by radio-occultation techniques in the upper troposphere and stratosphere, though this is less significant from the regional NWP point of view.

Humidity profiles

The assessments concerning current and planned satellite capabilities show large similarity for temperature and humidity profiles. However, as far as regional NWP is concerned, the humidity field is poorly sampled. This is both because of limitations of the instruments on board of the satellites and because the humidity field shows strong variability on scales of the order 10-100 km in the horizontal and hundred of meters in the vertical. A better utilisation of current satellite systems should improve on the moisture concentration in a few thick layers in the vertical only. Vertical resolution and accuracy is expected to improve with the launch of advanced sounders and interferometers (MHS, IASI) aboard METOP and NPOESS satellites, at least in cloud free areas. Radio occultation techniques from GPS technology will also improve the chances for denser networks to infer the moisture field.

Surface winds

Only polar satellites provide information on surface winds and techniques and data are not and will not be available for surface winds on land. Scatterometers are the main instruments deployed to give information on wind speed and direction, but because of their narrow swath they have so far had a marginal temporal resolution. Recently launched and planned scatterometers will provide better coverage via broader swaths. Passive microwave sensors, such as the Conical Microwave Image Sounders aboard the future NPOESS satellite will complement information on wind speed.

Other surface parameters

The surface parameter currently better retrievable from satellite measurements is the sea and lake surface temperature available with extensive coverage everywhere except in persistently cloudy areas. Skin sea-surface temperature is inferred with acceptable horizontal resolution from polar satellites, while geostationary satellites complement information with better temporal resolution. Visible/Infrared/Microwave imagery provide information on snow cover in day time and clear sky. Snow water content is experimentally retrieved by microwave imagery. Planned research satellites might help to consolidate such techniques, but with obvious limits on continuity. Microwave radiation emitted at the ground can be monitored to infer estimates of soil moisture.

Clouds and precipitation

Cloud cover and cloud-top height can be inferred from infrared imagers and sounders providing good horizontal/temporal resolution and good/acceptable accuracy. SEVIRI in particular should be close to the optimum threshold level for horizontal resolution and accuracy of these variables. Information on cloud liquid water and cloud ice can be retrieved from microwave imagers and sounders, offering good horizontal resolution and acceptable temporal resolution. Because most mesoscale models have sophisticated parameterisations of cloud physics, the microwave information is potentially valuable. At present, the primary problem is not with the observations themselves, however, but with their assimilation into regional NWP models.

No satisfactory precipitation estimates are available from satellites at present, although satellites are the only potential source of information over the oceans. The situation will improve for both geo-stationary and polar orbit planned systems. As an example, rain radar offers the potential for improved precipitation observations.

Ozone

Much attention has been devoted in the recent NWP development to ozone. Ozone profile observations are known to be very beneficial both for estimating winds and for improving model radiation calculations and therefore also for assimilation of infrared 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 infrared sounders and more accurate solar backscatter instruments.

4.2 The contribution of EUMETSAT MSG and EPS

4.2.1 Meteosat Second Generation (MSG)

The primary mission of MSG will be the continuous observation of the Earth's full disk via the SEVIRI (Spinning Enhanced Visible and Infrared Imager) imaging radiometer. SEVIRI will observe the Earth-atmosphere system with a spatial sampling distance of 3 km in eleven channels. A high-resolution visible (HRV) channel will cover half of the full disk with a 1 km spatial sampling. A repeat cycle of 15 minutes for full-disk imaging will provide multi-spectral observations of rapidly changing phenomena (e.g. deep convection) and will allow extraction of better and more numerous wind observations from cloud tracking. SEVIRI will contribute to retrieval of information about cloud cover, cloud top temperature, cloud top pressure/height and cloud type. For these variables, SEVIRI will be close to the level of performances required by regional NWP.

Probably the most important objective of SEVIRI for numerical weather prediction will be to support the generation of the Atmospheric Motion Vectors (AMV). The AMVs in the troposphere will be derived from cloud and water vapour motion using primarily the 0.6 or 0.8 μm channel, the 10.8 μm channel and the 6.2 and 7.3 μm channels, respectively. The utilisation of AMVs in NWP is very limited for low vertical levels at present. However, improved quality of low level winds is expected by utilising the full capabilities of the SEVIRI instrument.

