Guidelines for Nowcasting Techniques

2017 edition

WEATHER CLIMATE WATER

WORLD
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ORGANIZATION

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EDITORIAL NOTE

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EXECUTIVE SUMMARY

In response to a call by the Seventeenth World Meteorological Congress to initiate a process for an enhanced integrated and seamless WMO Data-processing and Forecasting System (DPFS), a task team of international nowcasting experts was established to form the Task Team for the Development of Guidelines for Nowcasting Techniques (TT-DGNT).

The purpose of the WMO nowcasting guidelines presented here is to help National Meteorological and Hydrological Services (NMHSs) by providing them with information and knowledge on how to implement a nowcasting system with the resources available to them and an understanding of the current state of science and technology.

For the purpose of these guidelines, nowcasting is considered as forecasting with local detail, by any method, over a period from the present to 6 hours ahead, including a detailed description of the present weather. In developing the guidelines the members of TT-DGNT have identified the recommendations that follow. NHMSs interested in building or developing nowcasting capability are thus encouraged to:

(a) Contact the WMO DPFS division, which will put the Member in contact with appropriate experts for assistance (see Chapters 1 and 6);

(b) Engage the end users to identify and prioritize their needs and requirements related to high-impact weather warnings (see Chapters 1, 2 and 5);

(c) Assess all the available observations in terms of high data quality, timely transmission to a central point, data display and storage, and address deficiencies (see Chapters 1 and 2);

(d) Identify, in consultation with experts, the gaps in observations, infrastructures and available resources, and determine feasible nowcasting solutions to address the high-priority needs of end users (see Chapters 1 and 2);

(e) Develop a plan for an efficient seamless nowcasting system that integrates observations, automated nowcasting techniques and models that are all displayed on a common workstation; this plan should include collaboration with neighbouring countries to share data and model products (see Chapters 1, 2, and 6);

(f) Develop a plan to ensure long-term technical support, training and expertise to keep equipment, hardware and software updated, calibrated and operational (see Chapters 2 and 4);

(g) Develop a plan that ensures sustainable nowcasting techniques, continuous forecaster training on all aspects of nowcasting processes and, where appropriate, takes advantage of WMO Severe Weather Forecasting Demonstration Project training workshops and available material (see Chapter 4);

(h) Verify the quality of nowcasting products according to the weather phenomena and users' requirements (see Chapter 3);

(i) Ensure that forecasters play a vital role in the nowcasting processes, despite the availability of automatic nowcasting techniques (see Chapter 6).

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INTRODUCTION

Weather, and especially severe weather, is responsible for many natural disasters that cause damage and loss of life. Weather forecasting is an essential component of early warning systems and consecutive actions within crisis management and risk prevention. In the last few years, much progress has been made in research and development on high-impact, multi-hazard and seamless weather prediction, including information on probability, for the improvement of weather forecasting services and early warning processes. The Seventeenth World Meteorological Congress (Geneva, 25 May–12 June 2015) noted that with technological advances, new research results will require transition to operations. The Congress therefore decided to initiate a process for the gradual establishment of a future enhanced integrated and seamless WMO DPFS, and adopted Resolution 11 (Cg-17) – Towards a future enhanced integrated and seamless WMO Data-processing and Forecasting System.

During the last few decades, one of the most important components of the seamless prediction system, nowcasting, which is the weather analysis and forecast for the next few hours, has improved significantly. Disasters at small scales of time and space, such as hail or flash floods, as well as sub-events within large-scale catastrophes such as flooding and storms can be detected and managed. Nowcasting plays an increasing role in crisis management and risk prevention, but its realization is a highly complex and integrated task. The Seventeenth Congress recognized the nowcasting achievement and in particular recalled the successful demonstration of nowcasting techniques by some Members at various international events. Moreover, Congress requested the WMO Secretary-General, in coordination with the Commission for Basic Systems (CBS) and other related technical commissions, to gather lessons learned and best practices from past WMO nowcasting activities and to develop guidelines on nowcasting techniques for the benefit of all WMO Members. It was considered that such guidelines would be a significant contribution to the seamless data-processing and forecasting endeavour.

In response to this request, the Open Programme Area Group on the DPFS (OPAG-DPFS) established TT-DGNT. The work of the team is to set the basis for proper implementation of nowcasting techniques in the effort to move to a seamless Global DPFS (GDPFS). To develop the guidelines, TT-DGNT considered all pertinent areas related to nowcasting, including observations, nowcasting techniques and systems, numerical weather prediction (NWP) and data assimilation, ensemble nowcasts, nowcasting applications, verification, training and implementation of nowcasting in operation.

Nowcasting was originally defined by Keith Browning during the first symposium on nowcasting (Browning, 1981) as “the description of the current state of the weather in detail and the prediction of changes that can be expected on a timescale of a few hours”. Later, in 2010, the WMO Working Group on Nowcasting Research defined nowcasting as forecasting with local detail, by any method, over a period from the present to 6 hours ahead, including a detailed description of the present weather. This is the definition we will use for these guidelines.

In general, nowcasts are issued by forecasters (nowcasters) who should be well trained in nowcasting concepts. Nowcasting relies heavily on rapidly updated, high-resolution observations available to the nowcaster on an integrated display system that can be easily operated by the nowcaster. Ideally, this display system contains observations from the various instruments and sensors on the same display with the same grid spacing for each dataset. Types of observations include radar, satellite, lightning networks, surface stations, wind profilers and radiosondes. During periods of high-impact weather the nowcaster should be continually monitoring the latest observations via the frequently updated, integrated displays. In addition to high-resolution observations, NWP analysis and forecast fields and products from nowcasting systems should be viewable on the same display.

The motivation for nowcasting, as advanced in the first book on nowcasting (Browning, 1982), was described as the great need for timely, location-specific predictions of high-impact weather that are of particular importance to commercial and general aviation for planning and routing air traffic, to the public for outdoor sporting events, and to the construction industry, power utilities and ground transportation organizations that conduct much of their work outdoors.

Nowcasting can cover any type of weather; however, the emphasis in the present publication will be on nowcasting convective weather events, primarily thunderstorms and related hazards, and also winter weather hazards. Nowcasting is particularly concerned with providing accurate warnings and watches. The use of the terms warnings and watches, as used here, is based on the *Glossary of Meteorology* (Glickman, 2000). A warning is issued when a hazardous weather or hydrologic event is occurring, is imminent or has a high probability of occurring. A warning is issued for conditions posing a threat to life or property. A watch is issued when the risk of a hazardous weather or hydrologic event has increased significantly but its occurrence, location, and/or timing is still uncertain. It is intended to provide enough lead time so that those who need to set their plans in motion can do so. The ability to issue warnings and watches is dependent on available observations and nowcasting techniques.

Nowcasting is generally applied to weather that occurs on the mesoscale and local scales and over very short time periods; thus the emphasis is on the need for rapidly updated, high-resolution observations. Because of the small-scale nature of convective weather phenomena (for example, thunderstorms and flash floods) it has not been possible to explicitly predict their location and time several hours in advance. However, warnings for intense precipitation and high winds associated with strong, large synoptic-scale weather can be provided hours in advance. Such large-scale weather events on longer timescales are not considered in the present guidelines. The table below shows the weather phenomena that are discussed in the present guidelines. Hazards driven by severe weather, such as landslide and dust storm, are also not the focus of these guidelines.

Weather phenomena discussed in the present guidelines

Thunderstorms
Tornado
Hail
Heavy precipitation, particularly flash floods
Severe wind (including wind shear: gust/downburst/microburst/vertical shear)
Visibility/fog
Winter precipitation types (snow, sleet, freezing rain, drizzle, icing)

In this publication, Chapter 1 discusses types of observations, including radar, satellite, lightning networks, surface stations, wind profilers and radiosondes. Chapter 2 gives an overview of observation-based, NWP-based and integrated nowcasting techniques and systems. The subject of nowcasting verification follows in Chapter 3, and nowcasting training capacities and activities in Chapter 4. In Chapter 5, nowcasting applications in different areas, for example, hydrology, aviation, road safety, civil protection and industry/energy are summarized. Chapter 6 discusses lessons learned and best practices of nowcasting implementations in international nowcasting activities.

REFERENCES

Browning, K.A., 1981: Forward to: *Nowcasting: Mesoscale Observations and Short-range Prediction* (B. Battrick and J. Mort, eds). Proceedings of an International Symposium, Hamburg, Germany, 25–28 August. European Space Agency SP-16.

Browning, K.A. (ed.), 1982: *Nowcasting.* London, Academic Press.

Glickman, T.S., 2000: *Glossary of Meteorology. American Meteorology Societ*y. Chicago, University of Chicago Press.

CHAPTER 1. OBSERVATIONS

Nowcasting and very short-range forecasting (VSRF) (0–6-hour and 0–12-hour forecasting, respectively) are highly dependent on observational data. Observations need to be quality controlled not only for a quality nowcasting system but also (a) to be assimilated particularly by high-resolution NWP with rapid update cycle; (b) to evaluate the value of model output by comparing the analysis and early frames of a forecast (regarding timing, location and intensity of synoptic-scale features); (c) to take appropriate mitigating action if a mismatch exists between model output and observations; (d) to capture smaller-scale details that are unresolved by the models; and (e) to verify forecasts a posteriori.

While surface and upper-air observations are very important, only remote sensing systems can adequately provide high-resolution spatial coverage. Sophisticated nowcasting techniques exist in developed countries where radar systems are mature and robust. However, in less developed countries and remote areas the required operational radar systems needed for nowcasting are still missing. In these data-sparse regions, “low-cost” nowcasting systems are created by using satellite and lightning data (blended with NWP).

In this chapter, an assessment is provided of the requirements, advantages, disadvantages and limitations of surface observations, upper-air observations, and also satellite, lightning and radar data for the purpose of nowcasting and VSRF.

