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EUMETSAT POSITION PAPER ON OBSERVATION REQUIREMENTS FOR NOWCASTING AND VERY SHORT RANGE FORECASTING IN 2015-2025

The attached document is submitted for information.

EUMETSAT Position Paper on Observation Requirements for Nowcasting and Very Short Range Forecasting in 2015-2025

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Executive Summary

Introduction

This paper provides a forecast of observation requirements in nowcasting and very short range forecasting for the period 2015-2025. Nowcasting and very short range forecasting encompass a wide range of user-driven services using appropriate meteorological and related science to provide information on expected conditions up to 12 hours ahead.

In an environment of rapid change, both in the requirements for meteorological and related services, and in the capability to produce and deliver them, such a forecast must be treated with caution.

Service Requirements

The requirement for nowcasting in 2015-2025 will be more demanding than the current requirement due to increased weather sensitivity arising from: climate change, greater concerns about gaseous pollution, the need to protect from accidental toxic releases, increased urbanisation, and a more protected lifestyle.

The ability to deliver nowcasts and very short range forecasts in 2015-2025 will be greater due to increases in computer power, improved observations (including weather radar and satellite sensing), improvements in science, but, above all, due to improvements in the telecommunications technology supporting dissemination to users.

The result will be both a continued increase in the provision of warnings of meteorological and related hazards, and a major development of general very short range forecasting in support of economic and leisure activities.

The key areas for which warnings will be required are:
- Threats to life
- Threats to property
- Threats to transport (air, land & sea)
- Threats to utilities (electricity, gas, fuel, water, drainage, telecommunications)
- Threats to industry (mainly construction on land & sea)
- Threats to the environment

The main areas for which general forecasts will be required are:
- Utilities (consumption and production planning)
- Transport (least time routing)
- Recreation (on land, sea & air)
- Agriculture, Horticulture, Water Resources
- Fishing
- Security & Law Enforcement

Key requirements for observational breakthroughs

The impact of improvements to observations has been assessed for the forecast service requirements using appropriate nowcasting and very short range forecasting techniques and have then been analysed to identify the key breakthroughs. The dominant forecasting method in 2015-2025 is expected to be Numerical Weather Prediction (NWP) which by then will be able to resolve the scales of interest in very short range forecasting. Observational breakthrough requirements for NWP are included in the position paper for Regional NWP and not here. However, those requirements should be considered of the highest priority for the applications listed in this paper.

Observation/extrapolation

The simplest approach to forecasting, suitable for warnings of severe weather already occurring, is to observe the hazardous weather and extrapolate, either using persistence or continued movement without change. This technique is suitable for a wide range of phenomena as listed below.

Precipitation
- Reliable detection (10km, 1hr) for general forecasting – to remove current problems with radar spurious echoes and missed light rain at long range.
- Accurate high rates (within 10mm/hr at 2km, 15min) for flooding – to improve on radar accuracy.

- Information over the sea (within 5mm/hr at 10km, 1hr) for general forecasting – to provide upwind information beyond radar range.
- Snow detection (within 0.2mm/hr at 10km, 1hr) for transport warnings.
- Large hail detection (10km, 15min) for protection of life and property.
- Freezing rain detection (10km, 1hr) for protection of life.

Wind
- Strong wind (10km, 1hr) for protection of life and property.
- Severe wind in tornadoes/gust fronts (200m, 5min) for protection of life.

Cloud
- Profile below 2km (10km, 1hr) for VFR aviation

Visibility
- Thick fog (5km, 1hr) for land transport.
- Fog (20km, 1hr) for marine transport
- Visibility (20km, 1hr) for VFR aviation

Land surface
- Flood area or depth (1km, 1hr) for rescue support
- Snow fraction (10km, 6hr) and depth (1km, 15min) for land transport and property protection.
- Location of fire (1km, 1hr) or smoke (10km, 1hr) for fire fighting and protection of life.

Icing & Frost
- Ice depth (1km, 1hr) for safety of life from falling towers and trees.

Aviation Turbulence
- Vertical velocity variance (50km, 1hr) for aviation warnings of CAT.

Ocean
- Wave height (10km, 1hr) for safety of small ships and ferries.
- Surge height (10km, 1hr) for coast protection.

Pollution
- Volcanic ash (10km, 1km, 1hr) for aviation warnings.
- Toxic chemical releases (1km, 1hr) for evacuation of downwind areas.
- Surface ozone concentration (10km, 1hr) for health warnings.
- Detection of oil spills (1km, 1hr) for environmental damage and public safety.

Convection forecasting techniques

Due to their importance as sources of severe weather, including lightning, hail and tornadoes, there are many techniques available which assist in prediction of convective storms.

Early warnings
- Temperature/humidity profile (50km, 2km, 3hr) for diagnosis of instability.
- Boundary layer wind (10km, 1km, 1hr) for identification of convergence areas.

Initiation
- Strength of capping inversion (30km, 200m, 30min) to track erosion ahead of initiation.
- Height of boundary layer top (30km, 30min) to track rise ahead of initiation.
- Cloud imagery (500m, 5min) to identify cloud lines indicating local convergence.

Monitoring
- Convective cloud rise (500m, 5min) to indicate possible development of severe weather.
- Intense rain (5km, 30min) indicating possible development of hail & lightning.

Non-convective forecasting techniques

Out of the wide variety of techniques available for short-range prediction of non-convective phenomena, the following have been selected as potentially benefiting directly from improved observations.

Mesoscale Precipitation

- Low level wind and humidity (10km, 1km, 1hr) for calculation of orographic precipitation enhancement.
- Melting level (10km, 1hr and rain rate (5km, 1hr) for predicting lowering of the melting level to give snow at the ground.

Fog and Low Cloud

- Surface temperature and humidity (5km, 30min) to track the approach to saturation and fog formation.
- Detection of shallow fog (5km, 1hr) as a precursor for fog development.
- Surface wind speed (5km, 30min) to detect calm conditions suitable for fog formation.
- Fog top height (5km, 30min) to detect resistance of fog to clearance and to track lifting into stratus.
- Fog area (5km, 1hr) to track erosion from edges.

Ocean models

Numerical models of ocean structure and surface waves, driven by atmospheric forcing, are increasingly complementing the role of NWP for marine requirements.

Wave models

- Wave energy spectrum (50km, 6hr) for initialisation of wave trains.
- Wind vector (50km, 6hr) for hindcasting wave trains.

Surge models

- Surface elevation (50km, 6hr) for initialisation of surges.

3D Ocean models

- Sea surface temperature (50km, 6hr) for initialisation of coastal ocean structure.

Land surface & hydrological models

At present, hydrological models and related models are run at a resolution too fine to be integrated with NWP and require observations at too fine a resolution for standard surface observing networks. Developments in the next 15 years are expected to lead to much greater integration of these vital hazard warnings systems.

Run-off models

- Rain and snow rate (5km, 15min) for hindcasting soil moisture and run-off.
- Soil moisture (50km, 1day) for initialisation.
- Snow water equivalent (5km, 1day) for initialisation.

Snow models

- Snow water equivalent (500m, 2hr) for initialisation.
- Snow rate (1km, 1hr) for hindcasting snow water equivalent.

Icing models

- Supercooled liquid cloud (50km, 1km, 1hr) for aircraft icing.
- Fog water and surface temperature (1km, 1hr) for icing of surface structures and public safety.
- Surface temperature (1km, 1hr) for road state.

Fire models

- Soil moisture and vegetation stress (3km, 1day) for fire risk warnings.
- Wind vector, soil moisture & vegetation stress (1km, 10min) for fire motion forecasts.

Dispersion, Chemistry & Biology Models

Dispersion and chemistry models are normally driven by NWP output except where simpler systems are required for very fast response, where single measurements for a nearby location are used. As systems become more integrated and responsive, the integration with NWP is expected to grow.

Dispersion models

- Boundary layer wind vector and stability (10km, 1hr) for short-range dispersion of toxic releases.
- Location of airborne material - industrial chemical, radioactive material, biological pathogens, smoke (50km, 1hr) for initialisation.
- Location of volcanic ash (50km, 3km, 1hr) for initialisation.

Air quality models

- Total column concentrations of ozone precursors - Ozone, Carbon Monoxide, Nitric Oxide, Nitrogen Dioxide, Formaldehyde, Volatile Organic Compounds, and Aerosol (10km, 1hr) for initialisation.
- Concentration of PM10 particles (10km, 1hr) for initialisation.

UV radiation models

- Total column ozone (50km, 6hr) for calculation of UV transmission and model initialisation.
- Total column aerosol (20km, 1day) for calculation of UV transmission.

Surface pollution models

- Wind vector and current vector at sea (5km, 1hr) for movement of oil slicks
- Wave height (5km, 1hr) for break-up of oil slicks.

1. Background

Unlike longer range forecasting, which has developed largely in response to improved forecasting methods, very short range forecasting had always been closely tied to meeting particular requirements. Indeed, the methods used have often been developed specifically to meet the needs of a particular customer in a particular country. In forecasting the requirements for observations to support nowcasting and very short range forecasting up to 2025, it is therefore necessary to ask what the demand for meteorological services will be? In order to answer this question, we must first identify the likely changes in human society that will impact on requirements for weather and associated environmental information. In this section we address that question, starting from an analysis of current requirements, then looking at the impact expected from social changes, and then addressing the technical changes that will affect the way in which requirements may be met.

1.1 Current status

The requirement for nowcasting is currently dominated by warnings of hazardous events. While general hazards are included, the main emphasis is on specific sectors, where there are well-developed means for responding to warnings. Historically, these have developed differently in each sector:

- Warnings to shipping date back to the earliest formation of weather services, and are exemplified by the gale warnings which were originally promulgated by visual signals at ports (cones and lights) and later by radio.

- Civil aviation has a large set of warning criteria, addressing the needs of different levels of poor weather capability in both aircraft and aerodrome. The main warning mechanisms are TAFs for aerodromes and SIGMETs for in-flight weather.

- With the development of road transport in recent years, warning procedures for winter weather conditions such as ice and snow have been developed in many countries, allowing road treatments to be deployed before the conditions reach the stage that major accidents are caused.

- Many countries have well developed flood warning procedures, often described by coloured warning states, allowing protective measures to be taken, and evacuation if necessary.

- Following Chernobyl, additional warning procedures have been put in place for radioactive and toxic chemical releases.

More general warnings have become possible with the development of mass communications, particularly television. In the UK, a system of early and flash warnings has been developed for severe conditions likely to cause loss of life, including severe winds, snow and heavy rain. Similar services are provided in other countries tuned to the hazardous weather that they suffer from.

Most of these warnings are provided with lead times of up to twelve hours, depending on the predictability of the event and the ability of the recipient to respond. Whereas, historically, a warning was often not issued until the event was observed, meteorological services are increasingly required to provide a forecast so that mitigating actions can be undertaken.

1.2 Social changes

1.2.1 Global Warming

- Climate change will result in increasing mean temperatures. Areas suffering seasonal hazards will change as the freezing and heat stress zones move.
- Climate change will result in higher sea levels resulting in an increased risk of coastal flooding.
- There is some evidence from climate simulations that parts of Europe will experience increased frequency of storms and floods
- There may be an increase in avalanche and landslide frequency in some mountainous regions
- If such hazards occur more frequently, the population may be more receptive to warning procedures, making forecasts more valuable, even at very short lead times.
- If hazards are more widespread as well as more frequent, as might happen if winter storms produce heavier precipitation, the logistics of evacuation will become more difficult, requiring increased warning lead-time.

1.2.2 Gaseous Pollution

- Levels of gaseous pollution, arising mainly from transport vehicles, have been rising steadily and now regularly reach dangerous levels in many European cities.
- Projections of vehicle growth indicate that pollution levels will continue to rise, even if there is a move to alternative fuels.
- Responses to this could include warnings to susceptible people, and forecasts to enable control strategies to be exercised.

1.2.3 Accidental Toxic Releases

- The frequency of accidental toxic releases has been rising on land and on the sea due to increased transport and use of such substances.
- With increasing demands for cheap consumer goods more complex chemicals will continue to be developed, many of which will be toxic.
- With increasing consumption, transport of large quantities of petro-chemicals will continue.
- Demands for protection of an increasingly fragile natural environment, with a greater number of species at risk, will lead to an increasing requirement for detection and forecasting of the movement of toxic material.

1.2.4 Urbanisation

- Assuming a continued trend to development of "mega-cities", there will be an increasing need to identify and isolate limited urban areas quickly.
- As the population becomes more urbanised it is likely that perception of the impact of natural events will decrease through the increasing insulation provided by urban infrastructure.
- Greater efforts will be required to maintain readiness to respond to hazardous events.
- Urban populations will be especially vulnerable when travelling, leading to greater need for active traffic control in hazardous weather.
- If development continues on flood plains, this will lead to increased risk of flooding.

1.2.5 Leisure

- Increased leisure time, especially amongst the increasingly aged population
- Increased travel, especially by air
- Increased participation in weather sensitive sporting activities
- Increased tourist pressure on wilderness areas, and hence for environmental warnings there

1.2.6 Agriculture

- The last half-century has seen tremendous intensification of agriculture in Europe and the "Green revolution" in the Tropics. Continuation of this trend might be expected to depend on the increased use of weather information to optimise timing of chemical and other treatments.
- Current trends indicate pressure for a move away from intensive agriculture in Europe. Optimisation of yields in a less controlled environment could be assisted by careful use of weather information, though this is likely to be most beneficial at the seasonal time-scale.
- In the developing world, introduction of genetically modified crops may be the next big change
- Use of more advanced techniques such as micro-irrigation are likely to benefit from improved meteorology
- Use of weather nowcasts in agriculture is and will remain very limited

1.2.7 Other

- An increased use of legal action, such as currently seen in the USA, will have an effect on the way in which warnings are issued.
- If home working replaces office working on a large scale, this could dramatically change both housing and transport patterns, possibly leading to many people having reduced weather sensitivity during their working hours.

1.3 Technical Changes

1.3.1 Communications technology

- The telegraph is ~160 years old. National Meteorological Services came into being in all developed countries within a short period after its invention. Electronic communication is fundamental to meteorological services.

- The Internet is ~20 years old. Most meteorological services are or soon will be available by e-mail, FTP, or through public or private web sites.
- The mobile phone is less than 10 years old. It is revolutionising the way meteorological services are provided. Within the next 10 years, it is expected that mass-market mobile communications devices will have the capacity to carry digital TV quality information and provide full access to the Internet.
- Through mobile phones, it is possible for the location of the enquirer to be provided automatically, so that automatically updated user-specific nowcasts can be delivered
- In combination with GPS route finders, it will be possible to provide automatically updated route nowcasts
- Current 2-way traffic is very limited through mobile phones. One might expect that restrictions will reduce on the 20-year time scale, enabling locally sensed data (e.g. by digicam) to be uploaded, analysed and returned.
- Noting the trials of instrumented roads in Austria and Finland, it is likely that the capability for responsive road control will become widespread enabling real time response to both local measurements and remote forecasts.
- We can expect another major communications innovation within the next 25 years. This may be expected to have as great an impact on weather services.

1.3.2 Observational technology

- Improved instrument technology, including remote sensing developments, will enable current and future requirements for meteorological and related observations to be met more easily and effectively.
- Increased demand for telecommunication bandwidth is likely to restrict the availability of microwave channels for space-based remote sensing.

1.3.3 Prediction methodology

- Increased automation resulting from improved NWP and nowcast techniques.
- The need to represent the predicted weather as a probability distribution is increasingly being recognised, and the tools developed to achieve it. On the time-scale of this study, all forecasts should be generated in probabilistic form, even if many customers continue to receive the "most likely" forecast (i.e. the mode).
- Increased integration of atmospheric and related processes into NWP, including ocean, waves, hydrology and chemistry. These processes, currently dealt with separately, are already becoming more integrated in climate modelling, and this will become the case in NWP as well. However, computing power constraints will probably prevent full integration on the time-scale of this study.
- New prediction model components to deal with biological processes are already being incorporated into climate models, and will probably be added to basic NWP and ocean models on this time-scale. These include terrestrial vegetation growth, and marine algal growth.
- Increased collaboration between forecast centres.
- Increased use of specialist centres dealing with a particular type of forecast over a wide area.

1.3.4 Computational technology

- The computer industry yardstick for growth of processor speed is x2 every 18 months. This gives growth of x1000 in 15 years and x100,000 in 25 years
- Each factor of 2 increase in NWP resolution requires a speed increase of up to x16, allowing for horizontal & vertical grids and a commensurate reduction in time step.
- Suggested processor growth allows a resolution increase of x6 in 15 years and x18 in 25 years.
- Thus we can expect 10km global grids and 1km regional grids during the lifetime of MTG, if not by the time of its launch.
- 1km grid regional models should be able to provide nowcasts of better quality than alternative nowcasting techniques for all periods beyond 1hr ahead.
- Chemistry models can be expected to be running operationally with a global grid length of ~50km and a regional grid length of ~10km on this time-scale.
- New processing techniques such as Geographic Information Systems (GIS) will change the way that end products are generated.

2. Nowcasting & Very Short Range Forecasting Services (0-12 hours lead time)

Nowcasting and very short range forecasting have traditionally been used mainly for the preparation of warnings of severe weather. The main reason for this has been the cost of ensuring receipt and response to the warning. Although warnings remain the most important use, recent developments in communications technology have made it possible for such forecasts to be received and used much more cheaply and easily. Applications of such information include leisure use, e.g. deciding whether to play a round of golf, and economic use, e.g. least time ship routing.

2.1 Warnings

Generally require a dissemination mechanism which alerts the vulnerable user. Response to warnings is a major problem. Warning services are justified only if the warning will reach the user and will be acted on. Dissemination is characterised by selective delivery using phone, radio, television, and personal calling. As capabilities increase, it should be possible to more precisely define the nature and location of the hazard, enabling mitigating actions to be taken more confidently. If systems are sufficiently accurate and reliable, it may be possible to deliver personal tailored warnings. In the following sections, detailed requirements for warnings are listed for different categories of threat. The information is expanded in Annex A under the four headings: impact, response, requirement and method. Impact describes the effect of the hazard, i.e. the nature of the threat. Response describes the way in which the hazard can be mitigated or avoided – there is no benefit in having a warning if there is no response, which will at least mitigate the impact. Requirement gives the information needed to enable the response to be made. This is not necessarily a meteorological requirement. Finally, Method indicates the tools that could meet the requirement. As far as possible, these are listed using the same headings as section 3 of this paper.

2.1.1 Direct threats to life

- Accidental releases of toxic gases & aerosols (chemical & radioactive)
- Accidental releases of toxic liquids (land & sea)
- Smog - elevated levels of gaseous pollutants including allergenic chemicals and aerosols, (industry, traffic, biomass burning, volcanic releases etc.)
- High UV levels
- Hail
- Lightning
- Floods
- Avalanche
- Snow and Ice
- Mud Slide
- Fire
- Wind chill
- Heat stress
- Freezing precipitation
- High Waves
- Storm Surge
- Severe wind (extratropical cyclone, tropical cyclone, local wind, gust & tornado)
- Toxic algae

2.1.2 Threats to property

- Severe wind (extratropical cyclone, tropical cyclone, local wind, gust & tornado)
- River or Surface Water Flood
- Large Hail
- Avalanche
- Heavy Snow
- Storm surge
- High waves
- Fire

2.1.3 Threats to transport

2.1.3.1 Air

Aerodrome and approaches

- Visibility (Fog and Low Cloud)
- Snow on the ground
- Icing conditions on the ground
- Strong surface winds, gusts, and wind shear (including microbursts)
- Heavy precipitation
- Wake vortices

In flight

- Turbulence (near jet streams and convective clouds)
- Volcanic ash
- Icing
- Low cloud and visibility-
- Cabin ozone
- Cosmic rays
- MSL pressure

2.1.3.2 Sea

- High wind
- Waves
- Fog
- Icing

2.1.3.3 Land

- Thick fog
- Heavy rain / Surface Water Flood
- Freezing precipitation
- Snow
- River flooding
- Mud slide/Avalanche
- Ice/frost
- Strong wind
- Sand /dust storm

2.1.4 Threats to utilities

Gas supply

- River flooding
- Mud slide/Avalanche

Electric supply

- Lightning
- High wind
- Icing

Water supply

- River flooding
- Mud slide/Avalanche
- Freezing temperatures

Liquid fuel supply

- Lightning

Drainage

- Flooding

Telecommunications

- Lightning and other electromagnetic disturbances (e.g. space storms)
- High wind
- Icing
- Precipitation and cloud

2.1.5 Threats to industry/business

Land Construction

- High wind

Offshore exploration & production

- High wind/waves

2.1.6 Environmental Threats

- Acid rain - requirements are at time scales greater than 12 hours
- Marine toxic releases

2.2 General Forecasts

The user will seek this information actively. It will often be required in conjunction with other sources of information such as traffic or sports fixtures etc. Dissemination is characterised by selective receipt using fixed or mobile phone, Internet etc. Such forecasts will, of course, include any hazard warnings in force, as described in section 2.1. The activities affected are listed here and more information is given in Annex B, including the variables of interest, the impact on the activity, the response that can be made given a forecast, the information required to enable the response to be made, and the forecasting method(s) for generating the required information.

Utilities

- Power demand planning
- Wind power
- Wave power
- Solar power
- Water demand planning
- Telecommunications
- Building control

Transport – least time route planning

- Air
- Sea
- Land

Recreation - planning a day or half day activity

- Land
- Sea
- Air

Agriculture/ Horticulture/Water resources

Insurance and Weather Derivatives

- Insurance of life and property
- Weather Insurance
- Weather Derivatives

Fishing

Security & Law Enforcement

- Target Acquisition
- Movement of personnel & equipment
- Ballistic accuracy
- Dispersion of toxic substances

3. Prediction Methods

As very short range forecasting shifts from nowcasting techniques to storm-scale NWP models, it is anticipated that the requirement for input information will shift from the existing distribution of the forecast variable, towards the underlying state variables (such as humidity), forcing variables (such as surface temperature) and proxies for these variables (such as cloud for humidity). Skilful convective forecasting, for instance, is currently dominated by extrapolation of existing rainfall areas. The skill of storm-scale NWP models will depend more on the assimilation of detailed wind and humidity information, and on an accurate representation of the surface characteristics, including vegetation and soil moisture. On the time-scale of interest it is anticipated that extrapolation and diagnostic techniques will remain the main nowcasting tools up to one hour ahead, and that NWP products will dominate for longer lead times, supported by diagnostic techniques for specific weather features. Requirements for diagnostic techniques are particularly difficult to define since a strong prediction may come from the combination of a number of weak indicators.

3.1 Observation/extrapolation

Nearly all service requirements include a contribution from observation and/or extrapolation of the existing state of the variable of interest. Even where the lead time requirement is such that an observation is of little direct help, it can offer reassurance that the forecast evolution is being followed. Since extrapolation is a technique appropriate only to very short lead times, the variables of interest are largely limited to those that directly pose a threat to life and property.