Operational NWP centres will use clear sky radiance products from the MSG infrared channels, and in particular 4D-Var data assimilation systems have the capability to utilise the frequent time observations from geostationary orbit.

SEVIRI will provide total ozone product useful for monitoring and forecasting UV radiation at the ground level. Preliminary studies have shown that ozone observations at high temporal and spatial resolution may provide useful information about the winds in the upper troposphere and lower stratosphere. Furthermore, it has been shown that the retrieved total ozone has distinct features on synoptic scales, which could potentially be used to derive Ozone Motion Vectors.

4.2.2 EUMETSAT EPS

There are great expectations for the EUMETSAT EPS Programme that together with the NOAA operational satellites will support meteorological service activities for many years to come. METOP-1 and METOP-2 will fly a set of sensors identical to those flying on the NOAA-N and N' satellites and additional European sensors. The European instrument payload is particularly important for regional NWP as it is meant to improve atmospheric soundings in terms of resolution and accuracy, as well as to measure atmospheric ozone and near-surface wind vectors over the ocean. The payload is consisting of:

- the Advanced Very High Resolution Radiometer (AVHRR/3) providing global visible, near infrared and infrared imagery of clouds, the ocean surface and the land surface

- the High Resolution Infrared Radiation Sounder (HIRS/4) measuring the temperature and humidity of the global atmosphere in cloud-free or partly cloudy conditions
- the Advanced Microwave Sounding Unit-A (AMSU-A) observing the temperature of the global atmosphere in nearly all weather conditions
- the Microwave Humidity Sounder (MHS) measuring the humidity of the global atmosphere
- the Infrared Atmospheric Sounding Interferometer (IASI) providing enhanced atmospheric soundings of temperature, humidity, ozone and trace gases
- the GPS Receiver for Atmospheric Sounding (GRAS) providing temperature of the upper troposphere and the stratosphere with a high vertical resolution and potentially humidity in the troposphere under known temperature conditions
- the Advanced Scatterometer (ASCAT) mission for providing near-surface wind speed and direction over the global oceans
- the Global Ozone Monitoring Experiment-2 providing profiles of ozone and other atmospheric constituents

Due to the larger number of microwave channels for temperature sounding and the better coverage of the stratosphere, the impact of soundings on NWP in general is expected to improve. In the retrievals from ATOVS and from IASI the AVHRR imager will be used to determine the cloud amount in the sounder field of view. Retrievals will not only comprise the temperature and moisture profiles but also fractional cloud cover, cloud top height, cloud top pressure, surface temperature and surface emissivity. Infrared soundings are complemented by microwave soundings. The increasing use of imager data to determine the cloud amount will improve the performance and the number of retrieved profiles. In general, IASI will increase sounding performance to a level very significant for regional NWP.

The mission of maintaining the capability of measuring wind at sea-surface from operational satellites will be essential for the direct use in regional NWP. The Advanced wind Scatterometer (ASCAT) with a high radiometric stability is the follow-on of the SCAT instrument on the ERS satellites and provides improved capability to measure near ocean surface winds. Its design aims at providing ocean surface winds at 50 km resolution over a 25 x 25 km^2 grid along and across both swaths. In addition a high resolution wind product is generated at 25 km horizontal resolution, using a 12.5 x 12.5 km^2 grid. Further potential of ASCAT lies in the measurement of sea ice boundaries, sea ice concentration and sea ice type. Scatterometer applications over land have emerged in the past from the use of SCAT data from ERS. There is potential for the retrieval of soil moisture, snow/ice coverage and vegetation type/ coverage. Operational use of ASCAT will cause these applications to be further developed.

4.3 Improvements in observations needed for critical improvements in regional NWP performance.

We have discussed and established prioritised observation requirements for regional NWP during the period 2015-2025. In particular, we have arrived at breakthrough levels with regard to the spatial and temporal resolutions of variables considered of very high priority to achieve a critical improvement of regional NWP performance. We have also reviewed expected contributions of present and planned satellite observations to meet these requirements. Considering these observation requirements and taking the expected contributions from present and planned observing systems into account, we may briefly summarise needs for further extensions and improvements of the observing systems in order to achieve the required improvements of regional NWP performance:

- There is a clear and very high priority need to get access to more wind profile measurements, in particular over ocean/sea areas and over the Arctic. Wind profile measurements will be provided over land from radiosonde stations in a sparse network, from doppler weather radars and from aircraft (AMDAR) reports in the vicinity of airports. Over ocean/sea and the Arctic areas, only single (or a few) level wind observations will be available, for example from Atmospheric Motion Vectors (AMV), from aircraft reports and from satellite scatterometer data close to the sea surface only. From a theoretical point of view, geostrophic adjustment theory tells us that wind profile information becomes relatively more important for the future regional NWP models with a horizontal resolution of the order of 1 km, as compared to the present situation with regional models having a more modest horizontal resolutions.