1.1 SURFACE OBSERVATIONS

In many regions of the world, surface weather stations are sparsely located and/or of poor quality. Existing stations may be sited incorrectly (not according to WMO standards), not well maintained, and have limited communications established at the sites for real-time monitoring. In developing countries, the lack of resources to acquire and deploy instrumentation and the lack of training of local weather service staff to properly site, calibrate and maintain the equipment amplify the issues of poor quality observations. Because commercially available meteorological instruments are relatively expensive, instrumentation that fails or is stolen is often not replaced. The result is that weather observations in critical regions are not available.

An international initiative has been established to develop and deploy low-cost weather instrumentation. The goal is to develop and provide technology to weather services in underdeveloped countries so that they can build, deploy and maintain their own surface observation network. Instrumentation has been designed using innovative new, low-cost technologies. such as 3-D printers, small, inexpensive computing systems (for example, Raspberry Pi), and wireless communications. If the station gets destroyed or a sensor fails, it can be replaced at low cost using the 3-D printer designs. With the advent of Internet, wireless communications, cell phone coverage and faster computers, the technology now exists for rapid transmission of surface-station data. Well-maintained surface stations that automatically measure, record and transmit the observations with high frequency to weather service offices are effective and efficient ways to provide forecasters with the latest in situ information for producing nowcasts.

1.1.1 Surface sensors for specific weather hazards

Thunderstorms, tornadoes, hail and ice pellets

Automated surface stations cannot currently report thunderstorms, tornadoes, hail or ice pellets. Only a weather observer can report surface observations of these phenomena. If a lightning detection system has been installed, automated messages can be generated. For example, lightning strikes within 8 kilometres of an automated surface station will result in a report of a thunderstorm at the station; lightning strikes 8–16 kilometres from the station will be reported as a thunderstorm in the vicinity of the station.

Heavy precipitation and flash floods

Rain gauge instruments report precipitation rate and accumulation, and provide information on instantaneous rainfall intensity and heavy rainfall over short periods of time that can lead to flash flooding in an area. If a particularly dense network of rain gauges is available, it is possible to combine the rainfall measurements using objective analysis techniques to produce a gridded, spatial map of rainfall that can be used by forecasters for detection and nowcasting purposes. Snow-water-equivalent accumulations can be obtained by measuring snowfall accumulation with double-shield snow gauges or hot plates, two types of sensor that have been documented to provide accurate information on accumulation.

Severe wind, including wind shear (gust fronts, microbursts, downbursts, vertical shear)

A network of surface wind measurements can provide information such as location, spatial extent and movement of synoptic fronts, gust fronts and sea breezes. A network of closely located surface stations can provide a relatively inexpensive detection and warning system for horizontal wind shear, particularly microbursts and downbursts. Wind sensors installed at various heights on a vertical tower can provide an inexpensive means to estimate vertical wind shear. However, a vertical profiling system provides a much better estimate of vertical shear.

Visibility/fog

Surface-station sensors used for the direct detection of visibility include forward scatter sensors and transmissometers, which measure the decrease in infrared or visible light, respectively, from the transmitter to the receiver due to reduced visibility. In addition, upward-pointing laser beam ceilometers are often used to detect cloud height and amount of cloud coverage overhead. Low cloud heights can cause a reduction in visibility and can be due to the presence of fog. The present weather detector optical sensor also provides visibility measurements. More recently, automated camera imagery posted on the Internet (web cameras) have been used to measure line of sight changes in visibility between the camera and a fixed target during daylight hours, and are especially useful in regions with few or no surface stations.

Precipitation types (snow, sleet, freezing rain, drizzle) and icing

The present-weather detector is one sensor that provides automated detection of precipitation type. A light-emitting diode weather-identifier sensor is used to measure the scintillation pattern of the precipitation falling through the sensor's infrared beam. A vibrating rod measures changes in resonant frequency as precipitation accumulates on it. The resonant frequency decreases with increasing accretion of ice, freezing drizzle, freezing fog, rime or wet snow.

1.2 UPPER-AIR OBSERVATIONS

Upper-air soundings are the standard way to get relevant data of the vertical profile of the atmosphere. The 3-D wind, temperature and humidity fields are the main sources of upper-air information to determine the 3-D structure of the atmosphere. Upper-air observations are particularly useful for nowcasting to determine atmospheric stability to predict convective storms initiation, precipitation type, the possibility of hail and the amount of frozen precipitation. Thus, such observations cannot be replaced by other currently available measurement systems. Upper-air observations may come from many different sources that complement each other. The three main types of measurement techniques are introduced in the following subsections.

1.2.1 Radiosondes

Radiosondes remain the reference observing system for determination of detailed vertical structure in the atmosphere. Rawinsonde observations are a valuable source of information on pressure, temperature, humidity and wind in the atmosphere. Radiosonde observations (if available) are of primary importance in NWP analyses and for nowcasting. At the same time, vertical stability analyses, seeking details that are not necessarily captured by the NWP models, are based mostly on radiosonde measurements.

1.2.2 Aircraft-based observations

In collaboration with the International Civil Aviation Organization (ICAO), commercial and other airlines, aircraft-based observations are received from over 3,000 aircraft per day, providing reports of pressure, wind, temperature, humidity, turbulence and other parameters during flight with very high temporal and spatial density. Aircraft-based observations are derived from several sources, including:

- The Aircraft Meteorological Data Relay (AMDAR) system, which provides high-quality observations (comparable to those of standard radiosondes) at cruising levels (in the high troposphere) as well as at selected levels in ascent and descent;

- AMDAR-like data from the Tropospheric Airborne Meteorological Data Reporting (TAMDAR) system in the lower troposphere (mostly below 600 hPa) over the United States of America and some other parts of the world;

- Data from pilot reports (PIREP), and aircraft reports (AIREP) under regulations and cooperative arrangements with ICAO.

The increasing availability of display software for AMDAR and TAMDAR data (particularly for ascent and descent profiles) is making the high-resolution profiles very useful for nowcasting, especially in data-sparse regions of developing countries.

1.2.3 Radars and profilers

The detection of wind, temperature and humidity at various levels in the atmosphere can be made by using profilers or specific radars:

- Doppler light detection and ranging (LIDAR) and Doppler sound detection and ranging (SODAR) instruments are very useful for wind profiling in complex terrain;

- Differential absorption LIDAR (DIAL) and Raman LIDAR instruments for temperature and humidity profiling are emerging technologies with potential for nowcasting;

- Radiometers for temperature and humidity profiling reflect the tendency of the atmospheric profile at fine temporal resolution;

- Satellite radiometers provide global coverage of retrieved smooth temperature and humidity soundings but with relatively small impact on nowcasting (used only over ocean areas).

The principal advantages of these systems over the more traditional radiosondes are their continuous and unattended operation. The good vertical and temporal resolution of profilers and the generally adequate data quality are making them quite useful for nowcasting, and they are critical in determining the internal structure of severe storms and for predicting convection, especially in tropical regions.

However, the high cost of installing and maintaining profiler networks means the spatial resolution of such networks is likely to remain marginal to poor, except in a few regions of the world (over limited areas such as those of China, Europe, Japan and the United States). Even if the cost for the profiler is quite high compared to that required for an upper-air sounding system, the quantity of data provided is high and much more frequent, and the annual operation costs are lower than those for a sounding system. Annex B provides more detail on this subject.

1.3 SATELLITE

Polar orbiting or low earth orbiting (LEO) satellites have the advantage of high spatial resolution (<500 m), but have the disadvantage that temporal coverage is in the form of swaths at times that do not always coincide with rapidly developing weather systems. These satellites are thus not as useful for nowcasting purposes as geostationary (GEO) satellites. The latter provide continuous surveillance from their positions much higher above the earth surface and, while having a lower resolution (~0.5 to 3 km) than the LEO satellites, have the major advantage that images and data of the full disk are available in near-real time every 10–15 minutes with rapid-scan imaging of select regions at less than 2-minute intervals. GEO meteorological satellite data are well suited to monitoring in a qualitative way the initiation and rapid development of weather systems both in space and time.

Frequent images from GEO satellites provide adequate to good horizontal resolution for identifying the initiation, evolution and movement of synoptic and mesoscale cloud systems or of local circulations over most of the tropical and temperate zones. While GEO satellites have good coverage over the mid-latitudes and tropical areas, however, their coverage over high latitudes is marginal (owing to the larger pixel size away from nadir) or absent. For these high latitudes, where GEO satellite data are missing, LEO satellites can provide valuable observations with acceptable frequency due to the convergence of orbital tracks.

The individual channels, as well as channel differences, can be combined in so-called red-green-blue (RGB) combinations to highlight specific cloud characteristics, such as cloud depth or phase. For the purpose of simplicity, a few common RGB combinations have been identified and standardized for the detection of different phenomena, such as those for dust, fog, ash, SO_2, jet streams, potential vorticity, fires, convection and severe convection, overshooting tops, sea-surface temperature, ocean colour, snow, vegetation and smoke.

Thunderstorms, tornadoes and hail events

The frequent and comprehensive GEO data collected by satellites such as Meteosat Second Generation (MSG), Himawari and the Geostationary Operational Environmental Satellite-R (GOES-R) series can aid weather forecasters in the fast recognition and monitoring of dangerous weather phenomena such as thunderstorms, thus making an important contribution to nowcasting.

