STATEMENT OF GUIDANCE FOR
HIGH-RESOLUTION NUMERICAL WEATHER PREDICTION (NWP)

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1. Introduction

Thanks to the increasing computer power, most Global NWP models nowadays have spatial resolutions in the order of ~10-30 km. This Statement of Guidance (SoG) focuses on observing systems that are required by high resolution NWP models producing forecasts of meteorological events with a 1-5 km horizontal resolution. Such forecasts are intended to be more detailed than those available from global models, due to more realistic descriptions of atmospheric phenomena such as clouds and precipitation. The added detail is made possible by a finer computational grid on a specific area, more detailed specification of terrain, more sophisticated prescription of physical processes mainly based on explicit rather than parameterized formulations, and, ideally, denser and more frequent observations (with respect to global NWP) to specify appropriately detailed initial conditions.

As high resolution models depend upon regional or global models for their lateral boundary conditions, the duration of high resolution forecasts is effectively limited by the size of the computational domain to 1 or 2 days' lead-time, or even less in case of fast moving weather systems. This argument is also valid for variable-resolution models which are another way to "regionalize" the forecast, the most common technique being LAM (Limited Area Models). The typical vertical resolution for a high resolution model is the similar to that of a global model, except there are generally more levels in the lower troposphere in order to better describe boundary layer processes, and fewer in the stratosphere; the top level is generally lower compared to global models and the vertical domain does not reach the mesosphere. High resolution models are more likely to cover land areas than oceans, but oceanic zones are often included when upstream from heavily populated areas, or areas often exposed to high-impact weather events. The tendency for the future is an increased variety of high resolution models operated routinely, for specific applications and very specific areas (aviation, marine, pollution, urban meteorology and hydrology).

Most of the time, high resolution models are initialized through the assimilation of observations. However some models are operated in "dynamical adaptation mode", which means that the initial state is simply interpolated from the global or regional analysis of the coupling model: in this case the high resolution model initial state is entirely dependent on the observations entering the coupling model. The high resolution data assimilation schemes often require more frequent analyses (every 6, 3 or 1 hour), and therefore more frequent observations with a shorter delivery delay. Otherwise, the high resolution data assimilation schemes use most of the observations entering the global models on their area of interest. The shorter background error correlation lengths allow furthermore to use them with higher spatial densities. It has however to be noted that the high spatial resolutions in the boundary layer can lead to resolution gaps with e.g satellite data in the vertical and with surface-based observations in the horizontal. Boundary layer observations are thus particularly valuable.

The key model variables for which observations are needed are the same as for global models: 3-dimensional fields of wind, temperature and humidity, and the 2-dimensional field of surface pressure. Research is ongoing in some centres to consider some microphysical quantities, such as cloud or rain mixing ratios, as extra model variables in variational data assimilation schemes. However the strong nonlinearities of moist physical processes imply that such schemes based on quasi-linear theory should be modified to better accommodate these new observations. Observations of clouds, rain and probably other different precipitation types may however become more and more important in the future for assimilation and for validation. Also very important for high resolution models are boundary variables describing the surface characteristics and those needed to estimate water and energy fluxes. On a time-range of 1 to 2 days, descriptions of the deep ocean and of the mesosphere are not needed, because these vary too slowly to affect the weather.

Compared to global NWP, high resolution models draw less benefit from polar orbiting satellites, and more from geostationary satellites: because of their analysis frequency, they can exploit the observation continuity of a geostationary satellite on a particular area. The LAMs which are operated on densely populated regions are however less dependent on satellite data in general than the global models. As stated above, they are more dependent on surface in-situ and boundary layer observations (profilers, frequent radiosonde launches or aircraft measurements, GPS receiving stations, radars…) because of their higher spatial resolutions especially at those levels. However, these additional high-resolution in-situ observations are largely available only over land.

The following sections provide an assessment, for the main variables of interest, of how well the observational requirements are met by existing or planned observing systems.