Use of extrapolation to forecast for a very short time ahead is at the heart of nowcasting. Its usefulness depends on the lifetime of features in the distribution of the variable concerned. At its simplest, persistence is a good forecast for many weather variables up to an hour or so ahead. Others, such as cloud and precipitation, are better predicted by extrapolating previous motion - or equivalently, by using persistence in a Lagrangian framework. Nowcasting schemes in operational use sometimes combine multiple extrapolation estimates obtained by identifying different lifetimes and motion for different scales of feature.

Where a realistic NWP prediction is available for the variable of interest, an extension of the extrapolation approach is to use persistence or extrapolation of its difference from current observations.

The observational requirement for these techniques is for spatial distribution at the resolution needed by the application, and temporal distribution at a fraction of the time-scale of variation. To achieve a true weather watch requires observations at least every 5 minutes. However, depending on the response time to a warning, there may be no benefit in obtaining an observation more frequently than every 15 minutes, especially if it includes information on the history since the last observation.

The requirements for observation/extrapolation are categorised according to groups of related observables under the following headings:

- Surface Precipitation
- Surface Wind
- Surface pressure
- Cloud
- Surface visibility
- Land surface
- Lightning
- Icing & Frost
- Aviation turbulence
- Ocean
- Pollution

3.2 Convection forecasting techniques

Convection forecasts are required for protection of life and property from flood, hail, lightning, snow, mudslide, avalanche & tornado, for aviation safety from heavy precipitation, turbulence and icing, for land transport from heavy precipitation and flood, for telecommunications from heavy precipitation and cloud, for power demand from low illumination and for leisure.

Convection is currently predicted poorly. NWP models can only predict its occurrence and properties statistically over broad areas. Current nowcasting methods predict movement of an existing storm, but are unable to predict initiation or development with any accuracy. By the period of interest for this study, computers will be powerful enough to enable regional NWP models to resolve the structure of convection. However, there are many difficulties to overcome, mainly in initialising the models and in interpreting their results. It is also necessary to run them very quickly if up-to-date observations are to be utilised. It is therefore anticipated that simpler diagnostic techniques will continue to be used and developed for lead times of an hour or so ahead.

Convection occurs when a vertical displacement of the air results in buoyant acceleration upwards. In the context of this study, only deep cloudy convection is of interest, with cloud base typically at the top of the boundary layer and cloud top at the tropopause or at a lower stable layer. Depending on the environment in which the convection occurs, it may occur as isolated cells, with a lifetime of up to one hour, as a succession of cells, as a long-lived supercell, as a squall line, as a mesoscale convective system or embedded in a front. Convection is associated with heavy rain, which may cause flash floods, snow, hail, which may be large and very damaging, outflow wind gusts, downbursts, which can cause plane crashes, tornadoes, and lightning or other electrical phenomena.

The techniques available to support forecasting are very varied, most being based on a combination of remotely sensed observations and NWP diagnostics. Forecasting of convection is organised in three phases:

Early warning
This phase is dominated by the use of NWP or observed diagnostic fields to assess areas at risk and of the likely characteristics of any convection that will occur.

- Instability (intensity and location)
- Low-level convergence (location)
- Moisture convergence (location)
- Helicity (character)
- Wind shear (character)
- DCAPE (negative buoyancy) (character)
- Vertical velocity (intensity and location)

Initiation
A wide variety of diagnostics is used to refine NWP guidance in providing an indication of the imminent outbreak of convection.

- boundary layer height and capping inversion erosion (timing and location)
- arc cloud lines (timing and location)
- cumulus-scale cloud top rise (timing and location)
- gravity waves (timing and location)
- low level convergence (timing and location)
- surface air temperature or land surface temperature (timing and location)
- solar radiation shielding by aerosols or upper level clouds
- low-level moisture and moisture tendency
- upper level cold advection (intensity)
- meso-scale pressure lows
- potential dry rear inflow (intensity)

Monitoring
Once convection is in progress, observation/extrapolation forms the basis for predicting the locations of severe weather. The following diagnostics are used:

- cloud top rise (intensity)
- precipitation profile (indicates severe characteristics)
- electrical activity (IC and CG) (intense rain & hail)
- squall line organization occurrence (gusts / microbursts, new cells)
- meso-gamma scale vortices (tornadoes)
- overshoots life cycle (intensity)

3.3 Non-convective forecasting techniques

The general structure of non-convective systems is well handled by NWP systems at 24 hours ahead and more, so nowcasting is relevant primarily to those systems that are less predictable, such as intense cyclones, and to the less predictable details of the weather within a well-predicted system, such as cloud and precipitation areas, fog and low stratus areas and local wind systems.

Extra-tropical cyclones
Extra-tropical cyclone forecasts are required for protection of life and property from damaging winds and for land transport from high winds.

Intense extra-tropical cyclones produce areas of strong pressure gradients and gale force winds associated with heavy precipitation and severe turbulence. NWP models predict the general structure of such systems adequately, but are unable to pinpoint the location of local wind maxima. Enhancement of NWP forecasts is carried out by comparing with observations and then extrapolating forward the differences. This requires near surface wind and pressure information at fine space and time resolution.

In the summary of requirements this is included under observation/ extrapolation. Techniques for longer lead times may also remain useful and are based on interpretation of developmental cloud patterns such as the baroclinic leaf. These show humidity structures which are correlated with potential vorticity structure that is favourable for rapid development.

Tropical cyclones
Tropical cyclone forecasts are required for protection of life and property from damaging winds and for land transport from high winds.

NWP models are becoming increasingly reliable at predicting the track of tropical cyclones once they have formed. There is also strong evidence from experimental studies, that NWP prediction of intensity will have reasonable accuracy once model resolution becomes fine enough, as it will on the time-scale of interest. Nevertheless, it will remain necessary to identify the small-scale structure which differs from the model evolution, and to extrapolate it. This requires near surface wind, precipitation and sea state information at fine space and time resolution. In the summary of requirements this is included under observation/extrapolation.

Local wind systems
Local wind forecasts are required for protection of life and property from damaging winds and for land transport from high winds.

In certain areas, the weather can be dominated for substantial periods by local wind systems. These mainly occur through the control of low level stability on airflow over or around mountainous obstacles. When flow over the mountains is permitted, the result can be sudden onset of damaging winds, either cold or warm according to the location, which may then last for several days. Apart from using NWP, nowcasts of these events can be produced by monitoring the balance between pressure gradient forcing across the mountains and the resistance to motion from the low-level thermal stability of the upstream air. The stability is modified locally by surface heating, modulated by cloud cover and snow cover.

Mesoscale Precipitation
Precipitation system forecasts are required for protection of life and property from flooding and dangerous snow accumulations, for land transport from flooding, heavy precipitation, snow, avalanches and mud slides and for aviation from heavy precipitation and snow.

Areas of precipitation produced by macro-scale or mesoscale ascending motion may lead to heavy rain or snow or freezing rain causing dangerous conditions especially for land transport. There is also danger of aircraft icing in clouds with supercooled droplets. The two main sources of mesoscale precipitation enhancement are slantwise circulations in a baroclinic atmosphere, and low level feeder clouds generated by orographic uplift. Tracking of existing cloud and precipitation areas is covered in the observation/extrapolation section 3.1.

Prediction of the intensity of slantwise ascent requires knowledge of the slantwise CAPE (SCAPE), constructed from the velocity, thermal and humidity fields at high vertical and horizontal resolution.

Prediction of low level orographic enhancement by feeder clouds requires the boundary layer wind, humidity and cloud water / ice.

Prediction of local snow in widespread precipitation requires knowledge of the height of the melting layer and its rate of descent due to melting of the precipitation.

Fog and low cloud
Fog forecasts are required for transport on land, sea and air.
Areas with fog or low stratus develop due to radiative cooling or mixing or other processes. Fog is a severe hazard for all forms of transport, especially for aviation, which is also affected by stratus cloud. Forecasting techniques are available for fog formation and fog clearance. Tracking of existing fog or stratus is covered in the observation/extrapolation section 3.1.

Prediction of nocturnal fog formation is carried out using energy-based techniques to predict cooling of the air until saturation is reached. Surface cooling is modified by cloud shielding and by turbulent mixing. The height at which cloud will form also depends on mixing, and hence on the wind profile. Fog formation is strongly modulated by surface moisture sources such as lakes and rivers and by drainage flows in heterogeneous terrain.

Prediction of diurnal fog clearance is based either on advection of a higher cloud sheet or on diagnosing the solar energy required to evaporate the fog, taking account of the radiative effects of the fog itself. For stratus clearance, the main mechanism is boundary layer mixing from beneath, prediction of which is also based on energy considerations.

3.4 Storm-scale NWP models

NWP models provide predictions of virtually all hazards for protection of life, property, transport and utilities from wind, heavy rain & snow, supercooled water, cloud and visibility, and by inference of hail & lightning, turbulence, icing. NWP also provides information on surface pressure, temperature and humidity.

There is now considerable experience in data assimilation for mesoscale models with grid lengths of 10-20km. Most such models use the same approaches as have been developed for larger scale NWP, with modifications to allow assimilation of additional data types. However, there have been some limited developments of data assimilation techniques specifically for mesoscale / storm scale NWP.

Dynamical theory suggests that geostrophic adjustment of the mass to the wind field will occur at small scales in the free atmosphere. Thus we may infer that for accurate prediction of intense cyclones and of frontal structure, the dominant additional requirement is for finer scale winds. Provision of this information is currently being developed using a mix of automatic aircraft relay data, radiosondes, wind profilers, Doppler radars, and satellite cloud track winds. With the introduction of 4D-VAR, it should be possible to gain additional tracer information implicitly, e.g. from satellite and radar imagery.

Unfortunately, this picture is complicated where ageostrophic motions dominate, as is often the case in areas of moist uplift. Here the distribution of moisture may be the dominant additional requirement. Currently, humidity is obtained largely from radiosondes, which are sparse in time and space and have poor accuracy near saturation. Cloud imagery has been successfully used to infer humidity in the Met Office mesoscale model for many years, and tests have shown that this data source is one of the dominant contributors to forecast quality. In the near future AMSU-B satellite soundings will provide significantly improved humidity data, especially over the sea, though at low temporal resolution. Assimilation of precipitation information, although very indirect, has also been shown to benefit predictions of mesoscale precipitation systems. Increasing amounts of microwave data are becoming available (e.g. TRMM) in addition to existing sources of radar data over land areas.

In the boundary layer, atmospheric evolution is dominated by surface forcing and stability structure. Knowledge of the height and strength of capping inversions is critical to prediction of many boundary layer features such as fog and stratus, and initiation of convection.

While most of the required phenomena are already predicted, to some extent, by existing mesoscale NWP models, convective phenomena are currently inferred diagnostically and direct prediction will be a new capability on the time scale of interest. Successful predictions of initiation of convection in forced environments have been published. However, these are subject to significant error, when considered as nowcasts. In order to provide accurate 1-2hr predictions, it will be necessary to accurately represent the conditions leading to initiation and the structure of existing storms. This will require a sophisticated 4-D assimilation procedure, such as 4D-VAR, which can directly assimilate fine space & time scale radiance and velocity measurements , but much more needs to be learned before it will become a practical possibility. No experimental systems have yet succeeded with this approach. Given the brief lifecycle of convective cells, deterministic prediction beyond an hour or two is unlikely to be possible. It is therefore anticipated that implementation of storm-scale prediction will involve use of ensembles.

3.5 Ocean models

Ocean models provide prediction of marine hazards including high waves & surf, surges and information on currents, temperature & salinity from which sound propagation, sediment transport and nutrient transport can be deduced.

Models which predict ocean structure, waves and surges are included here. The main driving force for these models is the surface wind stress, though surface atmospheric pressure is also important, particularly to surge models. With the possible exception of military applications, nowcasting requirements are largely limited to coastal and shelf seas. However, such models require boundary conditions from the deep ocean.

Wave models
Wave models predict the spectrum of surface gravity wave energy in frequency/direction space on a grid of points. Model initiation is currently largely achieved by hindcasting with analysed winds. However, improvements have been demonstrated through data assimilation of satellite observations of wave energy and significant wave height. Predictions depend crucially on the wind close to the height of the waves, which is obtained from NWP. Transformations that occur as waves approach the shore demand very fine scale models (5km or less). These are largely forced by inshore bathymetry, coastal shape and currents. Currents in shallow water may be obtained from a surge or shelf model.

Surf models
Surf models model the transformation of wave energy as it impinges on the coastline. Such models require a very detailed specification of the coast shape, bathymetry and seabed material. They range from simplified models for a single point depending primarily on beach slope, to sophisticated 2-D physical models, with a horizontal resolution of 100m or less.

Surge models
Surge predictions are currently carried out with 2-D depth-integrated models of water depth and motion. Currently these models do not use measured information, but are initiated from hindcasts using analysed meteorological conditions. Predictions depend on surface wind and pressure, obtained from NWP. Transformations close to the coast and especially in estuaries, are very important, and again depend critically on the bathymetry and coastal shape.

Ocean models
Depth-dependent predictions in shelf seas provide additional information for a number of purposes and may replace vertically integrated models for surge prediction. The requirements are similar but additional information on bottom conditions may be required to achieve accuracy in the bottom friction calculation. Initialisation may become possible using techniques developed for the deep ocean.

Mixed layer models deal with the near surface layers of the open ocean, including any ice layer at the surface. They describe the diurnal and seasonal changes of temperature profile. They are not currently applied to short range forecasting problems.

Deep ocean models represent the full 3-D dynamical structure of the ocean in terms of velocity, temperature and salinity, together with surface elevation and any surface sea-ice layer. Boundary conditions of surface stress and pressure, ice and fresh water flux are required. Initialisation procedures have been developed using *in situ* profile measurements and satellite-based surface measurements. Most such models are currently run with resolutions of 100km or so for the globe or major ocean basins. However, experimental eddy resolving models are close to large scale operational use, and some centres are already running such models with a horizontal resolution of a few kilometres covering small areas of ocean.

3.6 Land Surface and Hydrological models
Land surface models are used to predict surface hazards including floods, avalanches, mudslides and fire, and to infer crop growth and pest development conditions.
The models in use to predict surface and sub-surface land characteristics are very varied. In this summary, crop growth, ground water and land movement models are excluded as the processes represented in them generally work on longer time-scales than are represented in this study.

Run-off models
Hydrological modelling is fundamental to predicting many land surface properties and processes. Historically, the favoured approach has been to model at catchment scale, with various levels of sophistication in the treatment of catchment heterogeneity. More recent distributed models use gridded representations, with typical resolutions of a few hundred metres, though these must be of very fine resolution to deal with overland flow. Since run-off is dependent on the details of the land surface at its finest scale, responding to features such as the ridges and troughs in a ploughed field, it is not possible to physically model the process. It is therefore parametrized with each catchment usually being tuned to downstream river flow measurements. Hydrological models deal with surface and sub-surface water, both liquid and frozen, evaporation, melting and run-off, both from the surface and from impervious layers in the soil. They may, or may not, represent ground water changes. Most do not include lateral

water movement in the soil explicitly. Critical inputs to hydrological models are precipitation and its phase, solar radiation, soil and vegetation characteristics, topography, and the initial soil moisture and temperature profiles.

Models are not currently available to predict surface flooding as opposed to river flooding. For general use, such models would require very detailed information on surface topography (to an accuracy of tens of centimetres at spatial resolutions of metres). Alternatively, it may be possible to identify high-risk locations and develop threshold models to relate flooding in these locations to coarse resolution run-off predictions. Observation of existing floods is included in section 3.1.

River flow models

Once water has entered rivers, its behaviour is modelled using hydraulic models which may also deal with natural and man-made obstacles such as weirs and lakes. At the seaward end of a river, tidal forcing may be imposed. The main function of these models is to describe the evolution of flow magnitude along the channel. The key inputs are therefore the upstream river flow, flows from side channels, and the character of the river - its cross section and resistance to flow. If the predicted river flow exceeds the capacity of the channel, it will overflow and an inundation model can be used to determine the extent of flooding. In remote areas, information on the current extent of inundation can only be obtained by remote sensing. Given an accurate digital terrain model, the depth can be deduced if the extent is known, and vice versa.

Drainage System models

Hydraulic modelling is also used for Real Time Control of drainage systems where the appropriate control facilities have been implemented. These models are mainly concerned with the evolution of flow through complex pipe systems including valves, overflows and pumps. If overflow occurs, foul water may emerge into streets and watercourses. Inputs required are rainfall, either as a mean over the drainage area, or distributed at fine resolution (1km or less) and with fine time resolution - ideally every minute.

Snow models

Snow modelling is an important part of hydrological models. However, a further degree of complexity is required to model the evolution of the snow pack in order to predict avalanches. This involves modelling the growth of the snow pack with fresh snow under the influence of the surface wind, and the changing crystal structure of the snow in response to pressure and temperature. Such models depend on observations of snow depth and state, which are currently obtained manually at key locations.

Icing models

Icing models address two problems: surface riming of trees, structures and the ground, and aircraft icing. The physical equations are the same, relating accretion rate to cloud liquid water content, temperature and wind velocity. However, different approximations are made for surface and aircraft icing due to the effects of the much higher aircraft velocities, which delay the onset of icing by dynamic heating but then give much higher accretion rates. Unfortunately, the accretion rate also depends on characteristics of the underlying body. In the absence of such detailed information, icing rates can be quoted for standard bodies, such as a 1cm diameter cable.

Fire models

Recent developments in fire modelling indicate that it may be possible to determine the evolution of fire fronts using very fine resolution coupled fire/atmosphere models with resolutions of a few hundred metres. Three processes of particular importance to fire evolution can be identified: the response of a fire to changing wind, especially direction; the response of fire to topography, especially the enhancement of development up a slope, and its ability to jump across gullies; and the self-reinforcement of the fire arising from inflows generated by the heat of the fire itself. These models require detailed information on the mass and dryness of the vegetation, on the wind distribution, and on the underlying topography at better than 1km resolution.

Mudslide models

Experimental models of the stability of slopes depend on detailed knowledge of soil properties at very fine resolution.

3.7 Dispersion, Chemistry & Biology models

Dispersion Models

Gaseous and fine particulate pollution, including volcanic ash, in the atmosphere is predicted using a variety of dispersion and chemistry models. Models are also used for spread of surface liquid chemicals, especially on the sea. The results are used for protection of life and the environment.

A hierarchy of models is used to predict the dispersion of toxic releases into the atmosphere. All of these require detailed knowledge of the concentration, composition and height distribution of the initial injection of toxic material. Currently this is provided by in situ observation or is inferred manually. Direct observation of the initial stage of injection of material, for instance by observing a volcanic eruption itself, would provide a valuable advance. Since most injections arise from a high temperature source, this might be achieved if surface temperature were monitored at very high resolution (ideally 10m).

For short range dispersion, simplified models give ground-level concentrations as a function of distance and direction using the observed or predicted wind at the point of release, and a measure of the atmospheric temperature profile - usually a stability index.

For longer-range dispersion, simplifications are more difficult. However, a release wholly in the troposphere will be contained below the tropopause, and advected predominantly by jet stream level winds.

Both short and long range dispersion can be calculated using Lagrangian models, which track "particles" each of which represents a fixed amount of contaminant. This technique is used for industrial chemicals, radioactive releases and volcanic ash. Chemical reactions between contaminants may be parametrized. These models require full temperature, humidity and wind profiles from a NWP model so as to calculate advection and mixing. They also require observed or predicted cloud physics variables in order to calculate wet deposition.

Air quality models
Air quality modelling is usually carried out with Eulerian models which represent contaminants on a grid. This approach lends itself to integration with NWP, using the same grid. Chemical reactions between contaminants are normally represented in such models, and the number of chemical species may have to be very large in order to capture adequately the important reactions. A typical current generation model has ~50 species for tropospheric chemistry, and another ~50 species for stratospheric chemistry, in both cases focussing mainly on ozone creation & destruction. Whether or not the model is integrated, there is a requirement for full profiles of all NWP state variables at frequent intervals.

Pollution from fires can be addressed either as a set of point sources using a Lagrangian approach, or as an areal source in an Eulerian model. In either case, information on the temperature and material in the fire is required.

UV radiation models
The level of UV radiation depends on a number of atmospheric constituents (gases especially ozone, aerosols and clouds) and albedo. In order to monitor and forecast UV-B precise measurements of these quantities must be made. It is of importance to be able to distinguish urban and rural areas therefore good spatial and temporal resolution is required.

The depletion of the ozone layer leads on the average to an increase in the ground level UV-B radiation. A possible future stratospheric cooling due to the increase of greenhouse gases in the atmosphere could delay the recovery of Arctic ozone past the maximum in stratospheric chlorine abundance. Models predict Arctic ozone loss is likely to peak around 2015-2020. This will have impact on the levels of UV-B radiation over Europe in spring.

Current models use UV column measurements from satellite or ground based instruments. Aerosol and UV albedo are currently defined using climatology. Due to its high variability, prediction of UV under cloud is of limited use, and intensity is normally computed for cloud-free conditions.

Surface pollution models
Surface liquid and solid dispersion on the sea is computed using drift models which use wave, wind and current information as their inputs (see 3.4 above). Breakthroughs in marine dispersion modelling would be expected if current state was observed. This requirement is included under 3.1.

Surface liquid dispersion on land is mainly of concern when it reaches piped or open drainage and river systems. Models of flow through such systems are used by the relevant authorities. Meteorological input is limited to precipitation, generally assumed uniform over an area, though spatially distributed models are in existence. The main breakthrough would be achieved if the area affected could be observed. This is covered under 3.1.

Terrestrial and marine plant growth is a key component of the carbon cycle, now being built into climate models. For nowcasting use, the main requirement for terrestrial plant modelling is in support of hydrological models through the impact on evapo-transpiration. Marine plant growth is likely to have a more direct application if development of toxic algal blooms is predictable. Apart from observing the algae themselves, the main inputs for modelling are likely to be sea temperature and nutrient concentration.

3.8 Space Weather Models

Space weather covers a variety of electromagnetic disturbances mainly in the upper atmosphere, affecting aircraft and earth satellites. Occasionally the disturbances are so strong that surface electrical and communications facilities are affected.

Solar Wind

The origin of the disturbances is the solar wind, consisting of highly charged particles emitted by the sun. The energy and concentration of these particles is determined by conditions on the sun itself, which can be observed from earth, e.g. sun spots, solar flares etc.. The resulting changes in solar wind intensity can also be observed from satellites. Charged particles rarely reach the surface, but high-energy particles are dangerous to astronauts and can damage satellite systems. The lower atmosphere is protected from these particles by the magnetosphere. However, this is less effective above the magnetic poles, possibly posing a risk to passengers of high flying aircraft in the polar regions.

Ionosphere

The ionosphere has a complex meteorology of its own, and is strongly perturbed when large numbers of energetic charged particles arrive from the sun. Such disturbances affect long wave communications which work by bouncing electromagnetic signals off the ionosphere. More dramatic disturbances can produce electromagnetic fields of such strength that electrical and communications facilities at the surface are overloaded.

The main observations required to take this capability forward are of the solar wind itself, and of the structure of the earth's electromagnetic field. Observation of these variables lies outside the remit of EUMETSAT at present, so they are not included in the detailed table of requirements.