Retrievals of temperature and moisture from satellite data have been used in the United States since 1988 to determine indices for instability of air mass. The European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) has adjusted this technology for the MSG satellite and called it the global instability indices – this is a suite of instability indicators based on information from six channels from the MSG satellite in combination with information from an NWP model to assess the atmosphere stability in pre-convective (that is, usually still cloud-free) conditions. The greatest advantage of these fields is the added capability of the nearly continuous monitoring of the instability fields and their tendency, with improved temporal as well as spatial resolution compared to soundings made twice daily at only a limited number of radiosonde stations. Satellite-based instability indices, similarly to radiosonde information, could help a forecaster to focus their attention on a particular region where convection is likely to develop first, or to strengthen or weaken. It is still necessary to monitor the situation in real time, and a complete picture of the thunderstorm possibilities can only be obtained when instability indices are interpreted in combination with other triggering and/or lifting mechanisms. The satellite-based instability indices could indicate likely areas for convective development with a lead time of 3 to 9 hours.

Various RGBs exist that can help a forecaster identify convective systems, outflow boundaries and overshooting tops. Using colour-enhanced infrared images, so-called “cold-U/V and cold-ring-shaped storms” can be identified, which have proved to relate very well to severe weather on the ground. The continuous monitoring of these images can provide indications of the development and movement of thunderstorms and enhance forecaster situational awareness. Hail and tornadoes cannot be identified by any of the RGBs.

Rainfall and/or heavy rainfall

Satellite-based estimation of precipitation is the only effective alternative in the absence of radar and adequate rain-gauge data. Estimation techniques usually work better for convective precipitation, typically in tropical regions. The presence of lightning could complement the satellite information in the case of deep mixed-phase convection.

Precipitation estimates derived from satellite measurements are improving. The nature of the phenomena (short-lived convective cells and rain bands) can be a limiting factor. There are fairly simple products for rainfall rate estimated specifically from convective clouds based on cloud-top temperatures (using an infrared channel); these are best used as quantitative estimates of rainfall rates. To capture stratiform precipitation is generally more difficult and requires the use of cloud microphysical properties and/or data from available LEO satellites. Reliable and accurate precipitation estimates from satellites can represent an acceptable alternative for unpopulated regions or in regions without radar coverage.

Severe wind events (including wind shear: gust, downburst, microburst and vertical shear)

Wind vectors derived from GEO satellites are best used in combination with NWP data. However, next-generation high-density atmospheric motion vectors at 1 or 2.5 minutes may permit estimates of cloud top divergence and rotation. The latest GEO satellites have four times the spatial resolution, which leads to improved accuracy and precision, lower speed bias and more accurate height assignment.

Visibility and fog

Geostationary satellites can provide regularly updated information on areas with fog and low visibility by using the relevant RGB combination of channels. New methods combining satellite multispectral data with NWP information can provide quantitative estimates of the probability of fog and low cloud.

Precipitation types (snow, drizzle, freezing rain)

Geostationary satellites can be used to detect snow cover when snow has fallen and is lying on the ground, and also cloud particle effective radius and cloud phase at cloud top. However, a distinction cannot be provided for the different precipitation types inside the clouds.

1.4 LIGHTNING DETECTION

Ground-based total or separate cloud-to-ground (CG) and intra-cloud (IC) real-time lightning detection have demonstrated their value as early indicators of the location and intensity of developing convection, and also to track the movement of thunderstorms. By identifying electrically active storms in space and time, these systems increase warning lead times for dangerous thunderstorms. Flashes detected singly, including information on polarity, amplitude and flash type may be aggregated and accumulated in space and/or time to provide flash rates or flash-rate tendencies to users in order to be displayed or combined with other data such as radar and satellite. Single lightning flashes can be characterized by several attributes in addition to those of position and time, such as discrimination between CG and IC flashes as well as between positive and negative discharges (which can be relevant for many meteorological applications). Research has shown the importance of total lightning data for the early detection and evolution of storm intensity.

For meteorological applications, no single-flash information is necessary, but a good resolution in space and time of the lightning density is required, that is, the number of detected flashes in the corresponding time and space interval. These data can be easily combined with other remote sensing data (radar and/or satellite) to better characterize the convection.

A new generation of operational GEO lightning imager instruments is planned for the coming decade (GOES-R, Feng Yun (FY)-4, MTG, Electro-M). These detectors perceive the optical emissions from total lightning at cloud top in the near infrared (777 nanometres), but cannot discriminate between IC and CG on an individual flash basis. Forecasters intend to combine the space-based optical and ground-based radio frequency detection of lightning into a single all-source dataset that will combine the uniform, consistent detection of total lightning flashes from GEO satellites with the added detail and attributes of lightning made possible from the ground-based networks.

The strength of the lighting information is provided by the near-real-time sampling of the atmosphere, and provides added value to radar and satellite data. The “satellite–radar–lightning” trio becomes the basic building block for a superior nowcasting observation system for high-impact convective weather.

1.5 RADAR

Weather radar are the single most important instruments for nowcasting, particularly for convective weather phenomena. However, these instruments are also the most expensive, sophisticated and difficult to maintain. The following subsections discuss radar nowcasting capabilities and elements to consider when purchasing a radar.

1.5.1 Nowcasting capabilities

Radar is clearly the primary observation system for issuing warnings, with confidence, of severe convective weather (flash floods, hail, tornadoes, microbursts, and other damaging thunderstorm winds). Without a radar, in most cases there is only sufficient nowcasting skill to issue watches or advisories. Radar has distinct advantage over all other observing systems when it comes to nowcasting the phenomena associated with precipitation because it directly observes precipitation particles in three dimensions over a large area with an update rate of a few minutes. At radar ranges of <60 kilometres, the resolution of the precipitation is <1 kilometre. This makes it possible to (a) estimate rainfall rates and amounts; (b) observe the 3-D structure of a storm, which has proven useful in estimating storm severity; and (c) obtain the movement of storms, which is central to nowcasting. With the addition of Doppler capability, wind can be estimated – this has proven particularly valuable for the issuing of warnings for tornado, microburst and other damaging winds. With the further addition of dual polarization (transmitting and receiving two differently polarized wave forms), it is possible to differentiate precipitation particle type (rain, snow or hail) and to identify non-precipitation echoes such as insects and ground clutter. This is particularly useful for data quality control, identifying precipitation type and improving precipitation estimates.

Radar, particularly S-band wavelength radar, can observe strong gradients in the refractive index (Bragg scattering). These radar echoes, along with echoes from insects (often called “clear-air echo”) can be used to observe non-precipitating cumulus clouds, estimate wind and detect boundary-layer convergence lines such as gust fronts. The detection of wind convergence lines is particularly important in nowcasting thunderstorm initiation, growth and dissipation. It has been shown that thunderstorms initiate and grow along convergence lines and storms often dissipate if they move rapidly away from convergence lines.

When visibility is being restricted by either heavy rain or snow, estimates of visibility can be made based on relationships between radar reflectivity and precipitation rates. Extrapolation of the precipitation can then be used to make 0–60 minute visibility restriction nowcasts. When visibility is being restricted by heavy fog and rain begins to fall, the visibility will rapidly improve as the rain drops capture the small fog droplets by accretion. Thus, by extrapolating the rain into a dense fog area, nowcasts for dramatic improvement in visibility are possible.

While radar is the most useful tool for nowcasting, other observations are very important for nowcasts when used in conjunction with radar. The combined use of observations from different instruments is discussed in Chapter 2.

1.5.2 Purchasing a radar

Weather radar should not be purchased unless a specific plan with sufficient funding is in place for: operating the radar; conducting maintenance; conducting routine data quality checks; obtaining radar spare parts; establishing methodologies for transmission of the data to the forecast office; installing adequate displays at a forecast office for reviewing data; training of forecasters in interpretation of radar data and use in nowcasting; and assuring the provision of forecasters dedicated to nowcasting.

Many countries have bought radars without an operations plan and the necessary funding in place to support the instrument, only to find that their radar soon becomes inoperative, producing poor data, or not being used properly.

The purchase of a radar requires considerable expertise. The instrument must be able to detect the weather phenomena for which nowcasts are desired. Radar attributes, such as radar wave length, Doppler, dual polarization, sensitivity, and scanning capabilities must be considered. For example, if the primary use of the radar is for estimating heavy rainfall over large regions and to warn for high-wind events from thunderstorms, then an S-band, Doppler, dual polarization radar should be seriously considered. However, if the primary use of the radar is for nowcasting snow, then C-band or even X-band may be suitable. Annex C provides some general guidelines on radar attributes to consider depending on its desired use.

It is essential that a radar expert is involved in planning for the purchase of a radar. It is very important that the expert is not employed by any radar manufacturing company to ensure independence of advice given regarding choice of instrument. The expert could be chosen from a research institute or government agency in countries that operate radars. While the initial cost of the radar may seem high, the long-term costs are higher. These costs include properly maintaining and operating the radar to produce quality data, and to have well-trained nowcasters that can make quality nowcasts. The radar expert should be consulted to recommend nowcast tools and displays.

Further reading

Surface observations

3-D-printed automatic weather station (3-D-PAWS), http://3D-zambia.chordsrt.com.
Automated weather station networks, http://www.nws.noaa.gov/oh/hads.
Automated weather stations Wikipedia report, https://en.wikipedia.org/wiki/Automated_airport_weather_station.

Upper-air observations

Benjamin, S.G., B.D. Jamison, W.R. Moninger, S.R. Sahm, B.E. Schwartz and T.W. Schlatter, 2010: Relative short-range forecast impact from aircraft, profiler, radiosonde, VAD, GPS - PW, METAR and mesonet observations within hourly assimilation in the RUC. *Monthly Weather Review*, 138:1319–1343.
Dow, G., 2004: Developments in Observational Requirements for Global Numerical Weather Prediction. University of Reading, master's dissertation, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.475.6679&rep=rep1&type=pdf.
Lockett, D., 2014: Aircraft-based observations contributing to WMO Global Observing Systems. Presentation at the 2014 NOAA Aircraft Data Workshop, http://www.arinc.com/resources/customers/meetings/NOAA/NOAA_Aircraft_Data_Workshop_2014/presentations.html.
MetEd, Introduction to Aircraft Meteorological Data Relay (AMDAR), https://www.meted.ucar.edu/avn_int/amdar/.