- There is also a very high priority need for improved temperature and humidity profile measurements inside and below clouds. Planned infrared satellite sounding instruments like IASI are expected to provide the needed resolution and accuracy in cloud-free areas and above clouds, while the microwave sounders do not meet the required breakthrough levels for vertical resolution and accuracy to achieve the critical improvement of regional NWP performance.

- There is a high priority need for surface pressure observations over the sea with a horizontal resolution of 30 km and with a temporal resolution of 3 hours. On one hand, it is unclear whether such observations are physically feasible with satellite techniques or whether one has to rely on in situ measurements from ships and buoys. On the other hand, we may again refer to geostrophic adjustment theory, the direct measurement of surface pressure may be of less relative importance for the smaller horizontal scales of regional NWP models since, for example, scatterometer data will provide us with high resolution low level wind data.

- There is a very high priority need for improved precipitation intensity observations with a spatial resolution of 10 km and with a temporal resolution of 1 h, in particular for initialisation of mesoscale regional NWP models to be applied operationally for nowcasting purposes.

- There is need for soil moisture observations with a horizontal resolution of 10 km and with a temporal resolution of 6 h.

- There is a need for aerosole profile observations with a horizontal resolution of 30 km, with a vertical resolution of 2 km and with a temporal resolution of 6 h.

5. Contributions to other application areas.

Existing application areas

Environment, security and health:
- Air pollution dispersion models and related air chemistry models (SE, Ca)
- Forecasts of transport of radioactive constituents (D, SE)
- Mixing height calculation (D)
- Objective weather type classification (D)
- UV forecasts (ES, D)
- Insurance (ES)
- Pollen forecasts (A, CH)
- Avalanche risk prediction based on snowpack models (A, Ca, CH, F)

Transportation:
- Road condition information system (D, ES, F)
- Convection model for soaring forecasts (D)
- Cross sections along fixed flight corridors (D)
- Icing forecasts (D)
- Base of convective clouds (D)
- Top of blue thermals (D)
- Sea wave model (D, F)
- Ocean model (current, water level, temperature, ice, salinity) (D, F)
- Forecasts of drifting oil and other objects with a Lagrangian drift and dispersion model (D)

Agriculture:
- Agro-meteorological advisary system (ca. 60 application models for ca. 150 agro-meteorological parameters such as estimating occurrence of plant deseases (D)
- Irrigation (D)
- Application of chemicals (D)
- Forecast of canopy and soil conditions (D, F)
- Harvest conditions and quality (D)

Hydrology and oceanography:
- Forecasts of water level with precipitation run-off models (D)
- Cloud films (TRIVIS software) and animation of other scalar fields (D)
- Hydrological models to forecast floods (Ca)
- Coastal ocean model to forecast extreme tides (Ca)
- Wave, storm surge and deep ocean models (UK, F, D, SE,ES)

Power industry, electrical power (D, ES), wind energy

Leisure and tourist industry (sailing, surfing, sports,...) (D, ES)

Building industry (D)

Seasonal forecasting and Climate projection is envisaged make increasing use of regional NWP modelling (ES)

Future application areas

The above mentioned application areas will remain, but a lot of new follow-up applications will emerge in these areas dependent both on the technological developments and requirements and on the quality of NWP model output. Examples:

- Biometeorological models for heat load, cold stress, pollen flight (D)
- Agrometeorology forecasts of sub-foilage conditions (D)
- Coastal ocean models to forecast local currents and local changes of SST, salinity and transport of sediments.