4. Sources of Required Observations

4.1 Remote Sensing

4.1.1 High altitude remote sensing

Geostationary orbit

Provides maximum time frequency at the cost of lower resolution. However, active instruments are not feasible from this altitude, and increased antenna size limits the wavelength range of passive microwave instruments.

Current operational products are derived from images in visible and infrared wavebands and include cloud location and cloud top temperature, upper-tropospheric humidity, cloud motion vectors and simple instability measures.

Due to the rapid repeat frequency, these platforms are particularly suited to the following requirements:

Location of growing convective cloud top
Location of topography changes arising from landslides/avalanches
Location of fire hot spots

Polar orbit

Provides twice-daily observations from each satellite. Offers higher spatial resolution than geostationary.

Current operational products include profiles of temperature and humidity derived from multi-wavelength emission intensities across infrared and microwave wavebands. Active microwave instruments are also used to measure surface wind, surface characteristics, and precipitation.

Imagery is available in a greater number of wavebands and at finer spatial resolution than geostationary, enabling better definition of cloud and surface properties.

Due to the high space and waveband resolution, but poor temporal resolution, these platforms are particularly suited to meeting the following requirements.

Land surface topography
Vegetation type
LAI
Soil moisture
Sea ice
Sea surface temperature

If the temporal frequency were increased from 6-hourly to 3-hourly or even hourly, a much greater range of requirements would be met by satellites in polar orbit.

Aircraft

Aircraft are too expensive for most applications but the primary source of observations of oil slicks for marine dispersion forecasting, and of fires.

4.1.2 Ground-based remote sensing

Microwave

Scanning weather radars can measure the 3-D hydrometeor reflectivity, radial velocity and hydrometeor shape.
Wind profilers measure the velocity vector and refractivity profile at resolutions and vertical ranges depending on the radar frequency. The repeat frequency can be as high as every 5 minutes, but profiles are usually accumulated to remove spurious returns.
Radiometers measure temperature and humidity profiles with a coarse vertical resolution of 1-2km.
GPS provides integrated humidity along near vertical and slant paths using the delay time in signals from the GPS satellites.
Ground wave radar measures near shore wave height, direction & spectrum, wind speed and current velocity to about 20 km range
Sky wave radar measures ocean wave height & direction and wind speed and long ranges using radar waves bounced off the ionosphere. Performance varies according to the state of the ionosphere.

Optical

Lidars detect cloud layer bases but have limited vertical range and are unable to penetrate dense cloud.

Acoustic

SODARs provide velocity vector and refractivity profiles through a limited depth of the atmosphere – typically up to 1 km
RASS operated in conjunction with a wind profiler provides the temperature profile up to a few kilometres.

4.1.3 Submarine remote sensing

Acoustic

Sound can travel very long distances with modest attenuation underwater, and its velocity is dependent on temperature, so arrays of sound emitters and receivers can be used to diagnose the submarine temperature distribution.

4.2 In situ

4.2.1 Upper air in situ

Balloon Soundings

Pressure, wind, temperature and humidity at low time and horizontal resolution but high vertical resolution along a slant path. Expensive, so likely to be replaced by other techniques where possible. High accuracy except humidity, which is especially deficient near saturation.

Dropsonde Soundings

The capabilities are as for balloon soundings but require an aircraft to drop the sounding package from high level. At present such soundings are not cost effective for routine use but may occasionally be used for penetrating tropical cyclones. In the future it may be possible to use unmanned aircraft to drop sondes.

Civil Aircraft

Pressure, wind and temperature at high time, horizontal and vertical resolution near airports and high time and horizontal resolution along air lanes, during flying hours. Humidity capability to be added within a few years. Accuracy similar to balloon soundings except during aircraft manoeuvres.

Aerosondes

Lightweight, unmanned aircraft with an instrument package similar to a radiosonde, are capable of pre-programmed flight and real-time reporting. They are currently experimental, but if reliability is sufficient, costs are projected to be similar to a radiosonde. The advantage is that use can be adapted to the current synoptic situation, gathering observations from areas which are expected to have particular importance in determining the evolution of key weather systems.

4.2.2 Ground in situ

Requirements for aviation measurements at aerodromes are, in general, best met by ground-based in situ observations since they are for known sites, require very high precision in space, and there is supporting infrastructure. Cost is being reduced dramatically by automation.

4.2.3 Marine in situ

Fixed buoys

Expensive tethered buoys, in coastal or continental shelf locations, have a full suite of surface observation sensors. Some also with wave, current and sub-surface profile capabilities. Reports are provided in real time by direct radio link or via satellite.

Drifting buoys

Lightweight, inexpensive buoys which drift with the current provide real-time temperature and wind reports by satellite relay.

4.2.4 Submarine in situ

Submersible Floats

Floats which collect data during pre-programmed periods underwater and periodically surface to radio data back to a collecting centre via satellite. They are aimed mainly at climatological data, with a significant delay between observation and reception of the report.

Profilers

Ships of opportunity are used to deploy XBTs which radio the temperature, current and salinity profile back to the ship and hence to a central collecting station.

5. Contribution of Current and Planned Observations

5.1 Observation/extrapolation

Surface Precipitation

Currently provided by radar with adequate temporal resolution. Adequate horizontal resolution is only available over limited areas close to radar sites. Accuracy is insufficient for many requirements, especially in mountainous areas. Real time reporting raingauges provide adequate accuracy in most conditions, but insufficient horizontal resolution. Manually read gauges are available with higher horizontal resolution, but are only read daily. Over land, planned improvements to radar, including possible use of polarisation diversity, should improve accuracy, but cost will inhibit the closely spaced installations needed to meet the requirement. Over the sea, ground based solutions are impractical except in isolated cases. Current satellite capabilities are poor. MSG should provide some useful information over the sea. Active microwave instruments, such as those on TRMM, could provide a breakthrough if the temporal frequency could be improved to hourly. Precipitation phase, freezing precipitation and hail can only currently be identified reliably by in situ surface measurements. Polarisation radar could be used for hail, and precipitation phase can be inferred from the bright band height. However, this may not exceed the accuracy of NWP freezing level predictions.

Surface Wind
Currently provided by surface in situ observations hourly with a spacing of ~50km or more. Slight improvements are planned with increasing automation allowing more frequent reporting, and possibly a higher horizontal resolution, especially in more remote areas. More dramatic improvements may come from use of Doppler radar, although this will involve reduction to a standard height, and is only available in precipitation. Clear air radars would provide a more general capability but these are not planned for general implementation in Europe. Tornadoes and downbursts can be detected in Doppler radar images. Over the sea, winds are diagnosed from scatterometers and passive microwave radiometers, but do not meet the temporal resolution requirement. With additional satellites planned, this situation will improve, but not sufficiently to meet the requirement.

Surface pressure
Currently provided only by in-situ surface measurements, although scatterometer winds are used indirectly via NWP data assimilation.

Cloud
Cloud tops are diagnosed from Meteosat infrared imagery at 5km resolution but with insufficient accuracy. Cloud bases are available from surface reports at ~50km resolution, which is much too poor. AVHRR can provide estimates of top and thickness, from which base may be deduced, but accuracy and temporal resolution is insufficient. MSG will provide AVHRR quality at 3km resolution.

Surface visibility
Fog and stratus can only be distinguished from in situ surface measurements at present. These are of inadequate horizontal resolution.

Land surface
Land height is not currently available except for in situ measurements including GPS locations.
Fires are detectable from Meteosat to 5km resolution if they cover a large enough area. This will be improved from MSG.

Lightning
Currently provided by land-based remote sensing systems. These meet the resolution and accuracy requirements over Europe. Over other areas of interest, the Arrival Time Difference system, operated by the UK, provides adequate resolution, but does not currently fix a sufficient proportion of flashes, and has a lower accuracy than required.

Icing & Frost
Icing is only currently available from surface in situ measurements with ~50km resolution. Surface temperature is available with poor accuracy at 5km resolution from Meteosat. Better quality is available from AVHRR at poor temporal resolution. MSG will provide AVHRR quality at 3km, 15min resolution. Passive microwave instruments provide vertically integrated supercooled water estimates with poor temporal resolution.

Aviation Turbulence
Currently observed only by aircraft in situ measurements with inadequate resolution.

Ocean
Currently wave information is provided by a very sparse network of buoys and by low temporal resolution satellite scatterometers. Surge height can be provided by altimeters, but again at very poor temporal resolution.

Pollution
Currently observed from the surface and from AVHRR with inadequate temporal resolution if associated with smoke or sulphur dioxide. MSG should provide AVHRR quality with adequate temporal resolution.

5.2 Convection forecasting techniques

Early Warning

Current techniques for providing early warning of areas at risk are based on NWP.

Initiation

Current forecast techniques for convection initiation are based on radiosonde (and AMDAR and NWP) soundings, modified by surface synoptic temperature & humidity reports together with convergence and cloud type information from surface synoptic reports.

Monitoring

Prediction of severe characteristics in convective storms is also largely based on in situ soundings (and NWP). In the USA, satellite remote soundings from the VAS instrument are also used to indicate developing instability. While very crude, they provide a useful check on the evolution of NWP model predictions. Once the storm forms, the primary tool is analysis of Doppler radar together with any surface visual reports.

5.3 Non-convective forecasting techniques

Extra-tropical cyclones

Forecasts are based on NWP modified by manual interpretation of imagery.

Tropical cyclones

Forecast tracks are based on NWP. Intensity and structure are largely predicted using extrapolation

Local wind systems

Information is currently based on a “representative” radiosonde sounding and in situ surface pressure reports. The main deficiency arises from the temperature sounding being distant from the areas of interest. MSG should allow improved monitoring of surface temperature, cloud and snow, enabling better adjustment of the available sounding. However, the main requirements, local information on low-level stability will remain unfulfilled.

Mesoscale Precipitation

Information is currently based mainly on a “representative” radiosonde sounding. This is particularly unsatisfactory where the airflow is coming from the Atlantic. Surface in situ wind and humidity reports together with cloud imagery, showing upstream stratus, provide some useful information for low level enhancement. Planned enhancements will have little impact, except indirectly through NWP data assimilation. Radar data are used for identification of areas of intense precipitation which may turn to snow

Fog & low cloud

Information to support prediction of initiation is based on a “representative” radiosonde sounding modified by surface in situ reports of temperature and humidity and cloud information. The main weakness is in the sounding, and this will not be improved by planned changes.

Information to support prediction of fog clearance depends on having a radiosonde sounding through the fog, which is rarely available unless it is very extensive. Otherwise, the forecaster typically distinguishes depth only on the basis of whether the sky is visible or not. With increased deployment of surface in situ radiation measurements, it may become possible to infer fog depth and water content. Other possibilities for ground based improvements include developments of lidar and high frequency radar, both vertically pointing and scanning. MSG will provide improved detection of fog, but it is not clear whether it will be possible to diagnose fog depth with any accuracy.

5.4 Storm-scale NWP models

The capability of current and planned observations to meet storm-scale NWP requirements is addressed in the Regional NWP position paper.

5.5 Ocean models

Wave models

Wave spectral information for initialisation of models is currently available from polar orbiters at low temporal resolution using altimeter, scatterometer, and potentially SAR instruments. The main deficiency at present is in temporal resolution – the repeat frequency for a single instrument is several days. Planned instruments will improve this by increasing the scatterometer swath, and by flying more instruments.

Surf models

Satellites cannot currently observe wave information close to the coast, so offshore information is currently too far out.

Surge models

The only information currently available is from tide gauges at fixed points. Altimeter information is available too infrequently to be of use. This is unlikely to change.

Ocean models

Ocean models can use satellite based altimeter and sea-surface temperature information to infer ocean currents and thermal structure. Additional information is becoming available from in situ profiles observed by the autonomous ARGO floats.

5.6 Land surface & hydrological models

Run-off models

The principal inputs to run-off models are precipitation, short wave radiation, soil moisture and snow. The first is provided by ground-based radar over much of Europe and, at coarser resolution by raingauges. Short wave radiation can be derived from cloud information, which is currently provided by a combination of surface and satellite observations. Satellite information is limited because only cloud top is seen, and because resolution is inadequate to identify partial cover. Soil moisture is currently not available from any source except in situ measurements, which are representative of only very small areas, and which are not part of standard meteorological observations, and therefore not widely available. Experimental satellite observations have been obtained using passive and active microwave, SAR instruments, and indirectly from the diurnal temperature cycle in cloud-free conditions. However, none has yet demonstrated adequate routine accuracy. Additional information required by run-off models concerns topography and vegetation. Land height and soil type are important but do not change. Vegetation type is provided by the latest generation of radiometers such as MODIS, which provides weakly updates of leaf area. In cool climates it is important to distinguish the phase of the precipitation reaching the ground. Due to cloud cover, this can currently only be done using surface in situ measurements. Finally snowmelt must be calculated, which requires the water equivalent of snow to be measured. Again, this is only currently available from surface in situ measurements, which are at inadequate horizontal resolution.

River flow models

Once water is in a river, it is measured by in situ flow measuring devices.

Drainage system models

Observations of flow in drainage systems are available only where real-time control systems have been implemented. Undoubtedly there will be more of these in the future.

Snow models

Observations of snow cover from surface reports are inadequate in spatial resolution. Satellite observations are superior for relatively cloud free areas, but are of limited use in identifying areas of new snow cover, which typically lie beneath precipitation clouds. Snow depth and structure is only available from in situ measurements.

Icing models

Current in situ observations enable models to be run for the site of the observation only. Otherwise such models are driven by NWP.

Fire models

Surface in situ reports form the basis for assessments of fire risk at present, although the evolution of surface temperature in geostationary imagery provides additional qualitative information. MSG should improve the usefulness of this information. Quantitative soil moisture information is generally not available at present. Once fires have started, spotter planes usually identify their location. However, geostationary imagery can be used for locating fires once they are large. MSG imagery will provide a significant benefit in this regard due to its finer resolution. However, it will still be too coarse to be used as the primary source of information in European countries.

Mudslide models

No data are currently available for initialising or driving mudslide models in real time.

5.7 Dispersion, Chemistry & Biology Models

Dispersion

Initialisation of the pollutant in dispersion models is undertaken on the basis of visual observation or theoretical calculation. A major contamination of the atmosphere is sometimes identifiable on satellite imagery if associated with dust or smoke, as in the case of volcanic ash. Initialisation information can them be diagnosed manually from the imagery. Quantitative observations are not available. Short-range dispersion models rely on use of a "representative" sounding, modified by a nearby surface in situ report for wind and stability information. Otherwise NWP meteorology is used.

Air quality

Limited in situ chemistry observations are available mainly from urban sites. Otherwise there are no suitable data sources.

UV radiation

During the next few years several ozone measuring satellites will be launched to enhance the current mainly ground-based information, enabling better modelling of UV intensity. No routine aerosol data are available now, but limited aerosol information should be available from processing of MSG data.

Surface pollution

Major marine slicks are usually tracked by spotter planes. They may be visible in MSG imagery. There are no available observations to support tracking of land-based pollutants at present.

The NDVI diagnostic is used to derive leaf area index and other vegetation information over land, in support of crop modelling. Ocean colour has been studied in relation to the development of algal blooms.

5.8 Space weather models

Solar wind

Predictions of the affect of charged particles arriving in the vicinity of the earth are based either on observation of solar disturbances using manual analysis of telescopes, or on in situ measurements by high orbit spacecraft. Availability of the latter is increasing as the importance of this issue gains recognition.

Ionosphere

Observations are not currently available for initialisation of ionospheric models.

6. Key Observational Breakthroughs

The full set of observation requirements to support the forecasting methods described in section 3 is given in the table at Annex C. This identifies the physical variable that is observed, the variable that is required, the range of useful accuracy and resolution, any special conditions, the priority, the accuracy & resolution that would provide a breakthrough from the position planned prior to any MSG follow-on, the application of the information, and then a series of pieces of information about the ability of space-borne platforms to observe this variable.

Most requirements are independent of the time of day and location, whether over land and sea, under cloud or clear skies. Special conditions are only noted where they deviate from this or where there is a particular difficulty. Over inhomogenous surfaces the quality of satellite measurements is usually poorer than elsewhere, particularly for near surface variables. This is true over coastlines, urbanized areas and complex terrain, where the loss of quality and resolution can extend into the lower troposphere. Special algorithms will be needed to optimise information retrieval in these areas, possibly using multiple data sources.

The following sections identify the highest priority breakthrough requirements which could justify investment on the time-scale of this study. There is no significance to their order.

6.1 Observation/extrapolation

Surface Precipitation

Currently, weather radar supplemented by in situ raingauges, provides the primary source of rain rate data in developed countries. Radar provides adequate spatial and temporal resolution, but is currently not sufficiently accurate. In particular, light rain is missed in areas distant from the radar, and it is not currently possible to remove all spurious echoes. It is expected that advances in radar technology are the best route for addressing these deficiencies. However, a reliable independent detection of areas of rain (rate >1mm/hr with ≥90% hit rate, ≤10% false alarm rate, ≤10km horizontal & ≤1hr temporal resolution) would be a major contribution. For coastal areas, the limited range of radar means that there is currently poor knowledge of the rain rate associated with approaching weather systems. A moderately accurate source of information over the sea would therefore be valuable (accuracy ≤5mm/hr, ≤10km spatial & ≤1hr temporal resolution). For flood prediction, heavy rain needs to be observed more accurately than at present over land (10mm/hr accuracy, ≤2km horizontal & ≤15min temporal resolution). Satellite instruments may be able to contribute to some of these requirements either using radar or microwave radiometry.

Precipitation type is currently only available from surface observations, though it may be inferred from the temperature structure in NWP models or from a representative radiosonde sounding.

Snow can cause disruption to transport even in small amounts, so the information on its presence would be a valuable step forward (to ≤0.2mm/hr accuracy, with ≤10km horizontal & ≤1hr temporal resolution). Such small rates are not well detected by weather radar.

Large hail is a serious hazard to life and property, associated with convective clouds, which is currently only observed by sparse surface stations or inferred indirectly. Remote observation would be very valuable but are unlikely to be achievable (hail >2cm, with ≥70% hit rate, ≤40% false alarm rate, ≤10km horizontal & ≤15min temporal resolution).

Freezing rain is also a serious hazard to life, transport and the utilities. Since this can be associated with shallow cloud and light precipitation rates, it is even more difficult to diagnose than hail. Again direct information at fine resolution would be of very high value, but is unlikely to be achievable (≥70% hit rate, ≤40% false alarm rate, ≤10km horizontal and ≤1hr temporal resolution).

Surface Wind

Surface wind is of importance when it becomes strong enough to interfere with activities or to cause damage. Using current observations NWP models provide an adequate representation for general forecasting purposes. However, mesoscale maxima in the wind field may cause a serious hazard and are often missed by current models. Direct observation of these maxima would provide short time warnings for protection of life and property, land transport, utilities, marine safety and construction (wind >10m/s to ≤2.5m/s, $\leq 10^{o}$ accuracy, with ≤10km horizontal and ≤1hr temporal resolution). Over the sea scatterometer data from low earth orbit could provide this if temporal and spatial resolution and timeliness could be improved. Surface wind can also be inferred using low level cloud motion from geostationary orbit where not obscured by higher cloud. A more demanding requirement is to identify the damaging local wind maxima such as gust fronts and tornadoes (Surface wind speed >25m/s, with ≥70% hit rate, ≤40% false alarm rate, ≤200m horizontal, ≤5min temporal resolution). Ground-based Doppler radar offers the most likely source of such data, but needs higher power than current European weather radars to observe in clear air. A related problem is detection of downbursts and other strong vertical motions near ground such as rotors for aviation safety. Again ground-based Doppler radar is likely to offer the best solution.

Cloud

The main requirement for direct observation of cloud is in support of aviation. In situ observations are sufficiently accurate for airports, but have inadequate spatial resolution for VFR (non-instrument) flights at low level for which clear sight of the ground is critical. Current geostationary satellites provides limited information on cloud cover and height at the required spatial and temporal resolution, and this will be substantially improved with MSG. However the critical requirement is for knowledge of the cloud base and of breaks in the cloud below an overcast cloud deck (profile below 2km to ≤25% accuracy, with ≤10km horizontal, and ≤1hr temporal resolution).

Surface visibility

Fog is a severe hazard to all forms of transport, and is currently observed only sparsely using surface in situ measurements. An indication of areas of fog or low stratus is available from AVHRR and will be possible from MSG, but cannot indicate whether the visibility is low enough to be hazardous. Improved capabilities would be of considerable benefit, especially given the persistent nature of fog. The requirements over land is for detection of thick fog at fine resolution, mainly for road transport (visibility <200m, with ≥70% hit rate, ≤40% false alarm rate, ≤5km horizontal & ≤1hr temporal resolution) while that over the sea is more general (visibility <1km, with ≥70% hit rate, ≤40% false alarm rate, ≤20km horizontal & ≤1hr temporal resolution). Either of these might be met by improved measurement of cloud top height and thickness using infrared radiometry. In addition there is a more general requirement over land, related to the low cloud requirement, for low level flight without instruments, since fog may also make ground features invisible (to ≤25% accuracy with ≤20km horizontal & ≤1hr temporal resolution). This requirement includes conditions below cloud.

Land surface

There are several features of the land surface for which high resolution routine observations could provide valuable input to hazard response.

For floods, knowledge of the extent and depth of floodwater is of high value in protecting life, property and transport. Given a detailed terrain model, direct observation of either water depth of flood extent can be used to infer the other. At present only ad hoc in situ observations are available, supplemented by spotter planes for extensive floods. Water depth (to ≤0.5m accuracy, with ≤1km horizontal & ≤1hr temporal resolution) may be observable from low earth orbit using SAR. Identification of the flooded area (with ≥70% hit rate, ≤40% false alarm rate, ≤1km horizontal & ≤1hr temporal resolution) may be possible with visible and infrared imagery, but the information is ideally required under cloud.

For snow, the key variables are its depth (or water equivalent) and the fractional cover. Both are important for transport. The former is also important for protection of life and property. Current observations are limited to sparse surface in situ data except for snow cover which can be deduced using visible and infrared imagery from low earth orbit satellites under clear skies. A reliable snow fraction under all cloud conditions (to ≤30% accuracy, with ≤10km horizontal and ≤6hr temporal resolution) would be a significant step forward. This may be achievable using MSG except for lengthy cloud spells. SAR imagery may offer additional information from low earth orbit. Snow depth is a more difficult aim (to ≤0.1m accuracy, with ≤1km horizontal & ≤15min temporal resolution). It may be possible to obtain satellite measurements. Otherwise, the best approach will be to use a snow model with measured precipitation input.

For fire, the key direct observation is the location of the fire for protection of life and property). This is currently achieved firstly by manual observation from lookout towers, and then with spotter planes. Satellite observation would provide a valuable initial alert if sufficiently reliable. Two complementary approaches could yield benefits. Direct observation of high temperatures in the fire (surface temperature >500°C, with ≥70% hit rate, ≤40% false alarm rate, ≤1km horizontal & ≤1hr temporal resolution) uses infra-red imagery provided the spatial and temporal resolution is fine enough. This may be possible with MSG. Observation of the smoke depends on combined imagery channels and, again, may be possible with MSG (with ≥70% hit rate, ≤40% false alarm rate, ≤10km horizontal & ≤1hr temporal resolution). Low earth orbit satellites have the necessary channels and spatial resolution already, but the repeat frequency is inadequate for monitoring.