Petersen, R.A., L. Cronce, R. Mamrosh and R. Baker, 2015: *Impact and Benefits of AMDAR Temperature, Wind and Moisture Observations in Operational Weather Forecasting*. World Integrated Global Observing System Technical Report 2015-01 (also published as University of Winsconsin-Madison Space Science and Engineering Center Publication No.15.06.P1), Geneva, WMO, http://library.wmo.int/pmb_ged/wigos-tr_2015-01_en.pdf.

World Meteorological Organization, Aircraft-based observations, http://www.wmo.int/pages/prog/www/GOS/ABO/.

Satellites

De Coning, E., 2013: Satellite applications for very short-range weather forecasting systems in Southern African developing countries. In: *Recent Advances in Satellite Research and Development* (S. Gardiner and K.P. Olsen, eds). New York, Nova Science Publishers, Inc.

EUMETSAT, RGB products explained, http://www.eumetsat.int/website/home/Data/Training/TrainingLibrary/DAT_2042888.html?lang=EN.

Goodman, S.J., J. Gurka, M. DeMaria, T. Schmit, A. Mostek, G. Jedlovec, C. Siewert, W. Feltz, J. Gerth, R. Brummer, S. Miller, B. Reed and R. Reynolds, 2012: The GOES-R proving ground: Accelerating user readiness for the next generation geostationary environmental satellite system. *Bulletin of the American Meteorological Society*, 93:1029–1040, doi:10.1175/BAMS-D-11-00175.1.

Gravelle, C.M., J.R. Mecikalski, W.E. Line, K.M. Bedka, R.A. Petersen, J.M. Sieglaff, G.T. Stano and S.J. Goodman, 2016: Demonstration of a GOES-R satellite convective toolkit to “bridge the gap” between severe weather watches and warnings: An example from the 20 May 2013 Moore, Oklahoma, tornado outbreak. *Bulletin of the American Meteorological Society*, 97:69–84, doi:10.1175/BAMS-D-14-00054.1.

McCann, D.W., 1983: The enhanced-V: A satellite observable severe storm signature. *Monthly Weather Review*, 111:887–894, doi:10.1175/1520-0493(1983)111<0887:TEVASO>2.0.CO;2.

Mecikalski, J.R., C.P. Jewett, J.M. Apke and L.D. Carey, 2016: Analysis of cumulus cloud updrafts as observed with 1 min resolution Super Rapid Scan GOES imagery. *Monthly Weather Review*, 144:811–830, doi:10.1175/MWR-D-14-00399.1.

Setvak, M., D.T. Lindsey, P. Novak, P.K. Wang, M. Radova, J. Kerkmann, L. Grasso, S. Su, R.M. Rabin, J. Stastka and Z. Charvat, 2010: Satellite-observed cold-ring-shaped features atop deep convective clouds. *Atmospheric Research*, 97:80–96, doi:10.1016/j.atmosres.2010.03.009.

Sieglaff, J.M., D.C. Hartung, W.F. Feltz, L.M. Cronce and L. Valliappa, 2013: A satellite-based convective cloud object tracking and multipurpose data fusion tool with application to developing convection. *Journal of Atmospheric and Oceanic Technology*, 30:510–525, doi:http://dx.doi.org/10.1175/JTECH-D-12-00114.1.

Smith, W.L., P. Minnis, C. Fleeger, D. Spangenberg, R. Palikonda and L. Nguyen, 2012: Determining the flight icing threat to aircraft with single-layer cloud parameters derived from operational satellite data. *Journal of Applied Meteorology and Climatology*, 51:1794–1810.

Lightning

Albrecht, R.I., D. Cecil and S.J. Goodman, 2014: Lightning. In: *Encyclopedia of Remote Sensing* (E.G. Njoku, ed.). New York, Springer.

Albrecht, R.I., S.J. Goodman, D.E. Buechler, R.J. Blakeslee and H.J. Christian, 2016: Where are the lightning hotspots on Earth? *Bulletin of the American Meteorological Society*, 97:2051–2068, doi:http://dx.doi.org/10.1175/BAMS-D-14-00193.1.

Bedka, K., C. Wang, R. Rogers, L.D. Carey, W. Feltz and J. Kanak, 2015: Examining deep convective cloud evolution using total lightning, WSR-88D, and GOES-14 super-rapid scan datasets. *Weather Forecasting*, 30:571–590, doi:10.1175/WAF-D-14-00062.1.

Cummins, K. and M. Murphy, 2009: An overview of lightning locating systems: History, techniques, and data uses, with an in-depth look at the US NLDN. *IEEE Transactions on Electromagnetic Compatibility*, 51(3):499–518, doi:10.1109/TEMC.2009.2023450.

Goodman, S.J., R.J. Blakeslee, W.J. Koshak, D. Mach, J.C. Bailey, L.D. Carey, D.E. Buechler, C.D. Schultz, M. Bateman, E. McCaul and G. Stano, 2013: The GOES-R geostationary lightning mapper. *Atmospheric Research*, 125–126:34–49, http://dx.doi.org/10.1016/j.atmosres.2013.01.006.

Hutchins, M.L., R.H. Holzworth, K.S. Virts, J.M. Wallace and S. Heckman, 2013: Radiated VLF energy differences of land and oceanic lightning. *Geophysical Research Letters*, 40(10):2390–2394, doi:10.1002/grl.50406.

McCaul, E.W., S.J. Goodman, K.M. LaCasse and D.J. Cecil, 2009: Forecasting lightning threat using cloud-resolving model simulations. *Weather Forecasting,* 24:709–729.

Nag, A., M.J. Murphy, W. Schulz and K.L. Cummins, 2015: Lightning locating systems: Insights on characteristics and validation techniques. *Earth and Space Science*, 2(4):65–93, doi:10.1002/2014EA000051.

Poelman, D., W. Schulz and C. Vergeiner, 2013: Performance characteristics of distinct lightning detection networks covering Belgium. *Journal of Atmospheric and Oceanic Technology*, 30:942–951.

Pohjola, H. and A. Makela, 2013: The comparison of GLD360 and EUCLID lightning location systems in Europe. *Atmospheric Research*, 123:117–128.

Said, R.K., M.B. Cohen and U.S. Inan, 2013: Highly intense lightning over the oceans: Estimated peak currents from global GLD360 observations. *Journal of Geophysical Research – Atmospheres*, 118:6905–6915, doi:10.1002/jgrd.50508.

Schultz, C.J., W.A. Petersen and L.D. Carey, 2011: Lightning and severe weather: A comparison between total and cloud-to-ground lightning trends. *Weather Forecasting*, 26:744–755.

Stano, G.T., C.J. Schultz, L.D. Carey, D.R. MacGorman and K.M. Calhoun, 2014: Total lightning observations and tools for the 20 May 2013 Moore, Oklahoma, tornadic supercell. *Journal of Operational Meteorology*. 2(7):71–88, doi:http://dx.doi.org/ 10.15191/nwajom.2014.0207.

Thompson, K.B., M.G. Bateman and L.D. Carey, 2014: A Comparison of two ground-based lightning detection networks against the satellite-based lightning imaging sensor (LIS). *Journal of Atmospheric and Oceanic Technology*, 31(10):2191–2205.

Williams, E.R., B. Boldi, A. Matlin, M. Weber, S. Hodanish, D. Sharp, S. Goodman, R. Raghavan and D. Buechler, 1999: The behaviour of total lightning activity in severe Florida thunderstorms. *Atmospheric Research*, 51(3–4):245–265, https://doi.org/10.1016/S0169-8095(99)00011-3.

Radar

Battan, L.J., 1973: *Radar Observation of the Atmosphere*. Chicago, University of Chicago Press.

Fabry, F., 2015: *Radar Meteorology Principles and Practices*. Cambridge, United Kingdom, Cambridge University Press.

Rinehart, R.E., 2010: *Radar for Meteorologists*. Fifth edition. North Dakota, University of North Dakota.

Additional references

Cintineo, J.L., M.J. Pavolonis, J.M. Sieglaff and D.T. Lindsey, 2014: An empirical model for assessing the severe weather potential of developing convection. *Weather Forecasting*, 29:639–653, doi:10.1175/WAF-D-13-00113.1.

Cressman, G.P., 1959: An operational objective analysis system. *Monthly Weather Review*, 87:367–374.

Horel, J. and B. Colman, 2005: Real-time and retrospective mesoscale objective analyses. Bulletin of the American Meteorological Society, 86:1477–1480.

Joe, P., C. Doyle, A. Wallace, S. Cober, B. Scott, G.A. Isaac, T. Smith, J. Mailhot, B. Snyder, S. Belair, Q. Jansen and B. Denis, 2010: Weather services, science advances, and the Vancouver 2010 Olympic and Paralympic winter games. *Bulletin of the American Meteorological Society*, 91:31–36.

Koenig, M. and E. de Coning, 2009: The MSG Global Instability Indices product and its use as a nowcasting tool. *Weather Forecasting*, 24:272–285.

Wang, P.K., 2004: A cloud model interpretation of jumping cirrus above storm top. *Geophysical Research Letters*, 31(18):L18106, doi:10.1029/2004GL020787.

World Meteorological Organization, Observation components of the Global Observing System, https://www.wmo.int/pages/prog/www/OSY/Gos-components.html.

———, 2010: *Guide on the Global Observing System* (WMO-No. 488). (Updated 2013). Geneva.

———, 2014: *Guide to Meteorological Instruments and Methods of Observation* (WMO-No. 8). Geneva.