References:

(1) Answers to Questionnaire on Development of Regional NWP

(ES)	National Meteorological Institute of Spain
(UK)	United Kingdom Meteorological Office
(Ca)	Environment Canada
(SE)	Swedish Meteorological and Hydrological Institute
(D)	German Weather Service
(F)	Meteo-France
(NL)	The Royal Netherlands Meteorological Institute
(I)	Italian Weather Service
(A)	Austrian Weather Service
(CH)	MeteoSwiss
(Mesinger)	Fedor Mesinger, NCEP

(2) Michalakes, J., Chen, S., Dudhia, J., Hart, L., Klemp, J., Middlecoff, J., and Skamarock, W., 2000: Development of a next generation regional weather research and forecast model. Proceedings of the ninth ECMWF workshop on the use of parallel processors in meteorology, ECMWF, Reading, U.K., November 13-16, 2000.

(3) National Weather Service Local-scale Numerical Weather Preduction Workshop, December 13-14, 2000, NWS/Office of Science and Technology, Silver Spring, MD, USA.

(4) The scientific and technical foundation of the ECMWF strategy 1999-2008.

(5) Golding et al., 2001: Position Paper – Requirements of observations for regional NWP. EUMETSAT, 2001.

	A	B	C	D	E	F	G	H	J	K
1	**Required variable**	**Nearest WMO/CEOS parameter**	**WMO/CEOS code**	**Accuracy (Threshold/optimum)**	**dx (Threshold/optimum)**	**dz (Threshold/optimum)**	**dt (Threshold/optimum)**	**Conditions TG=possibly trageted CL=in, outside and below clouds**	**Priority level**	**Breakthrough level (if any)**
2										
3	Horizontal wind profile	Wind profile (horizontal component)	2	3 m/s - 1 m/s	200 km - 3 km	2 km - 100 m	12 h - 0.5 h	TG	VH	dx=30km,dz=1km,dt=3h
4	Vertical wind profile	Wind profile (vertical component)	3	5 cm/s - 1 cm/s	200 km - 3 km	2 km - 100 m	12 h - 0.5 h			
5	Water vapour profile	Specific humidity profile	4	10 % - 5 %	200 km - 3 km	2 km - 100 m	12 h - 0.5 h	TG, CL	VH	dx=30km,dz=1km,dt=3h
6	Temperature profile	Atmospheric temperature profile	1	1.5 K - 0.5 K	200 km - 3 km	2 km - 100 m	12 h - 0.5 h	TG, CL	VH	dx=30km,dz=1km,dt=3h
7	Boundary layer temperature profile	Atmospheric temperature profile	1	1.5 K - 0.5 K	50 km - 1 km	500 m - 10 m	3 h - 10 min		H	dx=10 km,dz=300m,dt=1h
8	Surface pressure	Air pressure over land surface	58	1 hPa - 0.1 hPa	50 km - 3 km	single level	3 h - 0.5 h	TG	VH	dx=30km,dt=3h (over sea)
9		Air pressure over sea surface	59	1 hPa - 0.1 hPa	50 km - 3 km	single level	3 h - 0.5 h	TG		
10	Surface wind	Wind vector (and speed) over land surface	65, 67	3 m/s - 1 m/s	50 km - 3 km	single level	3 h - 0.5 h	TG	H	dx=30km,dt=3h (over sea)
11		Wind vector (and speed) over sea surface	66, 68	3 m/s - 1 m/s	50 km - 3 km	single level	3 h - 0.5 h	TG		
12	Land surface air temperature (2m)	Air pressure over land surface	58	1.5 K - 0.5 K	50 km - 3 km	single level	3 h - 0.5 h			
13	Land surface air humidity (2m)	Air specific humidity (at surface)	61	10 % - 5 %	50 km - 3 km	single level	3 h - 0.5 h			
14	Sea and lake surface temperature	Sea surface bulk and skin temperature	70, 71	1.5 K - 0.5 K	50 km - 1 km	single level	24 h - 1 h		VH	dx=10km,dt=6h
15	Fraction of sea and lake ice	Sea-ice cover	85	50% - 5%	50 km - 3 km	single level	24 h - 3 h		VH	dx=10km,dt=6h
16	Sea and lake ice thickness	Sea-ice thickness	87	1 m - 0.1 m	50 km - 3 km	single level	24 h - 3 h			
17	Soil temperature	Land surface temperature (not profile)	100	2 K - 1 K	50 km - 1 km	2 - 5 layers	3 h - 0.5 h		H	dx=10km,dt=1h
18	Soil moisture	Soil moisture (not profile)	101	50 g/kg - 10 g/kg	50 km - 1 km	2 - 5 layers	24 h - 1 h		VH	dx=10km,dt=6h
19	Snow coverage	Snow cover	93	50% - 5%	50 km - 3 km	single level	24 h - 3 h		VH	dx=10km,dt=6h
20	Snow equivalent water	Snow water equivalent	95	20 mm - 5 mm	50 km - 3 km	single level	24 h - 3 h		H	dx=10km,dt=6h
21	Total cloud cover	Cloud cover	30	20% - 5 %	50 km - 3 km	single level	3 h - 0.5 h		H	dx=10km,dt=1h
22	Cloud top height	Cloud top height and temperature	32, 33	1 km - 0.5 km	50 km - 3 km	single level	3 h - 0.5 h		H	dx=10km,dt=1h
23	Cloud base height	Cloud base height	34	1 km - 0.5 km	50 km - 3 km	single level	3 h - 0.5 h		H	dx=10km,dt=1h
24	Cloud liquid water profile	Cloud water profile (<100μm)	5	50 % - 5 %	200 km - 3 km	2 km - 100 m	12 h - 0.5 h		H	dx=30km,dz=1km,dt=3h
25		Cloud water profile (>100μm)	6							
26	Cloud ice water profile	Cloud ice water profile	7	50 % - 5 %	200 km - 3 km	2 km - 100 m	12 h - 0.5 h		H	dx=30km,dz=1km,dt=3h