Icing & Frost

Deposits of ice on the surface are a hazard to transport and, if deep enough, can threaten life through the collapse of structures. Direct observation of surface frost and rime can be made currently by surface in situ instruments. A direct remote observation of ice accretion would be useful, especially for monitoring the safety of towers in rural areas (Ice accretion to ≤1cm accuracy with ≤1km horizontal & ≤1 hr temporal resolution). There may be signatures in both reflectivity and emissivity that can be detected from satellites to contribute to this, though the required accuracy will be very demanding. In the absence of direct measurements of ice, an accurate direct measurement of the land surface temperature would provide an indication of areas susceptible to icing (to ≤1K accuracy with ≤1km horizontal & ≤1 hr temporal resolution). Although low earth orbit satellites approach this requirement under clear skies, the critical requirement for information under cloud is only met by surface in situ observations at present.

Aviation Turbulence

Clear Air Turbulence (CAT) is a major hazard to aviation which is currently only detectable by in situ aircraft observations. Since it is statistical in nature, even these observations are of limited value. A direct observation would be of considerable value even with relatively low accuracy and resolution. The in situ measure of turbulence is currently aircraft acceleration., though turbulence is normally characterised by rapid changes in acceleration produced by waves or roll motions in the atmosphere. It is therefore suggested that measurement of the profile RMS gradient of vertical velocity may be possible from earth orbit (to ≤10 m/s/km accuracy, with ≤50km horizontal, ≤1km vertical & ≤1hr temporal resolution). Over land, wind profilers may be able to detect a CAT signature.

Ocean

The key requirements in very short range forecasting of ocean parameters are for improved wave and storm surge information. Wave height is currently available from very sparse buoy measurements in coastal waters and from low earth satellites with low spatial and temporal resolution. For warnings of hazards to small ships and ferries, and for marine construction, finer resolution information on wave height would be of value (to ≤0.5m accuracy, with ≤10km horizontal & ≤1hr temporal resolution). Surge height is of principal importance at the coast in support of protection of life and property. Current in situ measurements are available at only a few locations. Satellite altimetry currently provides inadequate space and time resolution. A significant step forward in capability could be achieved if adequate resolution were available from remote observations (to ≤0.2m accuracy, with ≤10km horizontal & ≤1hr temporal resolution).

Pollution

Detecting areas affected by atmospheric or surface pollutants would provide substantial benefits in the protection of life. Volcanic ash is a serious threat to aviation which is currently detected mainly by in situ observation of an eruption. Remote detection is particularly required for volcanoes in developing countries. Low earth orbit currently provides insufficient observation frequency, while geostationary satellites have insufficient accuracy. The requirement (location with ≥70% hit rate, ≤20% false alarm rate, ≤10km horizontal, ≤1km vertical & ≤1hr temporal resolution) may be met using MSG.

Other important sources of pollutants are mainly initiated from the ground. Current techniques are based mainly on modelling with calculated initial conditions. Direct observation of the pollutant distribution (e.g. Ammonia, Hydrocarbons, Radioactive material, with ≥70% hit rate, ≤40% false alarm rate, ≤1km horizontal & ≤1hr temporal resolution) would provide significant benefits. There is no information source currently capable of providing this information. For ozone, Current information comes from sparse in situ measurements. Remote satellite measurement of the near surface ozone concentration would be very valuable for providing warnings of health effects (to ≤5% accuracy, with ≤10km horizontal & ≤1hr temporal resolution).

Location of surface toxic material on land (e.g. Ammonia, Hydrocarbons, Radioactive material) or sea (mainly oil spills) currently depends on sparse in situ observations. Major improvements in the capability of managing such releases would be achieved if remote detection from space could be achieved (with ≥70% hit rate, ≤40% false alarm rate, ≤1km horizontal & ≤1hr temporal resolution).

6.2 Convection forecasting techniques

Convection forecasting techniques rely mainly on radiosondes and NWP, but geostationary cloud imagery is valuable in identifying initiation. Weather radar is the main tool for monitoring and identifying the development of severe characteristics such as tornadoes.

Early warning of areas of convection depends on identifying areas of instability and boundary layer forcing. Instability is currently identified using NWP forecasts and representative radiosonde soundings. The vertical resolution required is rather course and can be achieved with satellite soundings from low earth orbit, but these currently have inadequate temporal resolution (temperature profile to ≤2K accuracy, with ≤50km horizontal, ≤2km vertical and ≤3hr temporal resolution to compute instability index). Boundary layer convergence currently depends on sparse surface in situ observations or NWP, though use has been made of low-level cloud track winds. Improved resolution and accuracy could make this an attractive approach (to ≤1m/s vector accuracy, with ≤10km horizontal, ≤1km vertical and ≤1hr temporal resolution)

Initiation of convection can be diagnosed using several techniques depending on the available data. With sounding data (vertical temperature profile to ≤2K accuracy, with ≤30km horizontal, ≤200m vertical & ≤30min temporal resolution) erosion of the capping inversion can be tracked to give an indication of the time and location of initiation. With just the height of the boundary layer top (to ≤300m accuracy, with ≤30km horizontal & ≤30min temporal resolution) growth ahead of convective initiation can be tracked. The cloud top height of boundary layer cloud (giving cloud top rise to ≤1m/s accuracy, with 500m horizontal and 5min temporal resolution) gives similar information. Finally boundary local forcing can be identified in cloud lines (from cloud images with ≤500m horizontal, & ≤5min temporal resolution). All of these techniques require finer spatial resolution than MSG and finer temporal resolution than current low earth orbit capabilities.

Monitoring of convection is mainly for the purpose of identifying which clouds will develop severe weather such as lightning, tornadoes and large hail. The primary data source, when available, is Doppler radar, and this is likely to become available much more widely by 2015. However, other sources of information can also provide valuable indicators. Intense rain rates (to ≤10mm/hr accuracy, with ≤5km horizontal and ≤30min temporal resolution) indicate where severe weather may develop. Cloud top rise rate (to ≤3m/s accuracy, with ≤500m horizontal and ≤5min temporal resolution) can indicate where intense precipitation and severe weather may develop.

6.3 Non-convective forecasting techniques

Mesoscale Precipitation

For prediction of precipitation enhancement due to uplift and the seeder-feeder mechanism over hills, the low level wind and humidity, near the hill top height, are required (to ≤1m/s & ≤15% accuracy respectively, with ≤10km horizontal, ≤1km vertical & ≤1 hr temporal resolution). Again these are normally provided by NWP model output. For nowcasting, observations would be preferable but current radiosonde data are frequently not sufficiently representative of the airflow over the hills. The third technique provides a diagnosis of the lowering of the melting layer by heavy precipitation, leading to snow at the surface. While this is normally carried out using a representative nearby radiosonde sounding, knowledge of the current local melting layer height and the precipitation rate would provide a major step forward (height of melting layer to ≤200m accuracy, with ≤10km horizontal and ≤1hr temporal resolution and precipitation intensity to ≤2mm/hr accuracy, with ≤5km horizontal resolution & ≤1 hr temporal resolution).

Fog and Low Cloud

Techniques for forecasting the formation, development and clearance of fog rely on representative radiosonde soundings, modified by surface in situ observations. The current availability of soundings is inadequate for this purpose. However, the vertical resolution requirements are so demanding that it satellite soundings from either low earth or geostationary orbit are unlikely to be able to contribute. Remote satellite measurements may, however, be able to enhance the spatial resolution of the surface temperature and/or humidity under clear skies which indicate how near to fog formation the profile has become (to ≤0.5K & ≤3% accuracy respectively, with ≤5km horizontal & ≤30min temporal resolution). Development of fog is frequently preceded by a period of shallow fog, less than 1metre deep. If this could be observed in cloud imagery (with ≥70% hit rate, ≤40% false alarm rate, ≤5km horizontal and ≤1hr temporal resolution) it would provide a major improvement in warning time for land transport. Also, fog formation is frequently preceded by a marked reduction in the near surface wind (preferably observed at about 1m height). Remote observation of this quantity would be valuable (to ≤0.5m/s accuracy, with ≤5km horizontal and ≤30min temporal resolution). Forecasts of fog clearance depend on knowledge of the depth of fog (to ≤30m accuracy, with ≤5km horizontal and ≤30min temporal resolution), which is currently very poorly observed. Fog clearance could also be predicted by extrapolating the shrinkage of the fog area as it erodes from the edges if measurements of fog area were made with sufficient resolution (to ≥70% accuracy, with ≤5km horizontal & ≤1hr temporal resolution).

6.4 Ocean models

Wave models

Ocean wave models are driven by NWP predictions of surface wind. However, errors in waves generated at large distances can accumulate so a significant improvement in forecasts, especially of long wavelength swell, can be achieved by assimilating observations. These are currently available from isolated buoys and satellite altimeter and scatterometer data. A significant advance would be achieved with observation of the full energy spectrum (to ≤0.1m^2/s^2 in ≥8 direction and ≥5 frequency bands, with a horizontal resolution of ≤50km and a time resolution of ≤6hrs, resolving the principle wave trains). This is currently available from experimental SAR instruments in low earth orbit. Data close to the coast would be especially valuable as input to coastal surf models to provide warnings of overtopping or damage to coast defences. In the absence of direct observation, the initial wave state is deduced from the wind history. This is currently available over the sea from isolated buoys and from low earth orbit satellite scatterometer and microwave instruments. Improved wind observations would be valuable (to ≤2m/s accuracy, with ≤50km horizontal and ≤6hr temporal resolution).

Surge models

The accuracy of surge model predictions depends primarily on the wind and pressure forecasts provided by NWP, and the open ocean boundary conditions. However, initialisation with the current state (to ≤0.2m with ≤50km horizontal and ≤6 hour temporal resolution) would offer a significant benefit in the very short-range forecasts for nearby coastal locations. Current coastal measurements cannot usefully be fed into models.

3D Ocean models

The main applications in very short range forecasting use coastal models. Limited information is currently available, including very isolated profiles from buoys and sea surface temperatures (with a repeat frequency of about one week) from low earth orbit satellites. The update frequency for sea surface temperature should be much enhanced with MSG, since the opportunities for seeing through gaps in cloud will be greater. Surface remote sensing by ground wave radar may become an operational source of current data in the next decade. The main opportunity for enhanced observations would be to achieve full coverage of sea surface temperatures at sub-daily frequencies (to ≤1K with ≤50km horizontal and ≤6 hours).

6.5 Land surface & hydrological models

Run-off models

Hydrological run-off models depend on the budget of precipitation (rain and snow rates to ≤50% accuracy, with ≤5km horizontal & ≤15min temporal resolution) and evaporation (which can be deduced from incoming radiation), but need initialisation of the soil moisture profile (total soil moisture, in the root zone, to ≤10% accuracy, with ≤50km horizontal and ≤1 day temporal resolution) and, where appropriate, the snow water equivalent (to ≤5mm accuracy, with ≤5km horizontal and ≤1day temporal resolution). Soil moisture is currently available from only a very small number of experimental sites though a lot of work is being put into developing a satellite-based capability. Snow depth is available from standard meteorological observing sites but is still inadequate in accuracy and space/time resolution. There is also a requirement for vegetation information but this is expected to be met by MODIS.

Snow models

The key requirement for snow models is for information on snow water equivalent (to ≤200mm accuracy, with ≤500m horizontal and ≤2hr temporal resolution). Only surface in situ measurements are currently of adequate accuracy, and these are very sparse and infrequent. Significant advances could be achieved with a detailed map of snow amount. However, due to the complex terrain in which snow models are normally run, a very fine spatial resolution is required. Satellite observation of this quantity is not possible from geostationary orbit, but may be possible from low earth orbit using SAR. An increased repetition rate for low earth orbit would be required to meet the requirement. If measurements of snow water equivalent are not possible, snow state is best obtained using a model, calibrated at the few surface observing sites. This is only likely to be accurate given knowledge of the snow precipitation rate (to ≤1mm/hr accuracy, with ≤1km horizontal & ≤1hr temporal resolution). This is also not measurable with sufficient accuracy from geostationary orbit, but may be possible from low earth orbit using radar (e.g. the global precipitation mission). Again a high repetition rate would be required.

Icing models

Icing models fall into two groups: those that predict icing on aircraft and those that predict riming on surface structures. The physics used is the same, though aircraft velocity has a significant impact. Warnings of aircraft icing are critical for the safety of low flying aircraft including helicopters. Warnings of rime accumulation are important for utilities that use masts, pylons etc, and for general safety of life. For aircraft icing, the critical requirement is for knowledge of super-cooled liquid water content, especially at large drop sizes (to ≤1g/kg accuracy, with ≤50km horizontal, ≤1km vertical & ≤1hr temporal resolution). Experimental data have been derived from microwave instruments in low earth orbit. For surface riming, the inputs are fog water content, surface temperature and wind speed.

The latter can be deduced from sparse in situ measurements of models. The temperature can also be obtained from models, but improved accuracy from direct measurements would be useful (to ≤1K accuracy with ≤1km horizontal and ≤1 hr temporal resolution) The key input is the fog water content, which is currently diagnosed from sparse measurements of visibility. Remote observations at fine resolution would be a major advance (to ≤0.2g/kg accuracy with ≤1km horizontal and ≤1hr temporal resolution). For surface ice and hoar frost, the critical input requirement is the surface temperature (to ≤1K accuracy with ≤1km spatial and ≤1hr temporal resolution) which is currently only available from in situ road sensors.

Fire models

Two types of fire models are used. Advance warnings are based on soil and vegetation moisture content and are used to mobilise fire fighters, clear fire breaks etc.. Once a fire has started, models predict the speed and direction of advance of the fire front for direct support to fire fighters. For the advance warnings observations are currently very sparse. Remote satellite measurements of soil moisture (to ≤10% accuracy, with ≤3km horizontal and ≤1 day temporal resolution) and vegetation stress (from Normalised Difference Vegetation Index to ≤10% accuracy with ≤3km horizontal and ≤1 day temporal resolution) would be valuable. For prediction of fire motion, the same information is valuable at finer time and space resolution (soil moisture and vegetation stress from Normalised Difference Vegetation Index to ≤10% accuracy with ≤1km horizontal and ≤10min temporal resolution) but the key input is detailed wind information (to ≤2m/s vector accuracy with ≤1km horizontal and ≤10min temporal resolution).

6.6 Dispersion, Chemistry & Biology Models

Dispersion models

For short-range dispersion of surface releases, it is the boundary layer wind a stability that are the critical input parameters. These can be obtained from NWP models or from a representative radiosonde sounding. However, improved spatial resolution of direct measurements would be a significant benefit (Boundary layer stability index or temperature profile to ≤1K accuracy, with ≤10km horizontal, ≤1km vertical & ≤1 hr temporal resolution and surface wind to ≤1m/s, ≤10^o accuracy, with ≤10km horizontal & ≤1 hr temporal resolution). In addition, for both short and long range dispersion, the initial local and concentration of material is needed (location of near surface airborne material (industrial chemical, radioactive material, biological pathogens, smoke) with ≥50% hit rate, ≤50% false alarm rate, with ≤50km horizontal & ≤1 hr temporal resolution). Currently this is rarely the case, and models are initialised with artificial distributions based on the source of the release. In the case of volcanic ash, this is particularly uncertain, and direct information would be of critical benefit to aviation safety (location of volcanic ash with ≥50% hit rate, ≤50% false alarm rate, with ≤50km horizontal, ≤3km vertical & ≤1 hr temporal resolution). It is expected that MSG will provide useful information on volcanic ash, but is unlikely to fully meet the requirement.

Air quality models

The key outputs likely to be required from air quality models are ozone and fine particulate matter (PM10) concentrations. On this basis, the key requirement is for initialisation of precursor chemical species or indicators for them. Specifically, total column or boundary layer concentrations of Ozone, Carbon Monoxide, Nitric Oxide, Nitrogen Dioxide, Formaldehyde, Volatile Organic Compounds, Total aerosol and PM10 aerosol are required (to ≤20% of air quality standard, with ≤10km horizontal & ≤1hr temporal resolution). These are currently available only from isolated in situ measurements.

UV radiation models

The primary input to UV radiation models is the total column ozone. The ability to provide improved warnings of UV exposure under clear skies would be significantly improved if routine observations were available (to ≤10% accuracy, with ≤50km horizontal & 6hr temporal resolution). While cloud is also important, it is so variable that cloud observations make little contribution to forecast accuracy. However, total column aerosol is more persistent and is also of significant importance if it could be observed with adequate accuracy and resolution (to ≤25% accuracy, with ≤20km horizontal & ≤1 day temporal accuracy)

Surface pollution models

While chemical and biological spills on land and sea are of high importance, the key breakthroughs are identified in support very short-range prediction of the movement and break-up of oil spills. Movement requires knowledge of the detailed structure of wind (Surface wind vector over sea to ≤2m/s, ≤10^o

accuracy, with ≤5km horizontal & ≤1hr temporal resolution for prediction of movement of contaminant) and currents (Surface current vector to ≤1m/s, ≤10^o accuracy, with ≤5km horizontal & ≤1hr temporal resolution). Both are available only at isolated buoy locations at present, though ground wave HF radar may become an operational observing tool on the time-scale required. Space-based techniques may be based on active or passive microwave instruments. Break-up of a slick depends mainly on waves (Significant wave height to ≤0.2m accuracy with ≤5km horizontal & ≤1hr temporal resolution), which again are currently measured only at isolated points but for which active low earth orbit instruments show some promise.

Annex A Requirements for Warnings of Hazards

This Annex provides the detail to section 2.1, indicating the impact of each threat, the responses that can be made to counter it, the information required to enable this response to be made, and the method of generating that information. The methods match those listed in section 3 of the main paper.

A.1 Direct threats to life

Accidental releases of toxic gases & aerosols (chemical & radioactive) -

Impact - contact burns, internal injuries from inhaling fumes, cancers, respiratory effects

Response - evacuate area downwind of release, warn areas at risk to stay indoors, mobilise medical facilities in affected areas, prevent movement into the area.

Requirement - Identification of current height, spread, concentration & composition. Prediction of dispersion and deposition. Horizontal resolution required: 100m to 1km.

Method - Observation; Dispersion model driven by observed meteorology or NWP.

Accidental releases of toxic liquids (land & sea)

Impact - contact burns, internal injuries from inhaling fumes, wildlife killed in rivers and the sea.

Response - prevent liquid spreading in drains and watercourses, prevent marine spills reaching beaches.

Requirement - Identification of current spread, concentration and composition. Prediction of movement and dilution due to waves at sea, and drainage on land - including the effect of rain.

Method - Observation; Marine dispersion model.

Smog - elevated levels of gaseous pollutants including allergenic chemicals and aerosols, (industry, traffic, biomass burning, volcanic releases etc.)

Impact - breathing difficulties, possibly leading to death, especially for individuals with allergies such as asthma

Response - evacuate, warn those at risk to stay indoors, mobilise medical facilities in affected areas, warn vulnerable people to stay away from affected areas, limit city traffic, shut down certain industries (depending, for instance, on analysis of the local chemical balance in Ozone production).

Requirement - Current and predicted levels of O_3, NO, NO_2, CO, CH_2O, VOC, resolving areas where the near surface concentration exceeds or will exceed safe limits to an accuracy of 10km.

Method - NWP + observed ozone, Coupled atmospheric chemistry model.

High UV levels

Solar ultraviolet radiation is important due to its consequences on the biosphere. Of especial importance is the biologically effective part of the UV spectrum (UV-B), which can impose harmful effects on human beings, also plant growth and yield biodiversity in natural ecosystems and the productivity of seas. UV-A also plays a role in these processes, being therefore of comparable importance to UV-B.

Impact - skin cancer, eye damage, DNA damage, photoaging, alterations in the effectiveness of the immunity system etc.

Response - cover up with clothes, protect with sunscreen

Requirement - prediction of surface UV levels, dependent on stratospheric ozone and cloud absorption.

Method – Observation; UV model driven by observed/extrapolated ozone, aerosol & cloud or NWP.

Hail -

Impact - injury from being struck by large hail

Response - individual warnings - take cover

Requirement - general warnings 3-9hrs ahead to enable general precautions to be taken. 10-60min personal/local warnings could enable safe shelter to be sought. Horizontal resolution 1km.

Method - Observation; Extrapolation; Convection f/c; NWP.

Lightning

Impact - burns and death from lightning strike

Response - individual warnings - take cover

Requirement - general warnings 3-9hrs ahead to enable general precautions to be taken. 10-60min personal/local warnings could enable safe shelter to be sought. Horizontal resolution: 5km for lightning.

Method - Observation; Extrapolation; Convection f/c techniques; NWP.

Floods

Impact - injury or drowning if swept into fast flowing flood waters

Response - evacuate area under threat

Requirement - current area and depth of flood (100m - 1km resolution); prediction of future flood from upstream river flow, precipitation (1-5km, 10mins, to 1mm/hr), soil moisture (5km resolution) and snow melt using hydrological models. Requirements depend largely on size and steepness of catchment. For urban catchments, a spatial resolution of a few km is required. For realistic response, a three hour warning is required, though in many areas useful actions can be taken with shorter warning times.

Method - Observation; Hydraulic river flow model; Hydrological run-off model; Extrapolation; Convection f/c; Mesoscale precipitation; NWP.

Avalanche

Impact - death by burial & suffocation

Response - evacuation, closing of exposed roads and railways

Requirement - 3-12 hour warning over complex terrain of heavy snowfall causing strong increase in snow pack (>20cm/6hr, >30cm/12hr), high winds causing local snow accumulation (>20kn), heavy rainfall on snow slopes (>20cm/6hr, >30cm/12hr), temperature increase above 0^oC: (10K/6hr).

Method – Snowpack model using observation of snow depth and state, observation/extrapolation of precipitation, convection forecast, mesoscale precipitation, NWP for snow amount; NWP for wind & temperature.

Snow and Ice

Impact - injury and death from snow and ice falling off structures

Response - avoid areas at risk, pre-emptive clearing of roofs and other structures

Requirement - snow/ice accumulation, temperature change

Method - Observation/extrapolation of snow depth, Convection forecast, Mesoscale precipitation, NWP for snow accumulation and temperature.

Mud Slide

Impact - injury from material carried in slide, death by burial & suffocation

Response - evacuate area under threat

Requirement - rainfall accumulation at 1-5km resolution

Method – Mudslide model driven by precipitation observation, extrapolation, convection f/c, or NWP.

Fire

Impact - burns and death

Response - evacuate properties under threat, safety of fire fighters - evacuation ahead of wind change.

Requirement - evacuation is generally undertaken after fires have started. forecasts of fire movement and spread require detailed information of existing area, and of the wind and surface/vegetation conditions at very fine resolution. Require location of smoke and surface hot spots, surface wind and vegetation stress every 1-10 minutes at 100m-1km resolution, data available within 1-5mins, together with soil moisture every 1-6hrs at 100m - 1km resolution.

Method - Observation/extrapolation of fire location, fire model using observation/extrapolation or NWP.