2. **Gap Analysis: data requirements and observing capabilities**

The following terminology has been adhered to as much as possible:
- poor (minimum user requirements are not being met),
- marginal (minimum user requirements are being met),
- acceptable (greater than minimum but less than optimum requirements are being met), and
- good (near optimum requirements are being met).

3D wind field (horizontal component)

Wind profiles are available from radiosondes, aircraft (ascent/descent profiles), wind profilers and Doppler radars using algorithms such as VAD (Velocity Azimuth Display) with their own characteristics in terms of geographical coverage and observing frequency. These observing systems are all very useful for high resolution NWP, especially for prescribing pre-convective conditions. In densely populated areas, horizontal and temporal coverage may be marginal and vertical resolution is generally acceptable. In many regions however, the lack of reliable observations is obvious, and

the quality of data retrieved from wind profilers and the VAD technique may be questionable. In addition, geostationary satellite derived wind information gives acceptable information because of the high observing frequency and the high horizontal resolution, although generally limited to single level wind observation at few levels determined with a poor accuracy.

The best short-term opportunity for increasing 3-D wind information is to capitalize on reports available from commercial aircrafts world-wide, which provide wind measurements with a good spatial resolution around airports. Profiles may furthermore be available in those particular areas thanks to measurements performed during ascent and descent stages. Where scanning Doppler radars are available, data assimilation techniques aim at extracting information such as low level wind convergence or vertical shear of horizontal wind with an acceptable accuracy within precipitating areas from the very high-resolution radial winds (~1-km resolution along each radial). Long-term needs for more comprehensive wind information might be met by the development of AMDAR systems producing wind observations from airplanes on a national or regional basis. In the area covered by air traffic control, equivalent wind observations can also be inferred from Mode-S data by using the position of the aircraft, the ground track and the true air speed. For these two observation types, the difference between the motion of the aircraft relative to the ground and its motion relative to the air allows to retrieve the wind vector at the airplane location. In addition, wind measurements from wind-energy turbines and wind farms, especially off-shore, may be of great interest in the future.

For wider coverage, Doppler wind lidars, like the one planned for the ADM-AEOLUS mission will be exploited, although this observing system would appear less important for high resolution NWP than for global NWP because of its spatial and temporal data coverage. In addition it is expected that future hyperspectral infra-red sounders onboard geostationary satellites will contribute to the observation of 3D wind structure by continuous tracking of (e.g.) humidity and cloud features.

Surface pressure and surface wind

Over ocean, ships and buoys provide observations of acceptable frequency for most of the high resolution models operated routinely. Accuracy is good for pressure and acceptable/marginal for wind. By combining measurements from different azimuth angles, the near surface wind can also be retrieved from space-borne scatterometer observations over sea surface with acceptable accuracy. Such information is of great interest, especially for LAM implemented in the tropics to monitor cyclonic activities. Because scatterometers are onboard polar satellites, temporal resolution is poor.

Over land, surface observations have spacing that varies a lot from region to region. Accuracy is generally good. Data from many local meso-networks often provide denser observation sets which are very useful in the case that the data is made widely available. The interpretation of local wind data is complicated in mountainous terrain, where local diurnal circulations are common (e.g., mountain-valley winds or drainage winds). Mesoscale models with high-resolution terrain and good surface boundary physics are able to capture many of these local wind systems and are able to get some benefit from assimilating surface winds in those areas.

Surface pressure is not directly measured by satellites, but polar orbiting satellites provide information on sea-surface winds for high resolution models through the techniques described in "SoG for global NWP". Such surface wind information is very useful for global models, but its temporal frequency is marginal for forecasts at

mesoscale.

The use of ZTD (Zenithal Total Delays) from surface networks of GPS receiving stations (which contains mainly information on atmospheric humidity) has shown some marginal positive impact also on the surface pressure fields, which means that the GPS networks can also contribute to a small extent to the estimation of surface pressure.