	A	B	C	D	E	F	G	H	J	K
1	**Required variable**	**Nearest WMO/CEOS parameter**	**WMO/CEOS code**	**Accuracy (Threshold/optimum)**	**dx (Threshold/optimum)**	**dz (Threshold/optimum)**	**dt (Threshold/optimum)**	**Conditions TG=possibly trageted CL=in, outside and below clouds**	**Priority level**	**Breakthrough level (if any)**
2										
27	Cloud snow water profile	Cloud ice water profile	7	50 % - 5 %	200 km - 3 km	2 km - 100 m	12 h - 0.5 h			
28	Cloud drop size profile	Cloud drop size (at cloud top)	49							
29	Surface precipitation intensity	Precipitation rate (liquid)	35	1 mm/h - 0.1 mm/h	50 km - 3 km	single level	3 h - 0.5 h		VH	dx=10km,dt=1h
30		Precipitation rate (solid)	36							
31	Vertical precipitation flux	Cloud water profile (>100µm)	6	1 mm/h - 0.1 mm/h	200 km - 1 km	2 km - 100 m	3 h - 5 min		H	dx=10km,dt=1h
32	Turbulent kinetic energy profile	None								
33	Aerosole profile	Aerosol profile	8	20% - 10% (rel.)	200 km - 3 km	2 km - 100 m	24 h - 1 h		VH	dx=30km,dz=2km,dt=6h
34	Ozone profile	Ozone profile	9	20% - 5%	200 km - 3 km	2 km - 100 m	24 h - 3 h			
35	Boundary layer height	Height of the top of PBL	41	300 m - 100 m	50 km - 3 km	single level	3 h - 0.5 h		H	dx=10km,dt=1h
36	Sea wave significant height	Significant wave height	72	0.2 m - 0.1 m	50 km - 3 km	single level	3 h - 0.5 h		H	dx=10km,dt=1h
37	Sea wave direction spectra	Dominant wave direction	74	20 deg - 10 deg	50 km - 3 km	single level	3 h - 0.5 h			
38	Sea wave period spectra	Dominant wave period	73	1 s - 0.5 s	50 km - 3 km	single level	3 h - 0.5 h			
39	Surface albedo	SW Earth surface BRDF	55	10 % - 2 %	50 km - 3 km	single level	1 month-0.5 h		H	dx=10km,dt=6h
40	Fraction of vegetation	NDVI	102	30 % - 10 %	50 km - 3 km	single level	1 month-0.5 h		H	dx=10km,dt=6h
41	Leaf area index	Leaf area index	103	50 % - 20 %	50 km - 3 km	single level	1 month-0.5 h		H	dx=10km,dt=6h
42										
43	Notes :	(1) Required range of vertical profiles is troposphere and lower stratosphere (below 15 km)								
44										
45										
46										