Wind chill

Impact - Death by hypothermia

Response - take additional clothing, avoid going outside

Requirement - temperature, wind & humidity at 10km resolution

Method - NWP

Heat stress

Impact - loss of energy, possibly leading to incapacity and death

Response - reduce work rate, increase fluids intake, provision of shade, evacuation.
Requirement - temperature, humidity and wind prediction
Method - NWP

Freezing precipitation
Impact - Injury and death from collapsing trees and structures, injuries from slipping, especially amongst elderly pedestrians
Response - stay at home, pre-emptive salting, gritting, mobilise medical facilities for pedestrian casualties.
Requirement - 3-12hr warning at 10km resolution, 1hr warning at 1km resolution, surface temperature and profile below cloud + precipitation rate and phase of cloud.
Method - Observation; extrapolation; NWP

High Waves
Impact - on beaches and rock ledges, drowning from being knocked into the sea by a large wave. Injury from flying stones
Response - evacuate area under threat
Requirement - 3hrs warning of wave heights at 1-10km, 1hr resolution
Method - surf model and wave model driven by NWP

Storm Surge
Impact - drowning after being swept into water
Response - evacuate
Requirement - 3-12hrs warning of peak height and time of flood at 1-10km, 1hr resolution
Method - storm surge model driven by NWP

Severe wind (extratropical cyclone, tropical cyclone, local wind, gust & tornado)
Impact - injury from flying debris and falling trees
Response - move to safe place (e.g. refuge, basement), stay indoors, evacuate mobile homes.
Requirement - damage forecast 10mins ahead for tornado, increasing to 12 hours or more for tropical cyclone.
Method - Observation/extrapolation, Local winds, NWP, convection forecast for gusts and tornadoes.

Toxic algae
Impact – injury to water sports participants, poisoning of water supplies.
Response – chemical treatment to kill algae, evacuate area, use alternative water supplies.
Requirement – any observation or forecast.
Method – Observation/extrapolation.

A.2 Threats to property

Severe wind (extratropical cyclone, tropical cyclone, local wind, gust & tornado)
Impact - damage from flying debris and falling trees, lifting of roofs, overturning/lifting of mobile homes
Response - secure mobile homes, windows, shutters
Requirement - 1-2hrs warning of severity of damage
Method – Local winds, NWP, convection forecast for gusts and tornadoes.

River or Surface Water Flood
Impact - Damage to property, especially foundations and contents
Response - deploy sandbags, move furniture etc to higher floor
Requirement - 3hrs warning of flood area
Method - Observation; Hydraulic river flow model; Hydrological run-off model; Extrapolation; Convection f/c; Mesoscale precipitation; NWP.

Large Hail
Impact - damage to cars and roofs, especially of glass
Response - protect glass with nets, attempt suppression with cloud seeding
Requirement - 1-2hrs warning of occurrence of large hail at 1-5km resolution
Method - Observation; Extrapolation; Convection f/c.

Avalanche

Impact - destruction
Response - controlled release of snow with explosions
Requirement - 1hr warning of dangerous snow condition
Method - Snow pack model driven by observation/extrapolation, mesoscale precipitation, convection forecast or NWP snowfall, NWP temperature and wind.

Heavy Snow
Impact - damage from weight of snow
Response - clear before becomes too heavy
Requirement - 1 - 6 hrs warning of snow depth
Method - Snow depth observation; Precipitation observation/extrapolation, mesoscale precipitation, convection f/c, NWP; NWP forecast of temperature.

Storm surge
Impact - flooding of coastal properties
Response - Raise estuarial barriers, check status of coast defences, secure windows & doors.
Requirement - surge height - 3hrs warning for defences/ local response, 12hrs warning for barriers.
Method - Observed/extrapolated residual, Surge model driven by NWP.

High waves
Impact - flooding & damage from stones to coastal property, especially marinas.
Response - Secure windows & doors. Possibly evacuate.
Requirement - 1-6 hour warning of wave/surf height
Method - Observed/extrapolated surf, surf model driven by observed waves/water level or by wave and surge models, driven by NWP. Also requires information on beach material.

Fire
Impact - destruction
Response - prepare firebreaks, soak property with water.
Requirement - Risk reduction can be undertaken on the basis of advanced warning of fire risk at lead times of 6-24hrs. Require observations of vegetation stress and soil moisture daily at 1-3km resolution and forecasts of lightning without precipitation, surface temperature, humidity and wind at 1-50km resolution.
Method - NWP + observed soil moisture and vegetation stress.

A.3 Threats to transport

A.3.1Air

Provision of meteorological services in support of civil aviation is governed by international agreement through the International Civil Aviation Organisation (ICAO). However, the spectrum of interest is much broader than commercial airlines, ranging from lift-off and recovery of spacecraft to ultra-light aircraft. These requirements span the full range of weather systems in location, altitude and time-scale.

- Civil Aviation (jets), including commercial and private jets operating according IFR rules, fly mainly at high altitude (above 7000 m or even higher) except during take off and landing. The forecasting period can range from nowcasting (1 hour or less) to the limit of VSRF (up to 12 hours or more).
- Civil Aviation (propellers), including commercial and private planes operating according IFR rules, fly at lower levels than commercial jet aircraft and so are subject to both icing and turbulence. Icing affects both flight surfaces and engines.
- General aviation, including light tourist aircraft and helicopters, operates mainly at low levels, often very low, and generally requires visual contact with ground. Flights are mainly of short duration, so safety can benefit from shorter-range forecasts, though up to 12hrs is required for planning. Particular problems are icing, lightning strikes and cloud covered hills.
- Other air vehicles, including sailplanes, balloons, gliders etc., operate mainly at low levels, often very low and require visual contact with ground. In addition to the requirements of general aviation, these vehicles are very susceptible to turbulence and wind, both horizontal and vertical components. Forecasts of up to an hour can be used to enhance safety if available.

Safety services required for aviation are divided below into aerodrome and in-flight services, since they have different requirements.

Aerodrome and approaches

Visibility (Fog and Low Cloud)

Impact - For modern airliners, visibility at ground may be no longer a critical item, since it is foreseeable that in the future ILS systems will become more and more sophisticated and widely used, although this threat may continue to exist on small airports and in less developed countries. General and light aviation activity, subject to VFR rules, can be completely stopped or severely reduced. On the other hand visibility at ground is usually measured by in situ instruments. More important however is the possibility of detecting fog patches approaching the airfield. It can be argued that importance of visibility on jet planes may reduce in the future but not everywhere and not for every plane.

Response - Depending on the category of the airport, low visibility for thick fog or low clouds can force to close the airport or to restrict operations only to planes equipped with instrumental systems for that category. Spacing between aircraft has to be increased, with introduction of delays and flight cancellations. Divert approaching planes to alternate airports.

Requirement – horizontal, vertical and slant visibility at 0.5 km horizontal, 30m vertical & 5 min temporal resolution

Method - Observation/extrapolation, Fog/stratus forecast, NWP

Snow on the ground

Impact - Presence of snow on the runways and parkways makes braking and steering more difficult especially for single engine aircraft and when strong wind is blowing. In this case the airport can be closed with impact on the schedule of operations.

Response: - activate actions to clear the runways, increase spacing between aircraft, approaching planes diverted.

Requirement - Up to 1hr warning of snow cover/depth at 1km resolution, every 15 min.

Method - Observation/Extrapolation of snow cover/depth and wind.

Icing conditions on the ground

Impact - Icing conditions over airport can have an impact over control system of planes, due to the freezing of wet snow or slush over the airframes. Consequences on the schedule of operations. In the future this problem may be reduced due to better de-icing systems on board the planes.

Response - activate actions to de-ice aircraft and clear the runways.

Requirement - resolution: horizontal 1 km, repetition rate: 15 min

Method - Observation/extrapolation of temperature, precipitation & cloud water/visibility, NWP.

Strong surface winds, gusts, and wind shear (including microbursts)

Impact - The presence of strong wind can prevent light aircraft from flying and increases the effect of icing. Otherwise a steady wind, even if strong and partially across the runways, can be counteracted during takeoff and landing operations. More dangerous are the gust winds usually associated with the presence or approach of thunderstorms. Downdrafts associated with the gust front that can occur 15-20 km ahead the precipitating cell can produce a sudden loss of airspeed and altitude of aircraft with dangerous consequences. In the case of a microburst this can even lead to a crash.

Response - Delay landing of planes. Divert approaching planes to alternate airports. Avoid operations of light planes.

Requirement - Prediction of movement and speed of thunder cells, development of gust fronts, and downbursts. Resolution: horizontal 0.5 km, repetition rate: 1 min

Method - Convection forecast.

Heavy precipitation

Impact - reduced visibility, reduced braking effectiveness and aquaplaning on runway

Response - suspend operations, reduce taxi-ing speeds.

Requirement - 10min - 1hr forecast of rain rate

Method - Observation/extrapolation, Convection forecast.

Wake vortices

Impact - loss of control in take-off and landing, especially when a small aircraft follows behind a large one

Response - increase aircraft separations

Requirement - 10-20min forecast of advection & dissipation of wake vortices. Requires horizontal wind and natural turbulence at very fine space & time resolution

Method - Extrapolation; NWP.

In flight

Turbulence (near jet streams and convective clouds)

Impact - Turbulence rarely causes damage to commercial planes, although it may cause illness and even injuries to passengers and crew. Turbulence associated with convective cells is inferred by detecting the presence of convection areas. Clear Air Turbulence is associated with jet streams and gravity waves and more difficult to detect. VSRF for turbulence is also important in the process of route planning since a different route can be chosen before the flight. The capability of forecasting jet streams position is very important for fuel consumption predictions and selection of most economical route.

Response: Avoid areas concerned. Adopt safety rules on board the planes

Requirement - Identify existing areas and forecast high-risk areas to 5km resolution, updated every 15min.

Method – Observation/extrapolation; Convection f/c; NWP

Volcanic ash

Impact – Volcanic ash consists of fine particles of silica and metal oxides together with acidic gases. Principle effect on aircraft are failure of jet engines, abrasion of windows, damage to pitot-static system, surface abrasion. Costs >$250million since 1982.

Response - Avoid areas concerned.

Requirement – Predictions of the location, concentration and composition of ash up to 12 hours ahead. Resolution: horizontal - 3 km, vertical - 1km; repetition rate: 15 min

Method – Observation of ash or accompanying sulphur dioxode; Dispersion model driven by NWP.

Icing

Impact - loss of lift and control from icing on wings and control services, loss of power from engine icing. . For helicopters uneven ice accretion on the rotor blades, causing severe vibration and cyclic pitch controls may become jammed, causing loss of control.

Response - avoid areas at risk, operate de-icing devices

Requirement - Forecast areas of icing risk to 20km resolution

Method - NWP

Low cloud and visibility-

Impact - inability to navigate or see other aircraft. For general aviation and other vehicles operating with VFR rules and flying at very low level, low visibility can be particularly dangerous since obstacles (hills, buildings, trees and the ground itself) cannot be seen in time for dodging them.

Response - cancel flight, choose alternate route, or plan for IFR procedures.

Requirement - forecast critical cloud base and slant visibility thresholds to 20km resolution.

Method - Observation/extrapolation, Fog/stratus prediction, NWP.

Cabin ozone

Impact - respiratory damage

Response - Alter route or altitude of flight?

Requirement - 6-18hrs warning.

Method - Observation/extrapolation of ozone, Upper troposphere chemistry model driven by NWP.

Cosmic rays

Impact - cancer risk to frequent fliers, especially cabin staff

Response - Alter route of altitude of flight?

Requirement - 6-18hrs warning.

Method - Space weather model.

MSL pressure

Impact – Required for altimeter setting. Errors can result in a crash.
Response – Minimum pressures are provided for regions.
Requirement – 3 hours prediction of minimum msl pressure over regions of ~100km.
Method – Extrapolation, NWP.

A.3.2 Sea

High wind
- Impact - loss of manoeuvrability into port leading to increased risk of collision. Small yachts may be blown flat onto the water.
- Response - cancel sailing, close port.
- Requirement: Forecast of exceedance of safe threshold: ferries - 2hr warning, 5km res.; leisure - 6hrs warning, 20km resolution
- Method - Observation/Extrapolation; NWP

Waves
- Impact – Capsizing of small vessels, leading to drowning. Loss of manoeuvrability into port leading to increased risk of collision, damage to passengers, cargo (including vehicles) and fittings, risk of sinking if cargo shifts or if small vessels are swamped, sinking of larger ships by "freak" waves.
- Response - cancel sailing, close port, change route.
- Requirement: Forecast of exceedance of safe threshold: ferries - 2hr warning, 5km res.; leisure - 6hrs warning, 20km res.
- Method - Wave model driven by observation/extrapolation and NWP

Fog
- Impact - increases risk of collisions, both with other vessels and with land
- Response - cancel sailing, close port, avoid area at risk
- Requirement - forecast areas of fog 2-6 hours ahead. Observe fog 100m-10km resolution.
- Method - extrapolation/persistence + NWP

Icing
- Impact - vessel becomes top heavy - may overturn and sink.
- Response - avoid area at risk
- Requirement - forecast 6-24hrs ahead.
- Method - NWP + observed sea surface temperature

A.3.3 Land

Thick fog
- Impact - increased risk of vehicle collisions with visibility below 200m
- Response - discourage travel, close road, reduce speed (with automated signs and in-car displays).
- Requirement - 6-12hr general warning of risk of fog at 50km resolution, 1hr warning of existence of fog at 5km resolution, 5min warning of existence of fog at 100m resolution.
- Method - Observation/extrapolation, Fog/Stratus prediction, NWP.

Heavy rain / Surface Water Flood
- Impact - loss of control, including aquaplaning and loss of braking, and reduced visibility.
- Response - reduce speed
- Requirement - using automated signs or in-car information systems, forecasts of 5-15mins lead-time and 100m-1km resolution and/or observations of conditions ~1km ahead.
- Method - Observation/extrapolation, Convection prediction, NWP.

Freezing precipitation
- Impact - reduced traction leading to vehicle collisions.
- Response - pre-emptive salting, gritting, close road
- Requirement - 6-hour forecast for pre-emptive action. Observations every 5-10 minutes at 1km-10km resolution for reaction.
- Method - NWP; Observation.

Snow
- Impact - reduced traction, road/railway impassable
- Response - pre-emptive salting, gritting, clearance with snowploughs, close road/railway

Requirement - Snow depth observation at 100m-1km resolution, 0-1hours ahead for closure; 6 hour lead time for salting/gritting/clearance; 12-24 hour lead time for moving snowploughs to threatened area.
Method - Observation/extrapolation of snow depth, NWP.

River flooding
Impact - car or train breakdown, cars swept away, trains derailed
Response - reduce speed, close road or railway
Requirement - Identify flood has occurred - topography at ~10m-1km resolution, every 5-10mins. Prediction - see above at 2.1.1
Method - Observation of flood area/depth.

Mud slide/Avalanche
Impact - loss of road or railway section, potential major accident
Response - close road or railway, reduce speed
Requirement - Identify that slide has occurred - land height at ~10m resolution - every 5-10mins. Predict that slide will occur - rainfall accumulation at ~100m-1km resolution. One hour’s lead-time required.
Method - Observation of land height, Observation/extrapolation of rain rate, Convection forecast.

Ice/frost
Impact - road accidents
Response - pre-emptive salting, gritting.
Requirement - Road temperature and road state (wet/dry etc) forecasts, 6-18 hour lead time, 100m - 5km resolution
Method - NWP + Road model.

Strong wind
Impact - roads: cross winds, especially on bridges. rail: overhead power pickups
Response - reduce speed, close road or railway
Requirement - wind speed thresholds, 1-12hrs lead time, 5-20km resolution
Method - Observation; NWP.

Sand /dust storm
Impact – Loss of visibility, immobilisation of vehicles, covering roads
Response – avoid travelling, use alternate route
Requirement – formation and movement of sand/dust storms 1-12 hours ahead depends on surface wind, stability and soil moisture
Method – Observation/extrapolation; NWP

A.4 Threats to utilities

Gas supply

River flooding
Impact - Floodwater cuts new channel, rupturing gas pipe.
Response - mobilise staff to seal pipe and repair.
Requirement - Identify flood has occurred - topography at ~10m-1km resolution, every 5-10mins.
Method - Observation of flood area/depth

Mud slide/Avalanche
Impact - Pipes ruptured.
Response - mobilise staff to site to seal pipe, clear debris, and repair.
Requirement - Identify that slide has occurred - land height at ~10m resolution - every 5-10mins.
Method - Observation of land height.

Electric supply

Lightning
Impact - damage to transmission equipment and transformers.
Response - mobilise line repair staff in advance, repair damage once it occurs.

Requirement - warning of risk areas, 6-18hrs ahead, to 10-50km. Identification of location of damage to 100m
Method - observation, NWP.

High wind
Impact - arcing between clashing overhead cables. Trees falling on power cables.
Response - mobilise line repair staff in advance, repair damage once it occurs.
Requirement - warning of risk areas, 6-18hrs ahead, to 10-50km.
Method - observation/extrapolation, NWP.

Icing
Impact - weight of ice produces arcing from sagging cables & collapsing pylons
Response - mobilise line repair staff in advance, repair damage once it occurs.
Requirement - warning of risk areas, 6-18hrs ahead, to 10-50km. Identification of area of icing to 10km
Method - observation/extrapolation of precipitation, temperature & cloud, NWP.

Water supply

River flooding
Impact - floodwater contaminates water supply
Response - mobilise staff to divert flood water and to contain contamination
Requirement - Identify flood has occurred - topography at ~10m-1km resolution, every 5-10mins.
Method - Observation of flood area/depth

Mud slide/Avalanche
Impact - contamination of water supply
Response - mobilise staff to site to clear debris
Requirement - Identify that slide has occurred - land height at ~10m resolution - every 5-10mins.
Method - Observation of land height.

Freezing temperatures
Impact - Above ground: burst pipes when temperature falls, causing leak when temperature rises. Below ground: increased risk of cracking of old mains pipes
Response - in houses: raise temperature, for mains supply: mobilise staff to repair
Requirement - 6-24 hour temperature forecasts
Method - NWP

Liquid fuel supply

Lightning
Impact - risk of explosion
Response - implement heightened precautions against discharges, cease handling operations
Requirement - 15min-1hr lead time, 10-20km resolution (lightning can occur at considerable distances from storm clouds so finer resolution provides no benefit)
Method - Observation/Extrapolation; Convection f/c techniques.

Drainage

Flooding
Impact - drains overflow into streets and buildings
Response - implement control procedures to lower water levels
Requirement - Rainfall rate at 100m-1km resolution every 5-30mins.
Method - Observation/extrapolation of water flow, Observation/extrapolation of precipitation, Convection forecast.

Telecommunications

Lightning and other electromagnetic disturbances (e.g. space storms)
Impact - current surges on telegraph lines, damage to switches, risk of strike to linesmen
Response - cease line work
Requirement - Identification at 100m resolution, 1hr warning at 10km resolution

Method - Observation/extrapolation, Convection forecast.

High wind
Impact - falling trees breaking telegraph lines
Response - mobilise line repair staff
Requirement - Prediction of risk of falling trees at 10km resolution, 1hr ahead.
Method - Observation/extrapolation of surface wind, NWP.

Icing
Impact - telegraph lines break and poles/towers fall under weight of ice
Response - mobilise line repair staff
Requirement - 3-12hr warning at 10km resolution, 1hr warning at 1km resolution, surface temperature and profile below cloud + precipitation rate and phase of cloud.
Method - Observation/extrapolation of existing icing conditions; Observation/extrapolation of precipitation & surface temperature + temperature profile from NWP.

Precipitation and cloud
Impact - partial or total loss of signal of satellite and surface telecommunication channels (Ka band and above)
Response - adopt countermeasures (e.g. beam shaping and re-routing communications)
Requirement - quasi-real time precipitation intensity and vertical extent (15 - 30 min), 1-5 Km ground resolution, 1km vertical resolution, 1 mm/h accuracy.
Method - Observation/extrapolation, Convection forecast.

A.5 Threat to industry/business

Land Construction

High wind
Impact - possible collapse of cranes, scaffolding etc
Response - evacuate high cranes, evacuate site
Requirement - wind speed, lead time 30minutes, site-specific.
Method - Observation/extrapolation, NWP.

Offshore exploration & production

High wind/waves
Impact - affects all delicate positioning operations, including helicopter landing, supply ship docking, heavy lifts, connecting risers etc
Response - suspend delicate oil & gas operations
Requirement - early warning that operations may not be possible, at least one hour’s warning that safe limits will be exceeded at the site. In practice, 10km resolution wave & wind fields can provide this information.
Method - Observation/extrapolation, wave model driven by NWP with observed or modelled currents where these are significant.

A.6 Environmental Threats

Acid rain - requirements are at time scales greater than 12 hours

Marine toxic releases
Impact - wildlife killed in rivers and the sea by contact and ingestion of substance
Response - contain spread of substance
Requirement - Identification of current spread, concentration and composition. Prediction of movement and dilution due to waves at sea and flow in rivers.
Method - Observation; Marine dispersion model.

Annex B Requirements for General Very Short Range Forecasts

This Annex provides the detail to section 2.2, indicating the impact of weather on the activity of interest, the responses that can be made to counter it, the information required to enable this response to be made, and the method of generating that information. The methods match those listed in section 3 of the main paper.

B.1 Utilities

Power demand planning

Lead times for response are generally greater than the nowcasting range due to the time taken to procure and move supplies around. The fastest response is probably from the electricity industry. Information on peak loads a few hours ahead (at least 2 hours) can be responded to by bringing more capacity on stream and through pumped storage schemes. Short lead-time changes to predicted demand are likely to arise from:

Impact – a sudden drop in temperature increases demand due to additional heating and to people staying indoors instead of going out
Response – provide additional generating capacity
Requirement – 6-48hr prediction of temperature
Method – NWP

Impact – sudden darkness results in lights being switched on – including automatic switch-on of streetlights.
Response - provide additional generating capacity
Requirement - 6-48hr prediction of “day darkness”
Method – Convection f/c; NWP

Wind power

Impact – power output is a function of the wind speed cubed. Protective action is required at high wind speeds.
Response – adjust the mix of power sources providing energy to the grid
Requirement - near surface wind speed at 1km, 1hr resolution
Method - NWP

Wave power

Impact – power output depends on the wave energy.
Response– adjust the mix of power sources providing energy to the grid
Requirement - wave energy spectrum at generator sites (typically inshore) at 1hr resolution.
Method – Wave model + NWP

Solar power

Impact – power output depends on the amount of incoming solar energy.
Response – adjust the mix of power sources providing energy to the grid.
Requirement - solar energy at 1km, 1hr resolution.
Method - NWP

Water demand planning

Impact – strong demand for garden use in response to hot sunny days with no recent rainfall exceeds supply and results in pressure reductions and even cuts.
Response – move water from distant reservoirs in advance of requirement.
Requirement – at least a day’s notice of appropriate conditions.
Method - NWP

Telecommunications

Precipitation
Impact - microwave attenuation due to precipitation can cause network failures
Response - re-route networks through unaffected relays
Requirement - Prediction of precipitation rate and cloud water/ice contents at lead-time 1-5mins, with 1km horizontal, 1km vertical resolution. Accuracy of attenuation - 10-2dB
Method – observation/extrapolation

Severe weather
Impact - large increase in calls
Response - increase staff available to deal with problems

Requirement - advanced prediction of severe weather, probably beyond nowcast period
Method - NWP

Building control

With the development of "smart" buildings, there will be an increasing need for weather information to be fed into the control mechanisms. Simple control will probably be based on measurements taken on the building itself. However, scope for more complex control could include provision of forecasts.