3D wind – vertical component

High resolution NWP models are generally non-hydrostatic, considering vertical velocity as a prognostic variable of the model. However no specific assimilation on this variable is normally performed. The model derives its own vertical velocity field from the other meteorological fields in its first time-steps of integration. The reason behind is that no observing capability is able to produce some vertical velocity observations which are comparable to the model vertical velocity (at the scale of its mesh). A drastic increase on spatial resolutions of high resolution NWP models is needed before these models can resolve the clouds and produce some vertical motion which can be compared to (e.g.) Doppler radar vertical velocity observations.

3D temperature field

Temperature profiles are available from radiosondes and aircraft (ascent/descent profiles): such in-situ observations are very useful for high resolution NWP. In populated areas, horizontal and temporal coverage may be acceptable and vertical resolution is good. In addition, a lot of information can be derived from the different sounders onboard polar orbiting satellites. This last point is generally valid for global NWP, but also for meso-scale LAMs with the difference that many LAM areas contain more land than sea. Then they are more affected (compared to global models) by the difficulty of using satellite radiances over land. Data assimilation progress is still fast in this area, with the description of the land surface characteristics improving continuously, more and more satellite radiances are assimilated in high resolution NWP models. This is true for both microwave measurements and infra-red radiances (especially the ones coming from hyperspectral sounders). With respect to the high resolution NWP requirements in the boundary layer, the vertical resolution of satellite sounders is still marginal. Radio-occultation GPS measurements complement other temperature observations from the stratosphere to the mid troposphere. However because of their marginal horizontal resolution, they are less important for high resolution applications than for global NWP. Ground based microwave radiometers provide information on surface air temperature and mean temperature in the boundary layer with a high temporal but marginal horizontal and vertical resolutions.

The best short-term opportunity for increasing 3-D temperature information is to capitalize on reports available from commercial aircraft world-wide (like for winds). AMDAR programmes should be developed more in data-poor areas, and TAMDAR programmes should be initiated to cover the lower to mid troposphere in a similar way. Temperature can also be deduced from Mode-S data using the reported Mach number, the true air speed and the flight level (which is directly related to pressure). Compared to direct measurements from AMDAR, such information may however be of worse quality. From the space side, apart the continuous progress currently made on the use of microwave sounders, infra-red sounders and radio-occultations, in the long term, a significant advance can be expected from advanced infra-red sounders onboard

geostationary satellites (mainly because of its good temporal coverage on the area viewed by the satellite).

3D humidity field

For global NWP, observing the humidity is generally less important than observing the temperature or the mass field. This is because the global NWP forecast is more sensitive to the temperature (or mass) initial state than to the humidity initial state at large atmospheric scales. This is not the case for mesoscale models for which the initial humidity field becomes as important as the initial temperature/mass field. The humidity acts as a trigger for microphysical processes that are usually explicitly resolved at those scales.

Tropospheric humidity profiles are available from radiosondes over populated land areas, and this is currently the only in-situ observing system providing humidity profiles with a good accuracy to high resolution NWP, except the very few aircraft that are currently testing humidity sensors. In these areas, horizontal and temporal resolution is usually acceptable (but sometimes marginal, due to the high horizontal variability of the humidity field), vertical resolution is adequate and accuracy is good or acceptable. Polar satellites provide information on tropospheric humidity with good horizontal resolution, marginal time coverage and acceptable accuracy. Vertical resolution from passive microwave and infra-red radiometers is marginal, but advanced infra-red systems have improved (acceptable) vertical resolution. As mentioned for temperature, the difficulty to use these radiance data is greater over land than over sea, therefore LAMs suffer more than global models from this deficiency, although the assimilation of humidity-sensitive radiances is progressing continuously. Geostationary infra-red radiances, particularly in water vapour channels, are also helping to expand coverage in some regions by making frequent measurements and thus creating more opportunities for finding cloud-free areas. The total column water vapour is also currently observed (indirectly) by surface GPS networks (over populated land areas), and in the lower and middle troposphere the humidity profile benefits from information coming from GPS radio-occultation measurements. The vertical extent of ground-based microwave radiometers provide information about the integrated humidity restricted to the boundary layer with a high temporal and marginal horizontal resolutions, but with a rather coarse vertical resolution as a result of the weighting functions of the instrument.