———, 2014: Statement of guidance for nowcasting and very short range forecasting (NVSRF), (updated 2015), http://www.wmo.int/pages/prog/www/OSY/SOG/SoG-Nowcasting-VSRF.pdf.

Zapotocny, T.H., W.P. Menzel, J.P. Nelson and J.A. Jung, 2002: An impact study of five remotely sensed and five in situ data types in the Eta Data Assimilation System. *Weather Forecasting*, 17:263–285.

CHAPTER 2. NOWCASTING TECHNIQUES AND SYSTEMS

There are many different nowcasting methods. They vary from the simple extrapolation of radar precipitation echoes or animated loops of clouds observed by satellite, to sophisticated systems that combine output from feature detection and nowcasting algorithms with rapidly updating, integrated displays of observations and NWP output. The transitory nature and smaller scale of some types of weather (for example, tornadoes and microbursts) generally dictate the type of nowcasting techniques that can be applied for severe weather warnings; in this case, simple extrapolation techniques are frequently employed. For weather phenomena with longer timescales and larger spatial extent, nowcast systems have been designed to use observations in combination with NWP forecasts to extend the nowcast guidance out to 6 hours.

The following sections present the more common techniques being used around the world for 0–6-hour nowcasting. Section 2.1 discusses observation-based nowcasting techniques for the types of observations discussed in Chapter 1. Section 2.2 describes NWP-based nowcasting and its limitations. Section 2.3 describes the blending of observational nowcasting with NWP forecast fields. Section 2.4 discusses automatic nowcasting tools and systems that generally use heuristic[1] methods for combining observation-based nowcasting algorithms with NWP output. Finally, no automated nowcasting system is able to completely replace the human in issuing watches and warnings, thus the forecaster process for nowcasting high-impact weather is described in section 2.5 (Human/computer mix). At the end of Chapter 2, there are suggested reading references for readers interested in more detail on particular subjects.

2.1 OBSERVATION-BASED NOWCASTING TECHNIQUES

Nowcasting was originally – and to a large extent still is – based on the extrapolation of observations. As early as 1953, precipitation and severe storm nowcasts were based on extrapolating radar images from their immediate past motion. Other extrapolation examples are (a) nowcasts of thunderstorm location based on the extrapolation of maps of lightning occurrence from lightning sensor arrays; (b) nowcasts of thunderstorm location and intensity based on extrapolation of satellite imagery; (c) 1-hour nowcasts of temperature, moisture, winds and precipitation based on analysis of dense networks of surface stations (every 10 kilometres).

Quantitative nowcasts of rainfall are based on an extrapolation of the observed rainfall field forwards in time. The advection that is used for the nowcast is based on the apparent motion that has been analysed using the most recent radar images. Typically, the advection is estimated using a cross-correlation or optical flow technique that uses tiles of 20–40 kilometres in size. The technique that is used to advect the image forwards in time usually requires an estimate of the advection at each pixel in the field. Some form of interpolation is required to distribute the advection estimates from the tiles onto the entire image.

A number of extrapolation algorithms first identify storms as objects in the current radar scan and then track the motion of the storm by identifying the same object in successive scans. This approach is called cell tracking and is suitable for identifying and tracking severe convective storms. Typically the data are used as input to systems that generate warnings for the hazards that are associated with severe convection: large hail, damaging wind, heavy rain, and lightning.

The accuracy of a rainfall nowcast has been found to depend on the accuracy of the initial radar rainfall estimation, the degree of spatial organization of the rain, the rain rate, and the forecast lead time. Since the advection nowcasting technique assumes that the observed rainfall field will not change, the errors are greatest at the initiation and decaying stages of the storm’s lifecycle.

To utilize GEO satellite data beyond the observation stage (that is, not just looking at the individual channels or RGB images (as mentioned in Chapter 1), several products have been

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[1] Heuristic nowcasting techniques are those that incorporate expert forecaster experience (for example, forecaster rules and conceptual models).

developed that combine GEO satellite data with NWP. For example, the Nowcasting Satellite Application Facility has developed several such products, ranging from clear-air products for atmospheric stability estimates, to the identification and tracking of thunderstorms and estimation of convective rainfall rates. Some of the most useful products are listed below, but a more comprehensive list is available on the Facility's website (www.nwcsaf.org/).

Air mass variables (for example, precipitable water and instability indices) can be estimated where there are no clouds. Similar to the temperature and humidity profiles provided by upper-air soundings, instability indices can be calculated for each satellite pixel and can be used to issue severe weather watches with a few hours lead time, if they exceed a certain threshold. The thresholds are usually determined by local and regional factors and thus a skilled local forecaster is normally necessary for a correct interpretation.

The Rapidly Developing Thunderstorm product monitors and tracks intense or rapidly developing convective cells. The product highlights the most active cells in terms of phase – growing, mature or decaying – and can therefore be used for the automated convection detection where radar data are not available. Using the succession of images, the direction and speed of moving cells are calculated to provide an extrapolation of the cells' movement for the next 30 minutes.

The ProbSevere product is a Bayesian decision aid that produces a 90-minute nowcast of the probability of severe weather using high-resolution (3–4 kilometres) regional short-term forecasts of stability indicators combined with the maximum expected size of hail derived from radar, satellite indicators of cloud-top growth rate, and total lightning tendency indicators of rapid updraft and storm intensification. The forecaster can position the screen cursor over the individual storms displayed on their workstation to show the environmental stability, hail, radar, and lightning attributes for that storm.

Surface stations provide continuous measurements of state variables. Changes in trends of the state variables provide very short-term, localized indications of the change in weather. The most common nowcasting application is to identify changes in surface wind direction and speed associated with convergence boundaries (gust fronts) or low-level intense velocity features propagating through a network of stations, and extrapolate their location(s) forward in time. This is particularly useful for nowcasting thunderstorm initiation and nowcasting changes in wind shift and wind shear at airports. Surface sensor techniques specific to aviation applications will be discussed in more detail in section 5.1.

The more sophisticated and generally more accurate nowcast methods are based on combining multiple observation systems, not only to observe the location of the phenomena to be nowcast, but to obtain potential nowcast information. For example, thunderstorm nowcasting may use lightning, satellite, radar, surface stations and upper-air observations to be integrated into heuristic or expert nowcasting systems.

Visibility, fog and icing nowcasts are generally issued by the aviation forecaster. They are listed in Table 2.1 to provide guidance of usefulness of various instruments in issuing the aviation warning information. Surface sensors and human observers are still used for observations of visibility and ceiling height, and therefore for nowcasting. For icing, surface and inflight observations, radar reflectivity, satellite imagery and numerical model output (post-processing) can be useful when combined with each other.

An expert system to nowcast thunderstorm may use (a) satellite to monitor cumulus cloud lines (convergence lines) and cumulus cloud growth; (b) radar to identify thunderstorms, their intensity and motion as well as boundary-layer convergence-line location and motion; (c) lightning and lightning tendency to fill in locations of thunderstorms and their evolution not observed by radar; (d) upper-air temperature, moisture and winds to obtain vertical wind-shear and stability profiles to estimate potential storm type; (e) surface stations to monitor potential changes in atmospheric stability.

In many locations around the world limited observations are available and thus the ability to nowcast specific phenomena varies significantly. For this reason, Table 2.1 provides guidance

Table 2.1. Usefulness of observation type and NWP for issuing warnings and watches for specific weather phenomena. NWP is divided into global- and regional-scale models

Weather phenomena	*Surface stations*	*Dense surface station*	*Upper-air observations*	*Satellite*	*Lightning detection*	*Radar*	*NWP global/ regional*
Thunderstorm location	4	2	5	1*	1	1	5/3
Hail size	5	2	3	3	5	1	5/4
Tornado	6	5	5	4	5	1	6/5
Microburst	5	2	5	4	5	1	5/4
Strong surface wind	4	2	3	4	5	1	5/3
Heavy precipitation:							
Flash flood	4	1	5	3	5	1	5/3
Rain (large scale)	4	1	5	2	5	1	3/2
Snow (large scale)	4	2	5	2	5	1	3/2
Precipitation type (winter)	2	1	2	3	6	1	5/2
Visibility/fog	2	1	5	4	6	2**	5/3
Surface icing by freezing precipitation	2	1	2	4	6	2	5/3
In-flight icing	6	6	1	3	6	1	3/2

Notes:
1 Can often be used to issue warnings.
2 On limited occasions can be used to issue a warning.
3 Can often be used to issue a watch.
4 On limited occasions can be used to issue a watch.
5 Only useful when combined with other observations.
6 Limited usefulness even when combined with other observations.
* While warnings can be made on thunderstorm location, the location is generally not as specific as with radar or lightning.
** Only when restricted by heavy precipitation.

on what individual observation systems (as discussed in Chapter 1) may provide in the way of warnings and watches for specific weather phenomena (see Introduction table). In addition, NWP – to be discussed in section 2.2 – has been included in Tables 2.1 and 2.2 for ease of comparison. Table 2.2 summarizes the ability of each observation system and NWP to provide important predictor information for nowcasting.

Table 2.2. Usefulness of observation type and NWP in providing specific severe storm predictors

Nowcast predictor	*Surface station*	*Dense surface stations*	*Upper-air observations*	*Satellite*	*Lightning detection*	*Radar*	*NWP global/ regional*
Storm motion	3	2	2	2	1	1	3/1
Convergence-line detection and motion	2	1	4	2	3	1	4/2
Storm type	2	1	1	2	3	1	3/1
Storm evolution	3	2	4	1	2	1	3/2

Notes:
1 Often very useful.
2 Useful on some occasions.
3 Only useful when combined with other observations.
4 Not useful.

2.2 NWP-RELATED TECHNIQUES

Numerical weather prediction makes a fundamental contribution to VSRF[2] and nowcasting for daily weather services and for special meteorological services for major outdoor events. NWP has also demonstrated an irreplaceable role in modern seamless weather forecasts and extended meteorological services. It is more useful for large-scale weather events than convective-scale events.