Impact – weather affects the need for heating, lightning and ventilation
Response – automatic adjustment of heating, lightning and ventilation controls.
Requirement – Observations & forecasts of Temperature, Illumination & Wind.
Method – Observation/extrapolation

B.2 Transport route planning

Air

Impact - Aircraft flight times and fuel consumption depend on strength of headwind and avoidance of hazards, such as turbulence and thunderstorms. Late arrival at destination can lead to loss of landing slot
Response - use forecasts to prepare least time routes avoiding user-defined hazards
Requirement - forecast wind profiles + turbulence + convective cloud with lead-time of 3-6 hours. For supersonic transports, wind and temperature in the lower stratosphere are required.
Method - NWP

Sea

Impact – Costs depend on voyage time. Payment may also be tied to meeting specific deadlines.
Response – Computation of least time route
Requires - forecasts of Wind + Waves + Ice (+ currents?)
Method - NWP + Wave model + ice observation

Land

Impact – The efficiency of a haulage operation depends on lorries and drivers keeping to schedules so that goods arrive on time and laws on driving time are met. Bad weather results in slower traffic speeds, and increased risk of accident, resulting in major delays.
Response – Delay or re-route journeys to avoid bad weather.
Requirement - as for land transport warnings, but longer lead-time required.
Method - NWP

B.3 Recreation - planning a day or half day activity

Recreational activities are sensitive to many aspects of the weather, and also particularly susceptible to hazards. Requirements for warnings of hazards have already been dealt with in 2.1.

Land

Impact - Participation in land-based outdoor leisure activities increases markedly on warm, sunny and dry days, with water activities favoured at high temperatures. Many sporting events are affected by rain. In Alpine resorts, high temperatures can affect the condition and safety of snow slopes.
Response – Selection of an appropriate activity, or cancellation of an inappropriate one, saving wasted travel time and cost.
Requirement – For final decisions, 3-9hr forecasts of Precipitation, Temperature, Sunshine & Wind
Method - NWP

Sea

Leisure boating activities are largely confined to sea areas within a few kilometres of the coast, and include canoeing, sailboarding, dinghy sailing up to serious yacht racing. Other marine leisure activities include diving. For mass participation, the weather sensitivity is similar to that for land based activities, but with higher temperatures favoured. The main influence of waves is via the wind sea, which is itself a fairly direct response to the local wind. Note that the warning requirements for these activities include much lower wind speed thresholds than those for commercial sea transport. Timing of activities may be dominated by tidal flows. Forecast lead times are a little longer at 6-9hours due to the slow speed of most water-borne craft. The variables having most influence on these activities are:

Precipitation, temperature, visibility, sunshine, wind, sea temperature
Impact – leisure boating depends on conditions being not only safe, but also providing pleasant temperatures and good views.
Response – abandon the trip
Requirement – 3-24hr prediction of cold, wet of misty conditions.
Method – observation/extrapolation of sea temperature, NWP

Waves
Impact – steep waves make sailing small craft uncomfortable.
Response – abandon the trip
Requirement – 3-24hr prediction of wave height and period
Method – wave model

Tides
Impact – fishing, diving and other activities depend on water depth and currents.
Response – select time of trip according to tide state
Requirement – 24hr prediction of tidal height and current speed.
Method – astronomical tables + surge model

Water clarity
Impact – poor clarity affects diving
Response – change location and time of dive
Requirement – 1-6hr prediction of areas of good and poor water clarity
Method – Observation/extrapolation, sediment transport model, biological pollution model.

Air

Impact - Leisure aviation includes mostly low level flights by lightweight craft such as balloons, para-gliders and ultra-lights. In addition to safety considerations (see 2.1.3.1), the wind requirements for successful flights are quite critical, and differ between the types. Few flights are undertaken in precipitation and good visibility is generally favoured.
Response – Delay or cancellation of flight.
Requirement – 3-9hr forecasts of low level wind, low level turbulence, precipitation, cloud layers - bases & tops, thermal & mountain wave activity and inversions
Method - NWP

B.4 Agriculture/ Horticulture/Water resources

Soil moisture
Impact - wilting of plants in dry conditions
Response - irrigation
Requirement - daily observation or diagnosis
Method – NWP + Hydrological model

Temperature
Impact - frost kills tender plants, high temperatures produce wilting
Response - frost protection includes heaters, fans, covers and spraying; high temperature protection includes shade cloths.
Requirement - some mitigating actions can be taken with as little as one hour's lead-time. In general, protection of a whole farm requires a minimum 6-24hour forecast, 100m - 10km resolution(?), max/min or threshold exceedance
Method - Observation/extrapolation, NWP.

Humidity
Impact - affects pest development
Response - time spraying for optimum effects
Requirement - 1-6hrs notice of suitable conditions
Method - NWP.

B.5 Insurance and Weather Derivatives

Insurance of life and property

All warnings of threats to life and property (see 2.1.1 & 2.1.2)

Weather Insurance

Impact - Any specified weather event causing a loss. Normally weather that might effect the success of an outdoor event, such as a concert.
Response – Take action to minimise loss
Requirement – Normally more than 24hrs notice of the insured weather condition.
Method - NWP

Weather Derivatives

Impact - Any specified weather sensitivity of a business. Normally applied to power and water utilities.
Response – Alter price of instrument
Requirement – Forecasts for a month or more ahead.
Method - NWP

B.6 Fishing

Impact - fish congregate in preferred regions
Response - target preferred areas
Requirement - 3-24hrs notice of ocean temperature distribution
Method - Shelf seas model driven by NWP.

B.7 Security & Law Enforcement

Environmental conditions can affect substantially military and security operations mainly where sophisticated systems and equipment are used and general meteorological support is becoming no longer sufficient. Meteorological conditions can be specific for each application and for each system and equipment used. Present or foreseen conditions are used as a decision aid to select the best system(s) and modalities for the course of action. In order to make easier the decision making process, various Tactical Decision Aid (TDA) tools have been or are being developed, using as input the result of a meteorological processing output (observations, outputs from NWP, special models etc.) together with the profile of the mission or equipment considered and having as result the meteorological assessment for the operation concerned
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B.7.1 Target Acquisition

electromagnetic wave propagation – Temperature and Humidity profiles

Impact – The standard propagation of e.m. waves in the atmosphere is affected by refraction, attenuation, optical interference (earth's surface reflection), diffraction and tropospheric scatter. Furthermore the distribution of temperature and moisture within the atmosphere may lead to non-standard propagation mechanism of sub-refraction, super-refraction and trapping. All e.m. systems can be affected, with particular regards to radar probability of detection, electronic surveillance measures vulnerability, UHF/VHF communication range, surface search range displays.
Response: consider effects on systems, switch off or reduce radar power, consider alternative systems for surveillance, use proper frequencies for communications, change course in horizontal or vertical.
Requirement: temperature & humidity profiles, 50km horizontal, 100m vertical, 1 hr temporal resolution. Humidity profiles in lowest few metres over sea.
Method: Observation/extrapolation, NWP, TDA

visibility - in visible, solar IR, thermal IR wavelengths

Impact – visibility can substantially affect operations because of the capacity of detecting a specific target or area. Furthermore the possibility of having single or combinations of different wavelengths can enhance the target detection capability and flexibility in using different weapon systems.
Response: use night vision goggles, select the more appropriate equipment or system, cancel operation.
Requirement: forecast visibility 1-6 hours ahead, identification of foggy areas 0.1-1km resolution, repetition time 5-30 min, thermal spots 0.1-1 km resolution, accuracy 2K
Method: observation/extrapolation/persistence, NWP, TDA

Illumination

Impact – illumination has a major impact on the visibility level at surface mainly during night – Low level of illumination, due to moon elevation and cloudy conditions, can affect the useful range of night vision goggles and VIS/NIR guided systems, depending on the sensitivity of the sensor, both in visible and NIR.

Response: use night vision goggles, select the more appropriate equipment or system, cancel operation
Requirement: forecast illumination 1-6 hours ahead, resolution 0.5-1.5 km, accuracy: repetition time 30 min
Method: modelling/NWP, TDA

Acoustic propagation in the ocean
Impact: mainly submarines can detect or be detected by other ships
Response: decide operation plan
Requirement: forecast propagation 1-6 hour ahead
Method: ocean models

B.7.2 Movement of personnel & equipment

Movement of personnel & equipment for military operations are affected, as regards as the threat to transport, by the same hazards described in 2.1.3

Air

Contrails
Impact – Although less important than in the past, when visual reporting of contrails could be the main way to detect approaching planes, the need of limiting e.m. emission from radars has increased the importance of avoiding production of contrails that can be detected from the ground and from other planes.
Response: change flight level or route
Requirement: forecast areas favourable to contrail production 1-6 hours ahead. Resolution 5 km, repetition time 1 hour
Method: NWP, TDA

Atmospheric acoustic propagation
Impact – Noise produced by engines of planes and helicopters can be detected at very long distance, depending on the weather conditions, wind direction, temperature gradient, scattering by atmospheric turbulence and status of the ground.
Response: reduce noisy conditions, choose a route in the lee of the target.
Requirement: forecast of acoustic propagation 1-6 hours ahead. Resolution 0.5 km, repetition time 15 min.
Method: NWP + Acoustic Model, TDA

Cloud cover
Impact – Unlike the commercial aviation, military operation can use cloud cover as a screen not to be detected by passive sensors or visual surveillance systems. On the other hand presence of clouds or low ceiling can prevent from using visual sensors or parachute operation.
Response: change operation modalities, cancel operation
Requirement: forecast of cloud cover 1-6 hour ahead. Resolution 2 km. Repetition time 10 min
Method: modelling/NWP

Wind profile
Impact – The detailed structure of wind profile in the lower troposphere has a major impact on the parachute operations and in particular on the high altitude launches that can be performed even at 30-40 km from the target.
Response: change operation modalities, cancel operation
Requirement: forecast of wind profile 1-6 hour ahead. Resolution 0.5 km. Repetition time 15 min
Method: observation/extrapolation, NWP

Sea

sea surface temperature
Impact – risk of hypothermia for seamen in contact with cold sea.
Response – wear protective clothing
Requirement –1-24hr prediction at 1km resolution
Method – observation/extrapolation.

sea-ice

Impact – damage to ship on impact
Response – choose alternative route
Requirement – 24hr prediction at 1km resolution
Method – observation/extrapolation.

Land - on & off road

Soil moisture

Impact – wet soils deform under less pressure allowing vehicles to become bogged down.
Response – reduce speed, change route, change vehicle type
Requirement – soil type and moisture 1-24hrs ahead at 100m resolution
Method – observation/extrapolation, hydrological model using observed/extrapolated precipitation or NWP.

Visibility

Impact – loss of orientation, difficulty in route finding
Response – reduce speed, change route.
Requirement – visibility 1-24hrs ahead at 1km resolution
Method – observation/extrapolation, fog & low cloud, NWP.

B.7.3 Ballistic accuracy

Impact – Atmospheric conditions over a battlefield can influence substantially precision of long range firing due to the 3-dimensional variability of wind and temperature and hence of the air density and motion. Main consequences are the difficulty for achieving the target at first shot and the major cost in shells due to more consumption or danger to hit other targets than those selected.
Response: prepare to use remote guided shells.
Requirement: Wind, pressure and temperature forecasts up to 12 hours ahead, with 1 km horizontal and 0.5 km vertical resolution up to 30 km altitude.
Method: Observation/extrapolation, NWP

B.7.4 Dispersion of toxic substances

Impact – Conditions favourable to dispersion have to be considered to take into account consequences of release of toxic substances on people and equipment.
Response: consider operation modalities, prepare to use masks/life vests.
Requirement: 3-D distribution of toxic substance in atmosphere and 2-D distribution of deposition on ground up to 12 hours ahead with 0.5 km horizontal, 0.1 km vertical and 1hr temporal resolution.
Method: NWP + dispersion model.

Annex C

Consolidated table of observational requirements for nowcasting and very short range forecasting in the period 2015-2025, excluding requirements for the use of Numerical Weather Prediction models for these purposes.

The columns are:

A. Title – main heading of forecast method as used in chapter 3 of the main paper
B. Sub-title – sub-heading as used in chapter 3 of the main paper
C. Required variable
D. Conditions – any special conditions, e.g. over sea or land, through cloud, in mountainous terrain etc. If no conditions are mentioned it should be assumed that observations are required everywhere.
E. Applications – the main services that would benefit from these observations, as used in section 2 of the main paper.
F. Nearest variable from the WMO rolling review process
G. Code number of variable in WMO ….
H. Required altitude range – as in WMO … but with the addition of "boundary layer" covering the altitude range below the height of surface induced mixing.
I. Accuracy threshold – the accuracy of the WMO variable that is required before an observation can be used with any benefit. This may be expressed as an RMS error in the physical variable, as a percentage error or as a hit rate & false alarm rate for detection of the variable.
J. Accuracy optimum – the accuracy beyond which there is no further benefit from improvements.
K. dx threshold – the spatial resolution that is required before an observation can be used with any benefit.
L. dx optimum – the spatial resolution beyond which there is no further benefit from improvements.
M. dz threshold - the vertical resolution that is required before an observation can be used with any benefit.
N. dz optimum – the vertical resolution beyond which there is no further benefit from improvements.
O. dt threshold - the frequency that is required before an observation can be used with any benefit.
P. dt optimum – the frequency beyond which there is no further benefit from improvements.
Q. Priority level – VH: very high, major benefits expected, H: high, benefits expected, M: medium, benefits possible.
R. Breakthrough level – the combination of accuracy, spatial, vertical and temporal resolution that would provide a significant advance in forecasting capability relative to that currently available, or likely to be available before 2015.
S. Current observing techniques – e.g. surface in situ, satellite imagery.
T. Level met – the degree to which the current methods or those expected to come into use before 2015, will meet the requirement. D: desirable met, U: useful met, N: nothing met, [ ]: partly, L: met over land areas, O: met over ocean areas, R: met by radar.

Title	Sub-Title	Required variable	Conditions (1)	Applications	Nearest WMO/CEOS parameter	WMO/ CEOS code	Required Altitude Range (2)	Accuracy threshold (3)	Accuracy optimum (3)	dx threshold	dx optimum	dz threshold	dz optimum	dt threshold	dt optimum	Priority level	Breakthrough level (if any)	Current Observing Techniques	Level met
		Observation & Extrapolation																	
		Surface Precipitation																	
Observation & Extrapolation	Precipitation	Rain rate > 1mm/hr		Information	Precipitation rate (liquid)	35	surface	50% HR, 50% FAR	99% HR. 2% FAR	50km	1km	-	-	1hr	15min	VH	95% / 10% / 10km/ 1hr	Ground-based radar	[D: LR]
Observation & Extrapolation	Precipitation	Rain rate		Flooding, aviation, etc	Precipitation rate (liquid)	35	surface	10mm/h	0.1mm/hr	50km	1km	-	-	1hr	5min	VH	10mm/h / 2km / 15min	Ground-based radar	[U:LR]
Observation & Extrapolation	Precipitation	Rain rate		Information	Precipitation rate (liquid)	35	surface	1mm/hr	0.1mm/hr	50km	1km	-	-	1hr	15min	M	0.2mm/hr / 5km / 1hr	Ground-based radar	[U:LR]
Observation & Extrapolation	Precipitation	Rain rate		Telecommunications	Precipitation rate (liquid)	35	surface	1mm/hr	0.5mm/hr	50km	1km	-	-	1hr	10min	H	1mm/hr / 1km / 10mins	Ground-based radar	[U:LR]
Observation & Extrapolation	Precipitation	Rain rate	sea	Extrapolation over land	Precipitation rate (liquid)	35	surface	5mm/h	0.1mm/hr	50km	1km	-	-	1hr	15min	VH	5mm/hr / 10km / 1hr	Surface in situ	N
Observation & Extrapolation	Precipitation	Hail >2cm diameter	land	Life / Property	None		surface	50% HR, 50% FAR	85% HR. 20% FAR	10km	1km	-	-	1hr	5min	VH	70%/ 40% / 10km / 1hr	Surface in situ	N
Observation & Extrapolation	Precipitation	Snow rate		Telecommunications	Precipitation rate (solid)	36	surface	1mm/hr	0.5mm/hr	50km	1km	-	-	1hr	10min	H	1mm/hr / 1km / 10mins	Surface visual or present-weather sensor	[U:L]
Observation & Extrapolation	Precipitation	Snow rate	land	Road transport, property damage, aviation	Precipitation rate (solid)	36	surface	1mm/hr	0.1mm/hr	10km	1km	-	-	1hr	15min	VH	0.2mm/hr / 10km / 1h	Surface visual or present-weather sensor	N
Observation & Extrapolation	Precipitation	Freezing rain		Falling trees and structures due to ice accretion: life	None		surface	50% HR, 50% FAR	85% HR, 20% FAR	10km	1km	-	-	1hr	5min	VH	70%/ 40% / 10km / 1hr	Surface visual or present-weather sensor	N
		Surface Wind																	
Observation & Extrapolation	Surface Wind	Surface wind	Clear/ cloudy /precipitating	Life / Property/ Telecomms	Wind vector over land	67	surface	3m/s, 20deg	1m/s, 10deg	50km	10km	-	-	1hr	15min	VH	3m/s,10^{o} / 20km / 1hr	Surface in situ	[U:L]
Observation & Extrapolation	Surface Wind	Surface wind	Clear/ cloudy /precipitating	Marine transport & offshore industry	Wind vector (and speed) over sea	66, 68	surface	3m/s, 20deg	1m/s, 10deg	50km	10km	-	-	1hr	15min	VH	2.5m/s,10^{o} / 20km / 1hr	Surface in situ, scatterometer	N
Observation & Extrapolation	Surface Wind	Strong wind >25m/s	Under cloud	Tornado / extreme gust detection: Life	Wind speed over land	65	surface	50% HR, 50% FAR	85% HR, 20% FAR	50km	100m	-	-	1hr	1min	VH	70% / 40% / 200m / 5min	Ground - based Doppler radar	N

Title	Sub-Title	Required variable	Conditions (1)	Applications	Nearest WMO/CEOS parameter	WMO/ CEOS code	Required Altitude Range (2)	Accuracy threshold (3)	Accuracy optimum (3)	dx threshold	dx optimum	dz threshold	dz optimum	dt threshold	dt optimum	Priority level	Breakthrough level (if any)	Current Observing Techniques	Level met
Observation & Extrapolation	Surface Wind	Downward velocity >100cm/s	Under cloud	Microburst detection for aviation transport	Wind profile (vertical component)	3	boundary layer	50% HR, 50% FAR	85% HR, 20% FAR	200m	50m	-	-	5min	1min	VH	70% / 40% / 200m / 5min	Ground - based Doppler radar	N
		Surface Pressure																	
Observation & Extrapolation	Surface Pressure	msl pressure	land	Altimeter settings for aviation transport	Air pressure over land	58	surface	1hPa	0.2hPa	50km	10km	-	-	3hr	1hr	M	1hPa / 10km / 1hr	Surface in situ	
Observation & Extrapolation	Surface Pressure	msl pressure	sea	Altimeter settings for aviation transport	Air pressure over sea	59	surface	1hPa	0.2hPa	50km	10km	-	-	3hr	1hr	M	1hPa / 10km / 1hr	Surface in situ	
		Cloud																	
Observation & Extrapolation	Cloud	Cloud amount profile below 2km	land at forecast site	Aerodrome conditions for Aviation	Similar to Cloud Cover but profile	30	boundary layer	25%	10%	1km	200m	200m	50m	5min	5min	H	25% / 100m / 5min	Surface visual & ceilometer	D
Observation & Extrapolation	Cloud	Cloud amount profile below 2km		En route cloud for VFR Aviation	Similar to Cloud Cover but profile	30	boundary layer	25%	10%	50km	5km	200m	50m	1hr	5min	VH	25% / 10km / 1hr	Surface visual	[U:L]
Observation & Extrapolation	Cloud	Surface illumination	land under thick cloud	Mainly identification of "day darkness": Power consumption	Similar to Downwelling short wave radiation at earth's surface but optical wavelengths only	53	surface	10W/m2	1W/m2	50km	100m	-	-	1hr	5min	H	10W/m2 / 5km / 1hr	Surface radiometer	N
		Surface visibility																	
Observation & Extrapolation	Fog&Stratus	Fog < 1000m	sea	Marine Transport	Cloud type and top temperature/height	29, 32, 33	surface	50% HR, 50% FAR	85% HR, 20% FAR	50km	500m	-	-	1hr	10min	VH	70% / 40% / 20km / 1hr	Surface visiometer	N
Observation & Extrapolation	Fog&Stratus	Fog < 200m	land	Land Transport	Cloud type and top temperature/height	29, 32, 33	surface	50% HR, 50% FAR	85% HR, 20% FAR	50km	500m	-	-	1hr	1min	VH	70% / 40% / 5km / 1hr	Surface visiometer	[U:L]
Observation & Extrapolation	Fog&Stratus	Visibility	land at forecast site	Aerodrome safety	Visibility	62	boundary layer	50% / 30m	20%	1km	200m	-	30m	1hr	1min	H	50% / 500m / - / 15min	Surface visiometer	D
Observation & Extrapolation	Fog&Stratus	Visibility		VFR flight safety	Visibility	62	boundary layer	50%	20%	50km	1km	-	500m	1hr	15min	VH	50% / 20km / - / 1hr	Surface visiometer	[U:L]
		Land Surface																	
Observation & Extrapolation	Land Surface	Depth of surface water	land	Life / Property	Bathymetry	84	surface	0.5m	0.1m	1km	10m	-	-	1hr	5min	VH	0.5m / 1km / 1hr	In situ	N
Observation & Extrapolation	Land Surface	Area of surface water	land	Property / Land transport	Similar to Coastline but shallow water over land	112	surface	50% HR, 50% FAR	85% HR, 20% FAR	1km	10m	-	-	1hr	5min	VH	70% / 40% / 1km / 1hr	In situ or spotter plane	N
Observation & Extrapolation	Land Surface	Snow depth	land	Land transport	Similar to snow water equivalent	95	surface	100cm	1cm	50km	1km	-	-	6hr	15min	VH	0.1m / 1km / 15min		U
Observation & Extrapolation	Land Surface	Snow fraction	land	Land transport	Snow cover	96	surface	50%	10%	50km	1km	-	-	6hr	15min	VH	30% / 10km / 6hr		U
Observation & Extrapolation	Land Surface	Land surface temperature > 500K	land	Fire detection: Life	Fire area and temperature	107, 108	surface	50% HR, 50% FAR	85% HR, 20% FAR	10km	100m	-	-	6hr	1min	VH	70% / 40% / 1km / 1hr	In situ visual or IR satellite or spotter planes	U
Observation & Extrapolation	Land Surface	Smoke location	land	Fire detection: Life	Cloud imagery	28	boundary layer	50% HR, 50% FAR	85% HR, 20% FAR	10km	100m	-	-	6hr	1min	VH	70% / 40% / 10km / 1hr	In situ visual.	U