The best short-term opportunity for increasing 3-D humidity information is the development of humidity sensors for implementation on aircraft, either aircraft already equipped with temperature/wind profiling capabilities, or new aircraft operating on different areas or in the lower part of the troposphere. In precipitating areas, humidity can be indirectly deduced from weather radar reflectivities with marginal accuracy. Refractivity index, as measured by the latter instruments, can also give an insight of the horizontal variations of the humidity field in the boundary layer. Continuing progress is also expected on the use of existing satellite observing systems, such as sounders, microwave imagers, GPS-radio occultation and ground-based GPS stations. The point made for temperature, about the potential improvement coming from future hyper-spectral infra-red sounders on geostationary satellites, is also valid for humidity in high resolution NWP.

Clouds and precipitation

Because mesoscale forecasts have shorter time-ranges and are more detailed than global models, the early hours of the forecast are relatively more important. Diabatic processes must be properly initialized in order to minimize spin-up times. As mentioned earlier, high resolution NWP models now reach horizontal resolution where convection and convective clouds can be explicitly modelled (rather than parameterised).Weaknesses in data assimilation methods and in the representation of clouds and other aspects of the hydrological cycle within such models is however still a big issue. Improvements in the representation of the moments of the drop size distributions, especially for solid hydrometeors, are for instance needed to improve observation operators. Displacement errors are commonplace and model error can be serious, leading to strongly non-Gaussian variables. Forecast errors are also multivariate and strongly flow-dependent. Although substantial improvements have been made recently in clouds and precipitation data assimilation, the state of the art is fairly less advanced compared to assimilation of temperature, wind or humidity. Still substantial improvements in this area will be needed in order to make more use of the available observations over the next decade.

Observations of clouds still have many issues. Even if satellite visible/infrared measurements give marginal accuracy because of the poor relationships between cloud-top temperature and the underlying clouds and precipitation physics, cloud amount (fractional coverage) and cloud-top height can be retrieved using combinations of channels from imagers or radiometers aboard satellites. Some centres use this information using nudging algorithms in order to make the simulated cloud cover more consistent with the observations, and thus to improve the forecast of variables such as surface air temperature. Microwave measurements are affected by sensitivity to land surface emissitivity and by similar optical properties of cloud water and light rainfall. As a consequence and for high resolution NWP models, microwave imagers and sounders offer information on clouds of marginal accuracy, horizontal and temporal resolution.

After an appropriate quality control, 3D description of precipitation (liquid or solid) is given by reflectivity measurements observed by weather radar with good temporal and spatial resolutions, but with accuracy that depend on its frequency and on the rain intensity. The higher the frequency, the more the signal is affected by rain attenuation. The use of dual polarized technology to correct such attenuation allows however to reach acceptable accuracy. Sea clutters make observations performed by scans at low elevations difficult to be exploited above the sea. Beam blockage is also often an issue in mountainous regions and over populated areas because of buildings.

Clouds and precipitation observations are however very important data to verify model precipitation forecasts and to validate its physical processes. Over land the conventional observations of accumulated observations have a temporal resolution and an accuracy which are highly variable from one region to another. The horizontal resolution is marginal in many areas. Instantaneous precipitation can be deduced from volume scans of reflectivity observed by ground-based radars with good horizontal and temporal resolutions and acceptable accuracy, but over a few land areas only. Such conversion includes however a number of assumptions that highly varies between countries. There is little or no ground truth over oceans, although progress is being

made in developing acoustic rain gauges. Satellite-borne rain radars, together with plans for constellations of microwave imagers, offer the potential for improved observations, but the temporal resolution will still be marginal for a high resolution LAM (unless the constellation contains many satellites).