2.2.1 Global and regional models

It has been noted that both regional and global model resolution continues to increase and provide much-improved estimation of surface weather details than previously. Presently, the grid spacing for these models is around 9–45 kilometres. The grid spacing of many operational regional NWP models has improved to almost the lower bound (at about 2–4 kilometres) of the convection-permitting resolution range.

Although global models remain too low in forecast capability to resolve explicitly convective-scale systems and to target directly the convective storms, the gridded digital 4-D forecast products generated from global models are valuable and reliable in terms of VSRF for winter weather (cold waves, snow, icing, etc.), and for conventional meteorological elements (temperature, humidity, wind, visibility and moderate precipitation).

Regional models, with a grid spacing of a few kilometres, can explicitly represent convective processes without the need for cumulus parameterization schemes, and perform much better than global models in VSRF of convective phenomena (for example, squall line and heavy rainfall), cloud cover and detail distributions in time and space of surface meteorological variables. However, nowcasting requires accurate specification of the current weather condition and frequent updates with a much smaller tolerance for the timing and location errors.

2.2.2 High-resolution data assimilation and rapid-cycle NWP

When an NWP model is aimed at nowcasting applications, it must be tailored to meet the requirements of nowcasting. Assimilating high-resolution data into a high-resolution model in a rapidly cycled fashion is a first priority. The high-resolution observations available operationally can be obtained from surface networks (especially those only available locally), Doppler radar networks, lightning networks, and new-generation geostationary satellites, inter alia. These observations not only have high spatial resolutions but also high temporal resolutions, suitable for rapid update data assimilation. The main objective for data assimilation of high-resolution data is to improve the short-term prediction of high-impact weather. Therefore, accurate analysis of the mesoscale and convective-scale features in the atmosphere are essential. In recent years, several operational centres have shown progress in improved precipitation forecasting primarily due to the inclusion of radar observations in their data-assimilation systems. Although the goal of rapid-update NWP for nowcasting applications is to update with sub-hour frequency, currently most operational data-assimilation systems are run with a 3-hour update frequency. There are challenges to be met for NWP models to operate with higher update frequencies both computationally and technically. Improved analyses and forecasts from NWP models can be used directly as nowcasting guidance, or indirectly by extracting some useful information using post-processing diagnostic tools.

2.2.3 Convection-permitting Ensemble Prediction System

At convection-permitting scale, the inherent high nonlinearity of weather systems together with inaccuracies from model initial conditions and physics cause obvious uncertainties in convective storm forecasts and associated weather phenomenon. By introducing a range of perturbed initial conditions of clouds and hydrometeors, or even perturbations of the model physics, a

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[2] VSRF is defined as 0–12-hour forecasting with less space and time specificity than nowcasting.

range of forecasts can be obtained providing (a) an ensemble mean of forecast possibilities; (b) probabilistic forecasts of storm initiation and dissipation, reflectivity strength, and rainfall rate and amount; (c) extreme situations of rainfall, temperature, winds and high-impact weather possibilities.

2.2.4 Challenges for NWP-based nowcasting

There are three primary obstacles to overcome for NWP to provide high-resolution nowcasts of severe weather. These are: (a) the need for dense observation networks of wind, temperature and moisture – in most locations the density of radars is insufficient for radar data assimilation purposes; (b) insufficient dedicated computer power for nowcasting in operational centres; (c) rapidly growing model errors at convection-permitting scales.

2.3 BLENDING

Blending the extrapolation of observations with NWP forecasts is one of the preferred methodologies for combining short-term extrapolation of observations (radar, satellite or lightning data) with NWP forecasts to produce 0–6-hour nowcasts. The blending of corrected model forecasts with extrapolation forecasts allows for a smooth transition from the extrapolation to the model forecasts. Blending systems that use observations in the first few hours help to overcome the limitations of NWP in the 0–3-hour period due to "spin-up time" and the inability to provide the temporal and location-specific forecasts needed for nowcasting high-impact weather. Large-scale multicellular features such as squall lines and mesoscale convective systems can be tracked using radar, satellite or lightning data, and extrapolated 0–3 hours into the future. Thus, it is generally these larger-scale weather features that are more successfully predicted in blended nowcast systems. Small-scale features, such as single-cell storms, with durations typically of less than one hour, are too small scale and transitory to be blended or meshed with NWP forecast fields.

A seamless 6-hour nowcast product is obtained through (a) a calibration of the model data to reduce intensity biases; (b) a phase correction to reduce location errors in the predicted precipitation field; (c) a statistically based weighted averaging of the extrapolated observations with the phase-corrected numerical prediction. Generally, a full weight is assigned to the observational field in the first hour that gradually decreases with increasing lead time, while the weight assigned to the NWP predictions starts at zero initially and gradually increases to full weight at the 6-hour forecast lead time. Using time-varying weights ensures that the most representative, timely, and accurate information is being used at each forecast lead time. For convective weather, weights are allowed to vary as a function of valid time of day, with the model receiving more weight during the period of most rapid storm initiation and growth. Most blending systems have been designed to provide nowcasts for convective rainfall, snowfall or for the potential for severe weather. Examples of blending systems used for aviation, road weather and hydrology are discussed in Chapter 5.

2.4 AUTOMATIC NOWCASTING TOOLS AND SYSTEMS

Because of the very short time periods associated with nowcasting, automated tools and systems are highly desirable. A number of automated nowcasting systems have been developed worldwide, the majority for the extrapolation of precipitation and severe storms. Other nowcasting tools are used for quickly detecting trends in storm characteristics, such as intensity, size and movement. Many of these tools have proven particularly successful for warning purposes, for example for microbursts, mesocyclones and heavy rain accumulations.

Users of nowcasting systems are often in need of real-time information for their downstream applications and for a quick assessment of the current weather situation. Consequently, the available computation time is limited, in particular for meteorological parameters with a high update frequency such as precipitation (for example, 5 minutes). In contrast to NWP models, which feature a high level of sophistication and comprehensive physics, resulting in long computation times, nowcasting systems must be kept comparatively simple and often exhibit heuristic approaches. Heuristic, in this context, means that limitations in a method (for example, uncertainties, inaccuracies and limited applicability) are accepted with regard to an otherwise disproportionate expenditure of time or resources. These nowcasting methods or tools have different limitations depending on the regions they are designed for or the main goal they are used for. In section 2.1, sources of observation and their applicability for nowcasting purposes were introduced. The present section provides a summary of different operational and automated nowcasting tools used by (or available to) the nowcasting community. Table 2.3 provides a partial list of automated nowcasting systems used in meteorological services or institutions in an operational (or semi-operational) framework. Annex D provides a brief description of each of the nowcasting systems listed in Table 2.3.

Table 2.3. Examples of operational (or semi-operational) nowcasting systems used in meteorological services

Type of system	*Acronym (name)*	*Main reference*
Cell tracker	TITAN (Thunderstorm Identification Tracking Analysis and Nowcasting)	Dixon and Wiener (1993)
	SCIT (storm cell identification and tracking)	Johnson et al. (1998)
	TRT (thunderstorm radar tracking) algorithm	Hering et al. (2004)
	FAST (fuzzy logic algorithm for storm tracking)	Jung and Lee (2015)
Area tracker	CO-TREC (continuous tracking radar echoes by correlation)	Li et al. (1995); Reinhart and Garvey (1978)
	MAPLE (McGill algorithm for precipitation nowcasting by lagrangian extrapolation)	Germann and Zawadzki (2002)
	Optical flow in the GANDOLF (Generating Advanced Nowcasts for Deployment in Operational Land-based Flood Forecasts) system	Bowler et al. (2004)
	CASA (Collaborative Adaptive Sensing of the Atmosphere radar network)	Ruzanski et al. (2011)
Multiple observation system	ANC (Auto-Nowcast) system	Mueller et al. (2003)
	SWIRLS (Short-range Warnings of Intense Rainstorms in Localized Systems)	Li and Lai (2004)
	NowCastMix – Autowarn (nowcast mix – automatic warning)	James et al. (2015); Reichert (2009)
	CAN-Now (Canadian Airport Nowcasting) system	Bailey et al. (2009)
	INCA (Integrated Nowcasting through Comprehensive Analysis)	Haiden et al. (2011)
Probabilistic approach	STEPS (Short-term Ensemble Prediction System)	Bowler et al. (2006)

In summary, the main features of an automatic integrated nowcasting system are:

(a) Analysis based on multiple observations that are combined in an pragmatic way;

(b) Pragmatic solutions for nowcasting the analysis fields;

(c) Blending of the nowcasts and NWP forecasts;

(d) Multivariate nowcasting (that is, taking into account a set of parameters and their interdependencies).

2.5 HUMAN/COMPUTER MIX

The most accurate warnings of severe convective weather, with only a few exceptions, require the involvement of a human in the process. One exception is automated microburst warnings for aircraft in the terminal area (discussed in Chapter 5).

First, the nowcaster should examine the synoptic pattern and NWP forecasts; based on the nowcaster's knowledge of the local climatology and conceptual models of severe storm evolution for the local area, the nowcaster should decide if severe weather is likely for the day. Second, the nowcaster should conduct an analysis of the latest local sounding, if available, for vertical wind shear and stability and likely changes that may occur during the day. Based on this analysis, the nowcaster should estimate the type of storms that might occur, such as super cells, multi-cells, single cells and squall lines. Third, if rapidly updating satellite and/or radar are available the nowcaster should continually monitor for boundary-layer convergence lines – locations where storms are likely to first develop. Once storms develop, and if a radar is available, the primary focus should be to look for features or signatures that might signal imminent severe weather. These signatures include high reflectivity, velocity rotation couplets, divergence velocity couplets, and bow and flare echoes. The nowcaster should then use automated extrapolation techniques to pinpoint future locations of severe weather.