Title	Sub-Title	Required variable	Conditions (1)	Applications	Nearest WMO/CEOS parameter	WMO/ CEOS code	Required Altitude Range (2)	Accuracy threshold (3)	Accuracy optimum (3)	dx threshold	dx optimum	dz threshold	dz optimum	dt threshold	dt optimum	Priority level	Breakthrough level (if any)	Current Observing Techniques	Level met
Observation & Extrapolation	Land Surface	Change in land height	land	Landslide, mudslide and avalanche detection for warning to land transport, utilities etc	Land surface topography	113	surface	1m	0.1m	100m	10m	-	-	30min	5min	H	1m / 10m / 10min	In situ visual or GPS.	N
		Lightning																	
Observation & Extrapolation	Lightning	Electrical discharges		Life: Fuel/explosives handling	Lightning detection	38	-	30% HR (90% for isolated events), 10% FAR	90% HR (99% for isolated events), 10% FAR	2km (land) / 5km (ocean)	1km	-	-	15min	5min	H	50% (90%) / 10% / 2km (land), 3km (ocean) / 15min	Surface remote sensing by direction finding or arrival time differencing	D
Observation & Extrapolation	Lightning	Electric field		Life: Fuel/explosives handling	None		lower & higher troposphere	20% of breakdown value	5% of breakdown value	10km	1km	-	-	15min	5min	H		Surface in situ field mills	[U:L]
		Icing & Frost																	
Observation & Extrapolation	Icing & Frost	Surface ice accretion		Life / Collapsing structures / Aircraft icing on ground	Similar to Icing but for surface	63	surface	1cm	0.1cm	10km	500m	-	-	1hr	15min	VH	1cm / 1km / 1h	Surface in situ	N
Observation & Extrapolation	Icing & Frost	Surface temperature	Below cloud	Icing: Road Transport	Land surface temperature	100	surface	1K	0.2K	1km	10m	-	-	1hr	15min	VH	1K / 1km / 1hr	Surface in situ	[U:L]
		Turbulence																	
Observation & Extrapolation	Turbulence	RMS horizontal gradient of vertical velocity		Turbulence: Aviation	Turbulence	40	lower & higher troposphere & stratosphere	10 m/s/km	10 m/s/km	100km	10km	3km	1km	3hr	1hr	VH	10m/s/km / 50km / 1km / 3hr	None	N
Observation & Extrapolation	Turbulence	Vertical velocity >100cm/s		Wake vortices: civil aviation	Wind profile (vertical component)	3	boundary layer	50% HR, 50% FAR	85%HR, 20%FAR	50m	5m	-	50m	15min	1min	H	70% / 40% / 10m / 5min	None at present. Surface Doppler lidar.	N
		Ocean																	
Observation & Extrapolation	Ocean	Sig wave ht		Marine transport	Significant wave height	72	surface	0.5m	0.1m	50km	1km	-	-	6hr	1hr	VH	0.5m / 10km / 1hr	Surface in situ or HF radar	N
Observation & Extrapolation	Ocean	Sig wave ht	near shore	Marine construction	Significant wave height	72	surface	0.2m	0.1m	10km	1km	-	-	3hr	1hr	H	0.2m / 10km / 1hr	Surface in situ or HF radar	N
Observation & Extrapolation	Ocean	Wave period		Marine transport	Dominant wave period	73	surface	1s	0.5s	50km	1km	-	-	6hr	1hr	H	1s / 10km / 1hr	Surface in situ or HF radar	N
Observation & Extrapolation	Ocean	Wave direction		Marine transport	Dominant wave direction	74	surface	20deg	10deg	50km	1km	-	-	6hr	1hr	M	20deg / 10km / 1hr	Surface in situ or HF radar	N
Observation & Extrapolation	Ocean	Surge height	near shore	Life - Coastal flooding	Sea level	75	surface	20cm	10cm	50km	1km	-	-	6hr	1hr	VH	0.2m/ 10km/ 1hr	Surface in situ	[U]
		Chemistry																	
Observation & Extrapolation	Chemistry	Airborne toxic material	land	Toxic gases/aerosols	None		lower & higher troposphere	50% HR, 50% FAR	85% HR / 20% FAR	50km	100m	10km	100m	1hr	15min	VH	70% / 40% / 10km / 1km / 1hr	Visual observation or calculation	N
Observation & Extrapolation	Chemistry	Surface toxic material	land / sea	Toxic solids / liquids on land and sea	None		surface	50% HR, 50% FAR	85% HR / 20% FAR	1km	10m	-	-	6hr	15min	VH	70% / 40% / 1km / 1hr	Visual observation in situ or from aircraft	N
Observation & Extrapolation	Chemistry	Algal bloom	on water	Life: Toxic material on sea or inland lakes & watercourses	Ocean clorophyll?	79	surface	50% HR, 50% FAR	85% HR / 20% FAR	10km	100m	-	-	6hr	15min	H	70% / 40% / 5km / 6hr	Visual observation in situ	N
Observation & Extrapolation	Chemistry	Water clarity	water	Information: marine leisure	Ocean suspended sediment concentration	80	ocean total column	3 classes	10% of max	10km	100m	-	-	6hr	1hr	M	3classes		N
Observation & Extrapolation	Chemistry	Volcanic Ash concentration		Aviation - damage to aircraft	Similar to Volcanic Ash but profile	64	lower & higher troposphere	20%	5%	50km	1km	Total	300m	6hr	15min	VH	20% / 20km / total /1hr	Visual observation or calculation	N

Title	Sub-Title	Required variable	Conditions (1)	Applications	Nearest WMO/CEOS parameter	WMO/ CEOS code	Required Altitude Range (2)	Accuracy threshold (3)	Accuracy optimum (3)	dx threshold	dx optimum	dz threshold	dz optimum	dt threshold	dt optimum	Priority level	Breakthrough level (if any)	Current Observing Techniques	Level met
Observation & Extrapolation	Chemistry	Volcanic Ash location		Aviation - damage to aircraft	Trace gas profile SO_2		lower & higher troposphere	20%	5%	250km	1km	Total	300m	6hr	15min	VH	20% / 20km / total /1hr	AVHRR	N
Observation & Extrapolation	Chemistry	Volcanic Ash composition		Aviation - damage to aircraft	None		lower & higher troposphere	2 classes: 70% HR for each	2 classes: 85% HR for each	100km	1km	Total	300m	1hr	15min	M	70% / 20km / total /1hr	Calculation	N
Observation & Extrapolation	Chemistry	Sand/dust storm location			Cloud imagery and Aerosol profile	28, 8	total column	50% HR, 50% FAR	85% HR / 20% FAR	50km	1km	-	-	1hr	15min	H	70% / 40% / 50km / 1hr		N
Observation & Extrapolation	Chemistry	Ozone		Life - Respiratory effects	Ozone profile	9	surface	10%	5%	50km	10km	-	-	3hr	1hr	VH	5% / 10km / 1hr	Surface in situ	N
Observation & Extrapolation	Chemistry	UV intensity		Life - UV intensity	None		surface	20%	5%	50km	5km	-	-	3hr	1hr	H	10% / 10km / 1hr	Surface radiometer	N
		Convection Forecasting techniques																	
		Early Warning																	
Convection Forecasting techniques	Early warning	Instability index	Partial cloud	Instability: convective intensity	Atmospheric temperature profile	1	lower troposphere	2K	1K	50km	1km	2km	500m	1hr	15min	VH	2K / 50km / 2km / 3hr	radiosondes	N
Convection Forecasting techniques	Early warning	CAPE		Instability: convective intensity	Atmospheric temperature profile	1	lower & higher troposphere	500J/kg	200J/kg	50km	1km	1km	500m	1hr	15min	H	500J/kg / 50km / 1hr		N
Convection Forecasting techniques	Early warning				Specific Humidity profile	4	lower & higher troposphere			50km	1km	1km	500m	1hr	15min	H			N
Convection Forecasting techniques	Early warning	PBL Convergence		Moisture convergence: convective intensity	Wind vector (and speed) over land surface	65, 67	surface	2m/s in 10km	0.5m/s in 10km	10km	1km	-	-	1hr	15min	VH	1m/s / 10km / 1hr	Surface in situ	N
Convection Forecasting techniques	Early warning	Low level moisture	Partial cloud	Moisture convergence: convective intensity	Air specific humidity	61	surface	2g/kg	0.5g/kg	30km	1km	-	-	1hr	15min	H	2g/kg / 30km / 1hr	Surface in situ	N N[LC]
Convection Forecasting techniques	Early warning	DCAPE		Downdraught internsity from DCAPE: risk of downbursts and severe outflow gusts	Atmospheric temperature profile	1	lower troposphere	200J/Kg	100J/Kg	50km	1km	3km	300m	1hr	15min	H	200J/kg / 50km / 1hr	radiosondes	N
Convection Forecasting techniques	Early warning				Specific Humidity profile	4	lower troposphere			50km	1km	3km	300m	1hr	15min	H		radiosondes	N
Convection Forecasting techniques	Early warning	v(z)		Helicity & shear for type of convection	Wind profile (horizontal component)	2	lower troposphere	2m/s	1m/s	20km	1km	5km	500m	1hr	15min	H	2m/s / 10km / 1km / 1hr	radiosondes	N
Convection Forecasting techniques	Early warning	w(z)	Clear air	Inhibition & instability	Wind profile (vertical component)	3	lower troposphere	5cm/s	1cm/s	10km	1km					M		radiosondes	N
Convection Forecasting techniques	Early warning	T(z)	Partial cloud	Inhibition and instability	Atmospheric temperature profile	1	lower troposphere	2K	0.5K	20km	1km	300m	100m	1hr	15min	H	1K / 10km / 300m / 1h	radiosondes	N[LC]
Convection Forecasting techniques	Early warning	Hu(z)	Partial cloud	Inhibition & instability	Specific Humidity profile	4	lower troposphere	20%	5%	20km	1km	300m	100m	1hr	15min	H	15% / 10km / 300m / 1h	radiosondes	N[LC]
		Initiation																	
Convection Forecasting techniques	Initiation	Capping inversion		Inhibition	Atmospheric temperature profile	1	lower troposphere	2K	1K	30km	3km	300m	100m	1hr	15min	VH	2K / 30km/ 300m / 30min	radiosondes	N N[LC]

Title	Sub-Title	Required variable	Conditions (1)	Applications	Nearest WMO/CEOS parameter	WMO/ CEOS code	Required Altitude Range (2)	Accuracy threshold (3)	Accuracy optimum (3)	dx threshold	dx optimum	dz threshold	dz optimum	dt threshold	dt optimum	Priority level	Breakthrough level (if any)	Current Observing Techniques	Level met
Convection Forecasting techniques	Initiation	PBL height		Inhibition	Height of the top of the planetary boundary layer	41	-	300m	100m	30km	3km	-	-	1hr	5min	VH	300m / 30km / NA / 30min	radiosondes	N
Convection Forecasting techniques	Initiation	PBL convergence		Initation	Cloud imagery	65, 67	surface	50% HR, 50% FAR	85% HR, 20% FAR	3km	100m	-	-	15min	1min	VH	70% / 40% / 500m / 5min	Visible imagery	N[LC]
Convection Forecasting techniques	Initiation	PBL or surface convergence		Initiation	Wind vector over land surface (horizontal)	65, 67	surface	2m/s in 10km	1m/s in 10km	30km	1km	-	-	1hr	15min	H	2m/s / 30km / 1hr	Surface in situ	[U:L]
Convection Forecasting techniques	Initiation	Cloud top rise		Indication of likely location of initiation	Cloud top temperature	32, 33	-	100cm/s	10cm/s	1km	100m	-	-	5min	30s	VH	100cm/s / 500m / 5min	IR imagery	[U] N[LC]
Convection Forecasting techniques	Initiation	Cloud structures indicating upward motion		Initation by gravity waves, outflow boundaries etc	Cloud imagery	28	-	2m/s	0.1m/s	10km	100m	-	-	5min	1min	M	1m/s / 10km / 5min	Visible imagery	N
Convection Forecasting techniques	Initiation	LST		Initation	Land surface temperature	100	surface	2K	0.5K	5km	1km	-	-	1hr	15min	M	1K / 5km / 30min	Surface in situ or IR imagery	U
Convection Forecasting techniques	Initiation	Low level Hu		Initation	Air specific humidity	61	surface	2g/kg	0.5g/kg	30km	1km	-	-	1hr	15min	H	2g/kg / 30km / NA / 30min	Surface in situ	N
Convection Forecasting techniques	Initiation	Mesoscale pressure lows		Initation	Air pressure over land	58	surface	1hPa	0.1hPa	10km	1km	-	-	1hr	30min	M	0.5hPa / 5km / 1hr	Surface in situ	[U:L]
		Monitoring																	
Convection Forecasting techniques	Monitoring	Surface precipitation rate		Monitoring	Precipitation rate (liquid)	35	surface	10mm/hr	1mm/hr	5km	1km	-	-	30min	5min	VH	10mm/h / 5km / 30min	Radar	[D:LR]
Convection Forecasting techniques	Monitoring	Precipitation profile		Indicator of severe characteristics including tornado	Similar to Cloud water profile (>100µm) and Cloud ice profile	6, 7	lower troposphere	5mm/h	1mm/hr	5km	1km	1km	500m	15min	5min	H	5mm/h/5km/1km/ 15min	Doppler radar	[U:LR]
Convection Forecasting techniques	Monitoring	Thermal outflows		Indicator of downburst location	Air temperature or atmospheric temperature profile	60, 1	surface/ boundary layer	3K/10km over vertical layer 500m	1K/10km over vertical layer 500m	10km	1km	-	500m	30min	15min	H	3K/10km / 5km / 30min	Doppler radar	[U] N[LC]
Convection Forecasting techniques	Monitoring	Overshoot		Indicator of intensity	Cloud top temperature	32, 33	-	2K	1K	5km	1km	-	-	15min	5min	H	1K / 3km / 15min	IR imagery	U
Convection Forecasting techniques	Monitoring	Cloud top rise		Indication of intensity before precip seen	Cloud top temperature	32, 33	-	3m/s	1m/s	1km	100m	-	-	5min	30s	VH	3m/s / 500m / 5min	IR imagery	[U] N[LC]
Convection Forecasting techniques	Monitoring	Lightning intensity		Indicator of intensity & hail	Lightning detection	38	-	30% HR, 10% FAR	90% HR, 10% FAR	2km (land) / 5km (ocean)	1km	-	-	15min	1min	H	50% / 10% / 2km (land), 3km (ocean) / 15min	Surface direction finding or arrival time differencing techniques	[D:L]
Convection Forecasting techniques	Monitoring	Mesoscale cloud rotation		Indicator of tornado	Cloud imagery	28, 29	-	256 levels	1024 levels	2km	500m	-	-	15min	30s	H	1024 / 1km / 5min	Doppler radar	[U]

Title	Sub-Title	Required variable	Conditions (1)	Applications	Nearest WMO/CEOS parameter	WMO/CEOS code	Required Altitude Range (2)	Accuracy threshold (3)	Accuracy optimum (3)	dx threshold	dx optimum	dz threshold	dz optimum	dt threshold	dt optimum	Priority level	Breakthrough level (if any)	Current Observing Techniques	Level met
Convection Forecasting techniques	Monitoring	Mesoscale cloud rotation		development	Wind profile (horizontal component)	2	lower troposphere	2m/s	1m/s	2km	500m	2km	500m	15min	5min	M		Doppler radar	[U]
		Non-convective forecasting techniques																	
		Cyclones																	
Non-convective forecasting techniques	Cyclones	Cloud structures indicating rapid development		Cyclone development	Cloud imagery	28, 29	-	2K	1K	10km	1km	-	-	6hr	15min	H	1K / 1km / 15min	Satellite IR imagery	U
		Local Wind Systems																	
Non-convective forecasting techniques	Local Wind Systems	Surface pressure gradient		Forcing of flow	Air pressure over land	58	surface	2hPa	1hPa	10km	1km	-	-	30min	10min	H	2hPa / 10km / 30min	Insitu surface observations	[U]
Non-convective forecasting techniques	Local Wind Systems	Stability		Inhibition to flow	Atmospheric temperature profile	1	lower troposphere	2K/km	1K/km	10km	1km	-	-	30min	10min	H	1K/km / 10km / 30min	radiosondes	N[LC]
Non-convective forecasting techniques	Local Wind Systems	LST		Local changes to stability	Land surface temperature	100	surface	2K	1K	10km	1km	-	-	30min	10min	H		Insitu surface observations / IR imagery	U
Non-convective forecasting techniques	Local Wind Systems	Cloud cover		Local changes to stability	Cloud cover	30	-	25%	10%	10km	1km	-	-	30min	10min	H	25% / 10km / 30min	IR imagery	D
Non-convective forecasting techniques	Local Wind Systems	Snow cover		Local changes to stability	Snow cover	93	surface	50%	20%	10km	1km	-	-	30min	10min	H		Visible imagery	N[LC]
		Mesoscale Precipitation																	
Non-convective forecasting techniques	Mesoscale Precipitation	v(z)		Slantwise instability	Wind profile (horizontal component)	2	lower & higher troposphere	1m/s	0.5m/s%	10km	5km	1km	500m	1hr	30min	H	1m/s / 10km / 1km / 1h	radiosondes	N
Non-convective forecasting techniques	Mesoscale Precipitation	T(z)		Slantwise instability	Atmospheric temperature profile	1	lower & higher troposphere	2K	1K	10km	5km	1km	500m	1hr	30min	H	1K / 10km / 1km / 1h	radiosondes	N
Non-convective forecasting techniques	Mesoscale Precipitation	Hu(z)		Slantwise instability	Specific humidity profile	4	lower & higher troposphere	15%	5%	10km	5km	1km	500m	1hr	30min	H	15% / 10km / 1km / 1h	radiosondes	N
Non-convective forecasting techniques	Mesoscale Precipitation	v	Below cloud	Formation of feeder clouds over high ground	Wind profile (horizontal component)	2	lower troposphere	2m/s	1m/s	10km	5km	1km	1km	1hr	30min	VH	1m/s / 10km / 1km / 1h	Surface in situ	N
Non-convective forecasting techniques	Mesoscale Precipitation	Hu	Below cloud	Formation of feeder clouds over high ground	Specific humidity profile	4	lower troposphere	15%	5%	10km	5km	1km	1km	1hr	30min	VH	15% / 10km / 1km / 1h	Surface in situ	N

Title	Sub-Title	Required variable	Conditions (1)	Applications	Nearest WMO/CEOS parameter	WMO/ CEOS code	Required Altitude Range (2)	Accuracy threshold (3)	Accuracy optimum (3)	dx threshold	dx optimum	dz threshold	dz optimum	dt threshold	dt optimum	Priority level	Breakthrough level (if any)	Current Observing Techniques	Level met
Non-convective forecasting techniques	Mesoscale Precipitation	Height of melting layer	Land, Iin cloud	Prediction of lowering of melting layer to surface	cloud ice content (at cloud top)	31	-	200m	100m	10km	5km	-	-	1hr	15min	VH	200m / 10km / 1h	radiosondes / Ground based radar	N[LC]
Non-convective forecasting techniques	Mesoscale Precipitation	Precip rate	Land, below cloud	Prediction of lowering of melting layer to surface	Precipitation rate (liquid)	35	surface	5mm/hr	1mm/hr	10km	5km	-	-	1hr	15min	VH	2mm/hr / 5km / 15min	Ground based radar	[U:LR]
		Fog & low cloud																	
Non-convective forecasting techniques	Fog & low cloud	Hu surface		Fog formation	Air specific humidity	61	surface	3%	1%	10km	1km	-	-	1hr	10min	VH	3% / 5km / 30min	Insitu surface observations	N[LC]
Non-convective forecasting techniques	Fog & low cloud	T surface		Fog formation	Air temperature	60	surface	1K	0.5K	10km	1km	-	-	1hr	10min	VH	0.5K / 5km / 30min	Insitu surface observations	N[LC]
Non-convective forecasting techniques	Fog & low cloud	Hu(z)		Fog & stratus formation & stratus clearance	Specific humidity profile	4	lower troposphere	5%	1%	100km	5km	1km	200m	6hr	1hr	H	5% / 50km / 200m / 30min	radiosondes	N[LC]
Non-convective forecasting techniques	Fog & low cloud	T(z)		Fog & stratus formation & stratus clearance	Atmospheric temperature profile	1	lower troposphere	1K	0.5K	100km	5km	1km	200m	6hr	1hr	H	1K / 50km / 200m / 30min	radiosondes	N[LC]
Non-convective forecasting techniques	Fog & low cloud	v(z)		Fog formation	Wind profile (horizontal component)	2	lower troposphere	0.5m/s	0.1m/s	10km	1km	-	-	1hr	10min	H	0.5m/s / 5km / 30min	Insitu surface observations	N
Non-convective forecasting techniques	Fog & low cloud	Shallow fog		First formation of fog	Cloud type and top temperature/height	29, 32, 33 + A89	surface	50% HR / 50% FAR	85% HR / 20% FAR	5km	1km	-	-	1hr	5min	VH	70% / 40% / 5km / 1hr	Insitu surface observations	N
Non-convective forecasting techniques	Fog & low cloud	Cloud mixing ratio		Amount of fog/stratus to be dissipated and emissivity	Cloud water profile (<100µm)	5	lower troposphere	0.2g/kg	0.1g/kg	5km	1km	500m	200m	30min	10min	H	0.2g/kg / 5km / 200m / 30min	radiosondes	N
Non-convective forecasting techniques	Fog & low cloud	Cloud phase		Precipitation from cloud	Cloud ice profile (007)	6 , 7	lower troposphere	0.2g/kg	0.1g/kg	5km	1km	500m	200m	30min	10min	H	30% / 5km / 200m / 30min	radiosondes	N
Non-convective forecasting techniques	Fog & low cloud	Cloud droplet effective radius		Precipitation from cloud	Similar to Cloud drop size (at cloud top) but profile	49	lower troposphere	2 classes	5 classes	5km	1km	500m	200m	30min	10min	M	2 / 5km / 200m / 30min	None	N
Non-convective forecasting techniques	Fog & low cloud	Fog water content		Amount of fog/stratus to be dissipated and emissivity	Cloud water profile (<100µm)	5	lower troposphere	0.2 g/kg	0.1g/kg	10km	1km	-	-	1hr	10min	H	3% / 5km / 30min	Insitu surface observations	N[LC]