Precipitation types

Disdrometers provide the drop size distribution and velocity of falling hydrometeors at the surface, some of them allowing them to distinguish between hydrometeor types. Such data, that have good temporal resolution but poor horizontal resolution, could be useful to validate the microphysical schemes used by high resolution models.

In recent years, algorithms making use of data from polarimetric weather radars have been developed in order to retrieve the 3D distribution of precipitation types (rain, hail, snow, species of ice particles…) within precipitating systems with marginal accuracy. Such instrument also allows better characterization of non-meteorological targets and produces accurate rainfall accumulation estimates thanks to a better correction of the signal attenuation. Retrieved precipitation types are however subject to large uncertainties linked to hypothesis made in the retrieval methods, to the beam resolution, to the highly non-linear relationship between the size of the particle and power return and to the frequent presence of non-meteorological targets, especially near the ground. Their use in data assimilation raises the same issues than for clouds and rain, as stated in the previous paragraph. Such information is however of great interest for validating microphysical schemes.

Ozone

Ozone observations are generally not used in high resolution NWP models although they are often used in some global models. The potential ozone observations to be used are the same as for global NWP but they are likely to affect the forecast less because of its shorter time-range.

Sea surface temperature

The information on sea surface temperature (SST) used by high resolution NWP comes from the same observing systems as the ones used in global NWP. Some of these systems are in-situ, some others are space-based, combining information from infrared and microwave imagers and sensors with a good spatial and temporal resolutions. The statements made in global NWP SoG generally apply. Unlike short-range global NWP, a detailed analysis of SST and its diurnal cycle may be needed locally, especially in the case of important precipitation events which are very dependent on the evaporation. In these cases, because of the important cloud coverage, the SST information provided by satellite IR sounders is very limited. Extending the buoy and ship data coverage, which still is often marginal, may thus bring valuable information.

Sea-ice

Sea-ice cover and type are observed by microwave instruments on polar satellites with good horizontal and temporal resolutions and acceptable accuracy. Data interpretation can be difficult when ice is partially covered by melt ponds. Operational

ice thickness monitoring will be required in the longer term, but is not currently planned.

Ocean sub-surface variables

High resolution NWP is aimed at the 1 to 2 day range, and the description of the deep ocean is therefore not required in regional models. In the case of a coupling to an ocean-surface model evolution, locally observations of SST at very high resolution and frequent time intervals are however required.

Snow

Over land, surface stations measure snow cover with good temporal resolution but marginal horizontal resolution and accuracy (primarily because of spatial sampling problems). Visible / near infrared satellite imagery provides information of good horizontal and temporal resolution and accuracy on snow cover (but not on its equivalent water content) in the day-time in cloud-free areas. Microwave imagery offers the potential of more information on snow water content (at lower but still good resolution) but data interpretation is difficult. Data on snow equivalent water content is more important for high resolution models than for global NWP, especially if they are coupled to hydrological models. Snow cover over sea-ice also presents data interpretation problems, but this is less crucial for high resolution NWP than global NWP because of the very few models covering such areas.

Soil moisture

The information on soil moisture used by high resolution NWP comes (and will come in the future) from the same observing systems as the ones used in global NWP (see SoG for global NWP). A higher resolution estimation of soil moisture is much more important for high resolution models as they intend to describe details of the land surface which are normally not included in global models. Together with snow depth, vegetation and other parameters, soil moisture is very important for processes describing the surface fluxes and the atmospheric boundary layer. Measurement accuracy of microwave radiometers, as well as temporal resolution, is generally good, while the horizontal resolutions still is, at best, marginal.