Further reading

Radar extrapolation techniques

Bowler, N.E., C.E. Pierce and A. Seed, 2004: Development of a precipitation nowcasting algorithm based upon optical flow techniques. *Journal of Hydrology*, 288(1):74–91.

Dixon, M. and G. Wiener, 1993: TITAN: Thunderstorm identification, tracking, analysis and nowcasting – a radar-based methodology. *Journal of Atmospheric and Oceanic Technology,* 10:785–797.

Germann, U. and I. Zawadzki, 2002: Scale-dependence of the predictability of precipitation from continental radar images. Part I: Description of the methodology. *Monthly Weather Review*, 130:2859–2873.

Li, L., W. Schmid and J. Joss, 1995: Nowcasting of motion and growth of precipitation with radar over a complex orography. *Journal of Applied Meteorology*, 34:1286–1300.

Mandapaka, P.V., U. Germann, L. Panziera and A. Hering, 2012: Can Lagrangian extrapolation of radar fields be used for precipitation nowcasting over complex alpine orography? *Weather and Forecasting*, 27:28–49.

Rinehart, R.E. and E.T. Garvey, 1978: Three-dimensional storm motion detection by convective weather radar. *Nature*, 273:287–289.

Ruzanski, E., V. Chandrasekar and Y. Wang, 2011: The CASA nowcasting system. *Journal of Atmospheric and Oceanic Technology*, 28(5):640–655.

Blending techniques

Atencia, A., T. Rigo, A. Sairouni, J. Moré, J. Bech, E. Vilaclara, J. Cunillera, M.C. Llasat and L. Garrote, 2010: Improving QPF by blending techniques at the Meteorological Service of Catalonia. *Natural Hazards and Earth System Sciences*, 10(7):1443–1455.

De Coning, E., M. Gijben, B. Maseko and L. Van Hemert, 2015: Using satellite data to identify and track intense thunderstorms in South and Southern Africa. *South African Journal of Science*, 111(7/8), doi:http://dx.doi.org/10.17159/sajs.2015/20140402.

De Coning, E., M. Koenig and J. Olivier, 2011: The combined instability index: A new very short range convection forecasting technique for Southern Africa. *Meteorological Applications*, 18:421–439.

Golding, B.W., 1998: Nimrod: A system for generating automated very short range forecasts. *Meteorological Applications*, 5:1–16.

Koenig, M. and E. de Coning, 2009: The MSG Global Instability Indices product and it use as a nowcasting tool. *Weather Forecasting*, 24:272–285.

Advanced nowcasting techniques

Bailey, M.E., G.A. Isaac, N. Driedger and J. Reid, 2009: Comparison of nowcasting methods in the context of high-impact weather events for the Canadian Airport Nowcasting Project. International Symposium on Nowcasting and Very Short Range Forecasting, Whistler, British Columbia, 30 August–4 September.

Bellon, A. and G.L. Austin, 1986: The accuracy of short-term radar rainfall forecasts. *Journal of Hydrology*, 70:35–49.

Berenguer, M., C. Corral, R. Sánchez-Diezma and D. Sempere-Torres, 2005: Hydrological validation of a radar-based nowcasting technique. *Journal of Hydrometeorology*, 6:532–549.

Bowler, N.E., C.E. Pierce and A.W. Seed, 2006: STEPS: A probabilistic precipitation forecasting scheme which merges an extrapolation nowcast with downscaled NWP. *Quarterly Journal of the Royal Meteorological Society*, 132:2127–2155.

Dixon, M. and G. Wiener, 1993: TITAN: Thunderstorm identification, tracking, analysis, and nowcasting – a radar-based methodology. *Journal of Atmospheric and Oceanic Technology*, 10:785–797.

Germann, U. and I. Zawadzki, 2002: Scale-dependence of the predictability of precipitation from continental radar images. Part I: Description of the methodology. *Monthly Weather Review*, 130:2859–2873.

Haiden, T., A. Kann, C. Wittmann, G. Pistotnik, B. Bica and C. Gruber, 2011: The Integrated Nowcasting through Comprehensive Analysis (INCA) system and its validation over the Eastern Alpine region. *Weather and Forecasting*, 26(2):166–183.

Handwerker, J., 2002: Cell tracking with TRACE3D – a new algorithm. *Atmospheric Research*, 61:15–34.

Hering, A. M., C. Morel, G. Galli, S. Senesi, P. Ambrosetti and M. Boscacci, 2004: Nowcasting thunderstorms in the Alpine region using a radar-based adaptive thresholding scheme. Proceedings of the Third European Conference on Radar Meteorology, Visby, Sweden, 6–10 September.

Huang, L.X., 2011: Development of weighting, evaluation, bias correction and integrating system (WEBIS) for nowcasting. PhD dissertation, Department of Earth and Space Science and Engineering, York University, Toronto, Canada.

James, P., B. Reichert and D. Heizenreder, 2015: NowCastMIX – optimized automatic warnings from continuously monitored nowcasting systems based on fuzzy-logic evaluations of storm attributes. Presented at the Eighth European Conference on Severe Storms, Wiener Neustadt, Austria, 14–18 September.

Johnson, J.T., P.L. MacKeen, A. Witt, E.D. Mitchell, G.J. Stumpf, M.D. Eilts and K.W. Thomas, 1998: The storm cell identification and tracking algorithm: An enhanced WSR-88D algorithm. *Weather and Forecastin*g, 13:263–276.

Juanzhen, S., M. Xue, J.W. Wilson, I. Zawadzki, S.P. Ballard, J. Onvlee-Hooimeyer, P. Joe, D. Barker, P.W. Li, B. Golding, M. Xu and J. Pinto, 2014: Use of NWP for nowcasting convective precipitation: Recent progress and challenges. *Bulletin of the American Meteorological Society*, 95:409–426.

Jung, S.H. and G. Lee, 2015: Radar-based cell tracking with fuzzy logic approach. *Meteorological Applications*, 22(4):716–730.

Laroche, S. and I. Zawadzki, 1994: A variational analysis method for retrieval of three-dimensional wind field from single-doppler radar data. *Journal of the Atmospheric Sciences*, 51:2664–2682.

Li, P.W. and E.S. Lai, 2004: Short-range quantitative precipitation forecasting in Hong Kong. *Journal of Hydrology*, 288(1):189–209.

Mueller, C., T. Saxen, R. Roberts, J. Wilson, T. Betancourt, S. Dettling, N. Oien and J. Yee, 2003: NCAR Auto-Nowcast System. *Weather and Forecasting*, 18:545–561.

Novak, P., 2007: The Czech Hydrometeorological Institute's severe storm nowcasting system. *Atmospheric Research*, 83:450–457.

Pierce, C., A. Seed, S. Ballard, D. Simonin, and Z. Li, 2012: Nowcasting. In: *Doppler Radar Observations – Weather Radar, Wind Profiler, Ionospheric Radar, and Other Advanced Applications* (J. Bech and J.L. Chau, eds), Rijeka, Croatia, InTech.

Pinto, J.O., W. Dupree, S. Weygandt, M. Wolfson, S. Benjamin and M. Steiner, 2010: Advances in the consolidated storm prediction for aviation (CoSPA). Paper presented at the Fourteenth Conference on Aviation, Range and Aerospace Meteorology, *American Meteorological Society*, Atlanta, 18–21 January.

Reichert, B.K., 2009. *AutoWARN – Automatische Unterstützung der Herausgabe von Unwetterwarnungen* (AutoWARN – Automatic support for issuing weather warnings). *promet*, 35(1/2):98–103.

Rigo, T. and M.C. Llasat, 2004: A methodology for the classification of convective structures using meteorological radar: Application to heavy rainfall events on the Mediterranean coast of the Iberian Peninsula. *Natural Hazards and Earth System Science*, 4(1):59–68.

Rinehart, R.E. and E.T. Garvey, 1978: Three-dimensional storm motion detection by conventional weather radar. *Nature*, 273:287–289.

Schmid, W., S. Mecklenburg and J. Joss, 2000: Short-term risk forecasts of severe weather. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere*, 25(10):1335–1338.

Seed, A.W., 2003: A dynamic and spatial scaling approach to advection forecasting. *Journal of Applied Meteorology*, 42:381–388.

Wilson, J.W., N.A. Crook, C.K. Mueller, J. Sun and M. Dixon, 1998: Nowcasting thunderstorms: A status report. *Bulletin of the American Meteorological Society*, 79:2079–2099.

Wilson, J.W., Y. Feng, M. Chen and R. Roberts, 2010: Nowcasting challenges during the Beijing Olympics: Successes, failures and implications for future nowcasting systems. *Weather Forecasting*, 25:1691–1714.

Satellite nowcasting methods

Bedka, K.M., J. Brunner, R. Dworak, W. Feltz, J. Otkin and T. Greenwald, 2010: Objective satellite-based overshooting tops using infrared window channel brightness temperature gradients. *Journal of Applied Meteorology and Climatology*, 49:181–202, doi:10.1175/2009JAMC2286.1.

Bedka K.M., C. Wang, R. Rogers, L.D. Carey, W. Feltz and J. Kanak, 2015: Examining deep convective cloud evolution using total lightning, WSR-88D, and GOES-14 super rapid scan observations within deep convective clouds. *Weather Forecasting*, 30:571–590, doi:10.1175/WAF-D-14-00062.1.

Cintineo, J.L., M.J. Pavolonis, J.M. Sieglaff and D.T. Lindsey, 2014: An empirical model for assessing the severe weather potential of developing convection. *Weather Forecasting*, 29:639–653, doi:10.1175/WAF-D-13-00113.1.