Title	Sub-Title	Required variable	Conditions (1)	Applications	Nearest WMO/CEOS parameter	WMO/CEOS code	Required Altitude Range (2)	Accuracy threshold (3)	Accuracy optimum (3)	dx threshold	dx optimum	dz threshold	dz optimum	dt threshold	dt optimum	Priority level	Breakthrough level (if any)	Current Observing Techniques	Level met
Non-convective forecasting techniques	Fog & low cloud	T surface		Fog clearance	Air temperature	60	surface	0.5K	0.2K	10km	1km	-	-	1hr	10min	H	0.5K / 5km / 30min	Insitu surface observations	N[LC]
Non-convective forecasting techniques	Fog & low cloud	Hu(z)		Fog clearance	Specific humidity profile	4	lower troposphere	5%	1%	100km	5km	1km	200m	6hr	1hr	H	5% / 50km / 200m / 30min	radiosondes	N[LC]
Non-convective forecasting techniques	Fog & low cloud	T(z)		Fog clearance	Atmospheric temperature profile	1	lower troposphere	1K	0.5K	100km	5km	1km	200m	6hr	1hr	H	1K / 50km / 200m / 30min	radiosondes	N[LC]
Non-convective forecasting techniques	Fog & low cloud	Fog top		Fog clearance	Cloud top height	32	-	30m	10mm/h	5km	1km	-	-	1hr	10min	VH	30m / 5km / NA / 30min	radiosondes	N[LC]
Non-convective forecasting techniques	Fog & low cloud	Fog area		Extrapolation fo shrinkage of fog area	Cloud type	28, 29	surface	50% HR / 50% FAR	85% HR / 20% FAR	5km	1km	-	-	1hr	10min	VH	70% / 40% / 5km / 1hr	radiosondes	N[LC]
		Ocean models																	
		Wave & Surf models																	
Ocean models	Wave & surf models	Surface Wind	Sea	Wave & Surge models	Wind vector over sea (horizontal)	66, 68	surface	2m/s	1m/s	50km	5km	-	-	6hr	1hr	VH	2m/s / 50km / 6hr	Surface in situ / scatterometer	[U]
Ocean models	Wave & surf models	Surface Stability	Sea	Wave & surge models	Sea surface skin temperature	70, 71	surface	1K	0.5K	50km	5km	-	-	6hr	1hr	M	1K / 50km / 6hr	Surface in situ / AVHRR	U
Ocean models	Wave & surf models		Sea	Wave & surge models	Air temperature	60	surface	1K	0.5K	50km	5km	-	-	6hr	1hr		1K / 50km / 6hr	Surface in situ	[U]
Ocean models	Wave & surf models	Wave energy spectrum	Sea	Wave models	None		surface	0.1m^{2}s^{-2} in >=8 dirns & >=5 freqs	0.0001m^{2}s^{-2} in >=8 dirns & >=5 freqs	50km	5km	-	-	6hr	1hr	VH	0.1m^{2}s^{-2} in >=8 dirns & >=5 freqs / 50km / 6hr	SAR	N
		Ocean & surge models																	
Ocean models	Ocean & surge models	Sea Surface Temperature	Sea	Shelf models	Sea surface skin temperature	70, 71	surface	2K	0.5K	10km	1km	-	-	24hr	1hr	VH	1K / 50km / 24hr	AVHRR	U
Ocean models	Ocean & surge models	Sea Surface Elevation	Sea	Surge / Shelf modelling	Sea level	75	surface	0.2m	0.1m	50km	1km	-	-	6hr	1hr	VH	0.2m / 50km / 6hr	Altimeter	N
Ocean models	Ocean & surge models	Current vector	Sea	Surge / Shelf modelling	Ocean currents (horizontal component)	27, 77	surface and deeper than 10m	1cm/s	0.5cm/s	10km	1km			6d	6hr	H		In situ: XBT	N
Ocean models	Ocean & surge models	Salinity	Sea	Ocean model: boundary conditions for surge / shelf model	Ocean salinity	26, 82	surface and deeper than 10m	10%	1%	500km	10km	1km	100m	6d	6hr	M			N
Ocean models	Ocean & surge models	Sea ice	Sea	Wave & shelf models	Sea-ice cover	85	surface	20%	10%	10km	1km	-	-	24d	1d			AVHRR	U
		Land Surface & Hydrological models																	
		Run-off models																	
Land Surface &Hydrological models	Run-off models	Precipitation	land	Flood run-off	Precipitation rate (liquid)	35	surface	50%	10%, 0.5mm/hr	10km	1km	-	-	1hr	1hr	VH	50% / 5km / 15min	Radar / in situ rain gauges	U

Title	**Sub-Title**	**Required variable**	**Conditions (1)**	**Applications**	**Nearest WMO/CEOS parameter**	**WMO/ CEOS code**	**Required Altitude Range (2)**	**Accuracy threshold (3)**	**Accuracy optimum (3)**	**dx threshold**	**dx optimum**	**dz threshold**	**dz optimum**	**dt threshold**	**dt optimum**	**Priority level**	**Breakthrough level (if any)**	**Current Observing Techniques**	**Level met**
Land Surface &Hydrological models	Run-off models	Precipitation	land	Flood run-off	Precipitation rate (solid)	36	surface	50%	10%, 0.5mm/hr	10km	1km	-	-	1hr	1hr	VH	50% / 5km / 15min	Radar / in situ rain gauges	U
Land Surface &Hydrological models	Run-off models	Soil moisture	land	Flood run-off	Soil moisture	101	surface	10%	5%	50km	1km	total	3 levels	1d	1hr	VH	10%/ 50km/ total/ 1day	None	N
Land Surface &Hydrological models	Run-off models	Snow water equivalent	land	Snow melt	Snow water equivalent	95	surface	5mm	1mm	10km	1km	-	-	1d	1hr	VH	5mm / 5km / 1d	Surface in situ	N
Land Surface &Hydrological models	Run-off models	Snow cover	land	Snow melt	Snow cover	93	surface	25%	10%	50km	1km	-	-	1d	1hr	H		Surface in situ	U
Land Surface &Hydrological models	Run-off models	Vegetation type	land	Hydrological run-off model: evaporation	Land cover	106	surface	80% correct in 4 classes	80% correct in 10 classes	10km	100m	-	-	30d	1d	H	10 / 500m / 7d	MODIS	D
Land Surface &Hydrological models	Run-off models	Vegetation leaf area	land	Hydrological run-off model: evaporation	Leaf area index	103	surface	20%	10%	10km	100m	-	-	7d	1d	H	10% / 500m / 7d	MODIS	D
Land Surface &Hydrological models	Run-off models	Soil type	land		Soil type	110	subsurface	3 classes	10 classes	10km	100m	-	-	10y	1y	H		GPCP atlas	U
Land Surface &Hydrological models	Run-off models	Soil temperature	land		None		subsurface	2K	0.5K	10km	100m	3 levels	5 levels	6hr	1hr	M		Surface in situ	N
		River flow models																	
Land Surface &Hydrological models	River flow models	River flow rate		Floods	None		total column					-	-			H		In situ river gauges	U
		Snow models																	
Land Surface &Hydrological models	Snow models	Snow water equivalent	land	Avalanche: Life, Land transport, damage to pipes etc	Snow water equivalent	95	surface	200mm	40mm	500m	100m	-	-	3hr	30min	VH	0.2m / 500m / 2hr	Surface in situ	N
Land Surface &Hydrological models	Snow models	Snow crystal size profile	land	Snow stability: Avalanche: Life, Land transport, damage to pipes etc	None		surface	0.5mm	0.1mm	500m	100m	-	10cm	3hr	30min	H	0.5mm / 500m / - / 2hr	Surface in situ	N
Land Surface &Hydrological models	Snow models	Snow crust	land	Snow stability: Avalanche: Life, Land transport, damage to pipes etc	None		surface	-	-	500m	100m	-	-	3hr	30min	H	? / 500m / 2hr		N
Land Surface &Hydrological models	Snow models	Temperature	land	Change of snow stability	Air temperature	60	surface	2K	0.5K	500m	100m	-	-	3hr	30min	H		Surface in situ & IR emission	N
Land Surface &Hydrological models	Snow models	Precip rate	land	Build up of unstable snow accumulations	Precipitation rate (solid)	36	surface	1mm/hr	0.1mm/hr	500m	100m	-	-	3hr	30min	VH	1mm/hr / 1km / 1hr	Surface in situ & Ground based radar	N

Title	Sub-Title	Required variable	Conditions (1)	Applications	Nearest WMO/CEOS parameter	WMO/ CEOS code	Required Altitude Range (2)	Accuracy threshold (3)	Accuracy optimum (3)	dx threshold	dx optimum	dz threshold	dz optimum	dt threshold	dt optimum	Priority level	Breakthrough level (if any)	Current Observing Techniques	Level met
Land Surface &Hydrological models	Snow models	10m wind	land	Build up of unstable snow accumulations	Wind speed over land	65, 67	surface	2m/s	1m/s	500m	100m	-	-	3hr	30min	H	2m/s / 1km / 1hr	Surface in situ	N
		Icing models																	
Land Surface &Hydrological models	Icing models	Cloud water content		Aviation icing	Cloud water profile (<100µm)	5	lower troposphere	1g/kg	0.1g/kg	50km	1km	1km	100m	1hr	5min	VH	1g/kg / 50km / 1km / 1hr	None	N
Land Surface &Hydrological models	Icing models	Cloud water content		Aviation icing	Cloud water profile (>100µm)	6	lower troposphere	1g/kg	0.1g/kg	50km	1km	1km	100m	1hr	5min	VH	1g/kg / 50km / 1km / 1hr	None	N
Land Surface &Hydrological models	Icing models	Cloud droplet effective radius		Aviation icing	Similar to Cloud drop size (at cloud top) but profile	49	lower troposphere	2 µm	1 µm	10km	1km	1km	100m	1hr	5min	H		None	N
Land Surface &Hydrological models	Icing models	Surface fog water content		Life / Collapsing structures / Aircraft icing on ground	Visibility	62	surface	0.2 g/kg	0.1g/kg	10km	100m	-	-	1hr	5min	VH	0.2g/kg / 1km / 1h	None	U
Land Surface &Hydrological models	Icing models	Fog droplet effective radius		Life / Collapsing structures / Aircraft icing on ground	Similar to Cloud drop size (at cloud top) but surface	49	surface	2 µm	1 µm	1km	100m	-	-	1hr	5min	H		None	N
Land Surface &Hydrological models	Icing models	Surface temperature		Road Transport Icing	Air temperature	60	surface	2K	0.2K	1km	10m	-	-	1hr	5min	VH	1K / 1km / 1hr	Surface in situ	U
Land Surface &Hydrological models	Icing models	Wind speed		Life / collapsing structures / aircraft icing on ground	Wind speed over land	65, 67	surface	2m/s	1m/s	10km	100m	-	-	1hr	5min	H	1m/s / 10km / 1h	Surface in situ	U
Land Surface &Hydrological models	Icing models	Wind speed		Life / Marine superstructure icing	Wind speed over sea	66, 68	surface	2m/s	1m/s	50km	1km	-	-	3hr	1hr	H	2m/s / 50km / 3h	Surface in situ or scatterometer	U
		Mud slide models																	
Land Surface &Hydrological models	Mud slide models	Precipitation		Large accumulations cause mudslides	Precipitation rate (liquid)	35	surface	1mm/hr	0.5mm/hr	10km	100m	-	-	2hr	1hr	M		Surface in situ & Ground based radar	U
Land Surface &Hydrological models	Mud slide models	Soil moisture		Mud slide	Soil moisture	101	total	10%	10%	10km	100m	-	-	24hr	1hr	M		None	N
		Fire models																	
Land Surface &Hydrological models	Fire models	Precip		Moistening of vegetation, absorption of heat in evaporation	Precipitation rate (liquid)	35	surface	1mm/hr	0.1mm/hr	10km	100m	-	-	1hr	1min	H		Ground based radar	U
Land Surface &Hydrological models	Fire models	10m wind		Fire movement	Wind vector over land	65, 67	surface	2m/s, 10°	1m/s, 5°	10km	100m	-	-	1hr	1min	VH	2m/s, 10° / 1km / 10min	Surface in situ	N

Title	Sub-Title	Required variable	Conditions (1)	Applications	Nearest WMO/CEOS parameter	WMO/ CEOS code	Required Altitude Range (2)	Accuracy threshold (3)	Accuracy optimum (3)	dx threshold	dx optimum	dz threshold	dz optimum	dt threshold	dt optimum	Priority level	Breakthrough level (if any)	Current Observing Techniques	Level met
Land Surface &Hydrological models	Fire models	Vegetation stress		Life & property: fire initiation & spread: vegetation stress	Normalised Difference Vegetation Index (NDVI)	102	surface	20% of max	10% of max	10km	100m	-	-	1hr	1min	VH	1km / 10min		N
Land Surface &Hydrological models	Fire models	Vegetation stress		Property: fire risk: vegetation stress	Normalised Difference Vegetation Index (NDVI)	102	surface	20% of max	10% of max	3km	1km	-	-	24hr	6hr	VH	3km / 24hr		N
Land Surface &Hydrological models	Fire models	Soil moisture		Fire initiation & spread	Soil Moisture	101	total root zone	10% of max	5% of max	1km	100m	-	-	6hr	1hr	VH	1km / 10min		N
Land Surface &Hydrological models	Fire models	Soil moisture		Fire risk	Soil Moisture	101	total root zone	10% of max	5% of max	3km	1km	-	-	24hr	6hr	VH	3km / 24hr	Indirect: Diurnal temperature range	N
		Dispersion, Chemistry & Biology models																	
		Volcanic emissions and accidental releases																	
Dispersion, Chemistry & Biology models	Dispersion Models	Wind		Horizontal movement	Wind vector over land or Wind profile (horizontal component)	2	surface / lower troposphere	2m/s, 10^{o}	1m/s, 5^{o}	10km	100m	surface	100m	1hr	15min	VH	2m/s, 10^{o} / 1km / 1hr	Surface in situ	[U:L]
Dispersion, Chemistry & Biology models	Dispersion Models	Stability		Vertical spread	Atmospheric temperature profile	1	lower troposphere	2K/km	1K/km	10km	100m	1km	100m	1hr	15min	VH	1K/km / 10km / 1km / 1hr	Radiosonde modified by in situ	[U:L]
Dispersion, Chemistry & Biology models	Dispersion Models	Petroleum products		Poisoning by inhalation	None		lower troposphere	50% HR / 50% FAR	85% HR / 20% FAR	50km	100m	total	200m	1hr	15min	VH	50%/ 50% / 50km / - / 1hr	Surface in situ	N
Dispersion, Chemistry & Biology models	Dispersion Models	Radionuclides		Poisoning by inhalation	None		lower troposphere	50% HR / 50% FAR	85% HR / 20% FAR	50km	100m	total	200m	1hr	15min	VH	50%/ 50% / 50km / - / 1hr	Surface in situ	N
Dispersion, Chemistry & Biology models	Dispersion Models	Pathogens		Spread disease	None		lower troposphere	50% HR / 50% FAR	85% HR / 20% FAR	50km	100m	total	200m	1hr	15min	VH	50%/ 50% / 50km / - / 1hr	Calculation	N
Dispersion, Chemistry & Biology models	Dispersion Models	Location of volcanic eruption		Source of volcanic ash cloud for aviation warning	Fire temperature	108	surface	50% HR / 50% FAR	85% HR / 20% FAR	1km	100m	-	-	6hr	1hr	H	50%/ 50% / 50km / - / 1hr		N
Dispersion, Chemistry & Biology models	Dispersion Models	Precipitation profile		Wet deposition	Similar to Precipitation rate (liquid/solid) & (solid) but profile (Similar to Cloud Water Profile > 100µm)	6	lower troposphere	1mm/hr	0.1mm/hr	10km	1km	surface	1km	1hr	15min	H			U
		Air quality and biomass burning																	
Dispersion, Chemistry & Biology models	Air quality models	O_3, Ozone		Respiratory effects	Ozone profile	9	boundary layer	20% of air quality standard	10% of air quality standard	10km	1km	2km	200m	3hr	15min	VH	20%/ 10km / 1h	In situ	N
Dispersion, Chemistry & Biology models	Air quality models	CO, Carbon Monoxide		Ozone formation: Respiratory effects	Trace gas profile CO	12	boundary layer	20% of air quality standard	10% of air quality standard	10km	1km	2km	200m	3hr	15min	VH	20%/ 10km / 1h	In situ	N
Dispersion, Chemistry & Biology models	Air quality models	NO, Nitric Oxide		Ozone formation: Respiratory effects	Trace gas profile NO	16	boundary layer			10km	1km	2km	200m	3hr	15min	VH	20%/ 10km / 1h	In situ	N
Dispersion, Chemistry & Biology models	Air quality models	$NO_{2,}$ Nitrogen Dioxide		Ozone formation: Respiratory effects	Trace gas profile NO2	17	boundary layer	20% of air quality standard	10% of air quality standard	10km	1km	2km	200m	3hr	15min	VH	20%/ 10km / 1h	In situ	N

Title	Sub-Title	Required variable	Conditions (1)	Applications	Nearest WMO/CEOS parameter	WMO/ CEOS code	Required Altitude Range (2)	Accuracy threshold (3)	Accuracy optimum (3)	dx threshold	dx optimum	dz threshold	dz optimum	dt threshold	dt optimum	Priority level	Breakthrough level (if any)	Current Observing Techniques	Level met
Dispersion, Chemistry & Biology models	Air quality models	CH_2O, Formaldehyde		VOC indicator: Ozone formation: Respiratory effects	None		boundary layer			10km	1km	2km	200m	3hr	15min	VH	20%/ 10km / 1h	In situ	N
Dispersion, Chemistry & Biology models	Air quality models	VOC, Volatile Organic Compounds, inc. propane, isoprene, turpenes		Ozone formation: Respiratory effects	None		boundary layer	20% of air quality standard	10% of air quality standard	10km	1km	2km	200m	3hr	15min	VH	20%/ 10km / 1h	In situ	N
Dispersion, Chemistry & Biology models	Air quality models	Aerosol		Ozone formation: Respiratory effects	Aerosol profile	8	boundary layer			10km	1km	2km	200m	3hr	15min	VH	20%/ 10km / 1h	In situ	N
Dispersion, Chemistry & Biology models	Air quality models	Total suspended particulates		Respiratory effects	None		boundary layer			10km	1km	2km	200m	3hr	15min	H		In situ	N
Dispersion, Chemistry & Biology models	Air quality models	PM10 aerosol		Respiratory effects	None		boundary layer	20% of air quality standard	10% of air quality standard	10km	1km	2km	200m	3hr	15min	VH	20%/ 10km / 1h	In situ	N
Dispersion, Chemistry & Biology models	Air quality models	Black carbon		Respiratory effects	None		boundary layer			10km	1km	2km	200m	3hr	15min	H		In situ	N
Dispersion, Chemistry & Biology models	Air quality models	Lightning location		Natural NO_x formation	Lightning detection	38	-			10km	1km	-	-			M		Surface remote sensing	N
Dispersion, Chemistry & Biology models	Air quality models	Fire location		Smoke pollution	Similar to fire area and temoerature	107, 108	surface	50% HR / 50% FAR	85% HR / 20% FAR	10km	1km	-	-	1hr	5min	H	50% / 10km / 1hr		N
		UV radiation																	
Dispersion, Chemistry & Biology models	UV radiation models	Total ozone		Predicting UV exposure	Ozone profile	9	total column			100km	10km	-	-	1d	1hr	VH	50km / 6h	Surface	U
Dispersion, Chemistry & Biology models	UV radiation models	Total cloud water		Monitoring UV dose	Cloud water (<100µm) & cloud ice profiles	5, 7	total column			50km	10km	-	-	1hr	5min	M		Surface in situ	U
Dispersion, Chemistry & Biology models	UV radiation models	Total aerosol		Predicting UV exposure	Aerosol profile	8	total column	25%	10%	50km	10km	-	-	1d	1hr	VH	25% / 20km / 1day		N
Dispersion, Chemistry & Biology models	UV radiation models	Ozone profile		Predicting UV exposure	Ozone profile	9	lower troposphere			50km	10km	2km	500m	1d	1hr	M			N
Dispersion, Chemistry & Biology models	UV radiation models	CFC11		Stratospheric Ozone destruction	None	13	stratosphere			50km	10km			1d	1hr	M			N
Dispersion, Chemistry & Biology models	UV radiation models	CFC12		Stratospheric Ozone destruction	None	14	stratosphere			50km	10km			1d	1hr	M			N
Dispersion, Chemistry & Biology models	UV radiation models	UV albedo		Predicting UV exposure	None	47	surface	20%	10%	10km	1km	-	-	1 month	1 day	M			N
Dispersion, Chemistry & Biology models	UV radiation models	NO_2 (and other gaseous absorbers)		UVA exposure	None	17	total column			10km	10km	-	-	1d	1hr	M			N
		Surface pollution																	

Title	Sub-Title	Required variable	Conditions (1)	Applications	Nearest WMO/CEOS parameter	WMO/ CEOS code	Required Altitude Range (2)	Accuracy threshold (3)	Accuracy optimum (3)	dx threshold	dx optimum	dz threshold	dz optimum	dt threshold	dt optimum	Priority level	Breakthrough level (if any)	Current Observing Techniques	Level met
Dispersion, Chemistry & Biology models	Surface Pollution models	Waves		Marine dispersion & deposition	Significant wave height	72	surface	0.2m	0.1m	5km	100m	-	-	3hr	30min	VH	0.2m / 5km / 1hr	Deduce from wind or HF ground wave radar or in situ measurement	N
Dispersion, Chemistry & Biology models	Surface Pollution models	Surface wind		Marine dispersion	Wind vector over sea	66	surface	2m/s, 10^o	1m/s, 5^o	5km	100m	-	-	3hr	30min	VH	2m/s, 10^o / 5km / 1hr	Surface in situ or scatterometer	N
Dispersion, Chemistry & Biology models	Surface Pollution models	Surface current		Marine dispersion	Ocean surface currents (vector)	77	surface	1m/s, 10^o	20.5m/s, 5^o	5km	100m	-	-	3hr	30min	VH	1m/s, 10^o / 5km / 1hr	HF gound wave radar or in situ current meter	N
Dispersion, Chemistry & Biology models	Surface Pollution models	Precip		Washes chemicals into water courses	Precipitation rate (liquid)	35	surface	0.5mm/hr	0.1mm/hr	1km	100m	-	-	1hr	1min	M		Ground based radar	[U:LR]
Dispersion, Chemistry & Biology models	Surface Pollution models	Sea bed type	Sea	Prediction of sediment transport	None	84	surface	2 classes	5 classes	10km	1km	-	-	1y	1d	M			N
Dispersion, Chemistry & Biology models	Surface Pollution models	Nutrient concentration	Sea	Prediction of algal blooms	Ocean clorophyll	79	surface			50km	10km	-	-	1d	6hr	M		MERIS	N

Footnotes:

1. Over inhomogenous surfaces the quality of satellite measurements is usually poorer than over other areas, particularly for near-surface parameters. This is true over coastlines, heavy urbanized areas and even more over complex terrain, where the effects (i.e. less quality and resolution reduction) can extend in the lower troposphere (usually the mixing layer).
   To cope with these effects it will be necessary to develop special algorithms to retrieve, as far as possible, the best information from the measurement (some time combined with some kind of surface measurements).
2. An additional height range has been introduced: Boundary Layer = 0 - 2km
3. HR = hit rate = fraction of actual events that are identified; FAR = false alarm rate = fraction of identified events that are false