Surface air temperature and humidity

Because they are more representative of their mesh size, the use of surface air temperature and humidity is more important in high resolution atmospheric analyses than in global analyses. The 2m temperature and humidity observations are also often used to provide indirect information to soil moisture and skin temperature in the models, because direct soil measurements are lacking most of the time. Over land, surface stations measure with horizontal and temporal resolutions which are good in some areas and marginal in others. Measurement accuracy is generally good, though this can be difficult to use where surface terrain is not flat, because of the sensitivity of the measurements to local variability that high resolution NWP models still resolve more accurately than global models. Satellite instruments do not observe these variables, or do so only to the extent that they are correlated with geophysical variables that significantly affect the measured radiation (i.e. skin temperature and atmospheric layer-mean temperature and humidity). Over ocean, the same observations are used as in global NWP, and the same statements apply. Upstream of populated areas, it may

however be of interest to icrease their spatial coverage.

Land and sea-ice surface skin temperature

The same observations are used and the same statements apply as the ones of global NWP. The same difficulties of interpretation and representativeness exist, but they are continuously reduced with the reduction of model mesh sizes which become more and more representative of the horizontal scale of the observations.

Vegetation type and cover

Same remarks as before for land and sea-ice surface skin temperature.

Wave height, direction and period

High resolution models are generally not used as input in wave models, mainly because they are more likely to cover land areas than ocean. For marine applications, several operational wave models are rather using information from regional or global NWP models (mainly the surface wind over sea). The corresponding observing systems are buoys, ships, altimeters and radars on polar orbiting satellites.

3D aerosol

The remarks made for ozone are also valid for aerosol: aerosol assimilation is immature in high resolution NWP. When it becomes mature, the potential observing systems to be used are satellite imagers, polar orbiting satellite radiometers, which provides information on the total vertical content. Lidar measurements will be required to provide vertically resolved information, but only demonstration lidars exist.

Additional observations for model validation

Compared to global NWP models, high resolution ones have higher requirements in terms of horizontal resolution over land, for validation and verification. This is especially true for precipitation observations (already mentioned before). Other parameters are the same as for global NWP, but with more emphasis over land, and stronger requirements on horizontal/temporal resolution: radiation fluxes, surface emissivity and surface albedo.

3. Summary

High resolution NWP centres:

- make use of the same observations as global NWP, except the ones in the upper stratosphere and mesosphere, plus some local surface-based observing systems , mostly located over land (like weather radars which are generally unused in global NWP);

- are less dependent on polar orbiting satellites than global centres, and more dependent on geostationary satellites or surface-based observing systems;

- have tighter operational constraints on the assimilation computer cost, which makes it more difficult than in global modelling to draw the full benefits from 4D data assimilation systems; more frequently cycled assimilation strategies are usually used to alleviate this problem.

- are still doing a lot of research on advanced data assimilation algorithms in order to make better use of cloud and precipitation observations.

- are faced with a variety of observation densities, depending on the area where they operate;

- would benefit from increased coverage of data in the boundary layer, which is characterized in particular by high vertical resolutions in the models

- would still benefit from increased coverage of aircraft data in all the regions of the globe, particularly from ascent and descent profiles;

- would benefit from in-situ high resolution observations over sea areas upstream of populated areas, or of high-impact weather areas

- are likely to draw more benefit in the future from Doppler radar data (including precipitation types deduced from polarimetric measurements) and from ground-based GPS stations (which are relatively new observations in terms of assimilation).

The critical atmospheric variables that are not adequately measured by current or planned systems are (in order of priority):

- wind profiles at all levels;

- temperature and humidity profiles of adequate vertical resolution in cloudy and rainy areas;

- precipitation;

- snow equivalent water content;

- soil moisture.

Focus should particularly be made on boundary layer observations, as this is where the NWP vertical resolution is highest and so the vertical resolution gap (especially compared to satellite data) is largest.

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