Gravelle, C.M., J.R. Mecikalski, W.E. Line, K.M. Bedka, R.A. Petersen, J.M. Sieglaff, G.T. Stano and S.J. Goodman, 2016: Demonstration of a GOES-R satellite convective toolkit to “bridge the gap” between severe weather watches and warnings: An example from the 20 May 2013 Moore, Oklahoma, tornado outbreak. *Bulletin of the American Meteorological Society*, 97:69–84, doi:10.1175/BAMS-D-14-00054.1.

Line, W., T.J. Schmit and D. Lindsey, 2016: Use of geostationary rapid scan imagery by the Storm Prediction Center (SPC). *Weather and Forecasting*, 31(2):483–494, doi:10.1175/WAF-D-15-0135.1.

Nowcasting Satellite Application Facility website, http://www.nwcsaf.org.

McCann, D.W., 1983: The enhanced-V: A satellite observable severe storm signature. *Monthly Weather Review*, 111:887–894, doi:10.1175/1520-0493(1983)111<0887:TEVASO>2.0.CO;2.

Mecikalski, J.R. and K.M. Bedka, 2006: Forecasting convective initiation by monitoring the evolution of moving cumulus in daytime GOES imagery. *Monthly Weather Review*, 134:49–78, doi:10.1175/MWR3062.1.

Mecikalski, J.R., C.P. Jewett, J.M. Apke and L.D. Carey, 2016: Analysis of cumulus cloud updrafts as observed with 1 min resolution super rapid scan GOES imagery. *Monthly Weather Review*, 144:811–830, doi:10.1175/MWR-D-14-00399.1.

Pavolonis, M.J., A.K. Heidinger and J. Sieglaff, 2013: Automated retrievals of volcanic ash and dust cloud properties from upwelling infrared measurements. *Journal of Geophysical Research – Atmospheres*, 118(3):1436–1458, doi:10.1002/jgrd.50173.

Pavolonis, M.J., J. Sieglaff and J. Cintineo, 2015: Spectrally enhanced cloud objects – a generalized framework for automated detection of volcanic ash and dust clouds using passive satellite measurements: 1. Multispectral analysis. *Journal of Geophysical Research – Atmospheres*, 120(15):7813-7841, doi:10.1002/2014jd022968.

Pavolonis, M.J., J. Sieglaff and J. Cintineo, 2015: Spectrally enhanced cloud objects – a generalized framework for automated detection of volcanic ash and dust clouds using passive satellite measurements: 2. Cloud object analysis and global application. *Journal of Geophysical Research – Atmospheres,* 120(15):7842–7870, doi:10.1002/2014jd022969.

Sieglaff, J.M., D.C. Hartung, W.F. Feltz, L.M. Cronce and L. Valliappa, 2013: A satellite-based convective cloud object tracking and multipurpose data fusion tool with application to developing convection. *Journal of Atmospheric and Oceanic Technology*, 30:510–525, doi:http://dx.doi.org/10.1175/JTECH-D-12-00114.1.

Wang, P.K., 2004: A cloud model interpretation of jumping cirrus above storm top, *Geophysical Research Letters*, 31(18):L18106, doi:10.1029,2004GL020787.

Lightning nowcasting methods

Gatlin, P. and S.J. Goodman, 2010: A total lightning trending algorithm to identify severe thunderstorms. *Journal of Atmospheric and Oceanic Technology*, 27:3–22.

McCaul, E.W., S.J. Goodman, K.M. LaCasse and D.J. Cecil, 2009: Forecasting lightning threat using cloud-resolving model simulations. *Weather Forecasting*, 24:709–729.

Schultz, C.J., W.A. Petersen and L.D. Carey, 2009: Preliminary development and evaluation of lightning jump algorithms for the real-time detection of severe weather. *Journal of Applied Meteorology and Climatology*, 48:2543–2563.

Schultz, C.J., W.A. Petersen and L.D. Carey, 2011: Lightning and severe weather: A comparison between total and cloud-to-ground lightning trends. *Weather Forecasting*, 26:744–755.

Stano, G.T., C.J. Schultz, L.D. Carey, D.R. MacGorman and K.M. Calhoun, 2014: Total lightning observations and tools for the 20 May 2013 Moore, Oklahoma, tornadic supercell. *Journal of Operational Meteorology*, 2(7):71–88, doi:http://dx.doi.org/10.15191/nwajom.2014.0207.

Icing nowcasting

Smith, W.L., P. Minnis, C. Fleeger, D. Spangenberg, R. Palikonda and L. Nguyen, 2012: Determining the flight icing threat to aircraft with single-layer cloud parameters derived from operational satellite data. *Journal of Applied Meteorology and Climatology*, 51:1794–1810.

CHAPTER 3. NOWCAST VERIFICATION

Nowcast verification is the process of assessing the quality of nowcast information. The verification can be qualitative ("does it look right?") or quantitative ("how accurate was it?"). In either case, it should give information about the nature of the nowcast errors.

3.1 THE PURPOSES OF NOWCAST VERIFICATION

Different users of verification results will have quite different needs, which means that the target user(s) must be known before the verification system is designed, or the system must be broadened to ensure that the needs of all (or most) of the users can be met. Users of verification information could be:

(a) Forecasters and managers of an NMHS, to assess and monitor the quality of nowcast and warning production systems within the NHMS (*administrative verification*);

(b) End users of nowcasts, to judge how much added value nowcasts can bring to their specific decision-making processes (*user-oriented verification);*

(c) Scientists or nowcast system developers, to assess the nowcast system quality, aiming at its improvement (*scientific verification*).

Thus, the first step in verification is to understand the needs of the nowcast users, including characteristics such as user-specified thresholds. Moving toward user-relevant verification will increase both the usefulness and quality of nowcasts.

3.2 TYPES OF NOWCASTS, OBSERVATIONS AND VERIFICATION METHODS

Verification approaches depend not only on the users and the purpose of the verification, but also on the nature of the variables being verified, as well as characteristics of the nowcasts and reference observations (gridded versus points), each of which may call for different verification methods.

The second step in verification is to identify verification attributes that can provide answers to the verification questions and then to select metrics and graphics (for example, plots, histograms or diagrams) that appropriately measure and represent the attributes.

No single verification measure or score can assess all attributes (or characteristics) of nowcast performance. Nowcast quality is multifaceted, and more than one verification measure is needed to provide a full picture of performance. Moreover, specific metrics are needed to answer different questions. Metrics can be quantitative scores or diagnostics.

The table in Annex E provides one way of classifying nowcasts, along with verification methods that are appropriate for particular types of events and forecasts.

3.3 PREPARING DATASETS FOR VERIFICATION

Nowcasts should be compared (or verified) using a corresponding observation of what actually occurred, or some good estimate of the true outcome. The nowcast cannot be verified without relevant observations. Thus, an important step for verification activities is the identification and collection of a matched set of nowcasts and observations. Stratifications of the verification dataset are also important to ensure that the results obtained are meaningful; stratifications can be based on the forecast period, lead time and verification area, or other factors that lead to distinct groupings of nowcasts.

Matching the nowcast with the corresponding observation is not always simple, especially in the case of rare or extreme events. If observational data are sparse, it may be difficult to determine whether severe weather occurred, as there may be large distances between stations for smaller-scale convective storms that characterize many severe weather occurrences. In the case of extreme weather, nowcasts and warnings can be evaluated against radar observations and information from satellites (for example, against visible images and cloud-top temperature values). Proxy data such as reports of flooding may also be used to infer the occurrence of severe weather in the absence of observations, but full justification of these subjective decisions must be included with verification reports.

3.4 VERIFICATION OF RARE AND EXTREME EVENTS

The ability of nowcasts to predict very rare and extreme events has become increasingly important over the past decade due to the large impacts of these events on people and property. However, the ability to verify nowcasts of these kinds of events is impacted by the fact that:

(a) The phenomena are mostly rare events in the tail of the distribution;

(b) The sample sizes of severe phenomena are very small;

(c) Often there is a lack of suitable observations of the events.

In particular, severe weather poses a special problem because it is infrequent, poorly documented by observations, and at the limit of predictability of those events that are often the subject of weather warnings. Furthermore, in situations where rare events are important to the decision-maker, traditional measures become virtually useless due to the statistical properties of extremes.

To proceed despite these limitations, precipitation has often been used for verification as a surrogate for severe weather. However, traditional evaluation of precipitation forecasts can be misleading because many statistics tend to focus on the "central tendency" of all precipitation and not the nowcasting of the heavy precipitation (which is more, but not completely, representative of all severe weather). This issue can be alleviated through the use of precipitation thresholds (and categorical verification methods), which allow focus on more extreme precipitation events.

3.5 OBJECTIVE AND SUBJECTIVE VERIFICATION

While objective verification procedures for severe weather nowcasts have extra significance, there is a role for subjective verification, and in fact it may be difficult to completely eliminate all subjectivity from the process even within the context of an effort to verify objectively. In particular, subjective verification can provide an initial assessment of nowcast performance through the collection of subjective evaluation information from operational forecasters and nowcast end users. Also, subjective verification or evaluation of nowcasts is necessary in data-sparse regions, and is useful for the evaluation of specific events (for example, tornadoes).

The emphasis of subjective verification is not only on the assessment of the meteorological content of the nowcasts, but also of their perceived or real value to users, or of the effectiveness of the nowcast delivery to users, both of which require additional information to evaluate.

Real-time verification systems that verify forecasts operationally and provide immediate feedback to the forecasters may also be used to evaluate the performance of the nowcasting system while an event is occurring, allowing the forecaster to adjust the nowcast and making it possible to better understand the strengths and weaknesses of the nowcasting system. However, real-time verification tends to be subjective in nature, based on graphical displays of nowcasts and observations. Real-time verification may also suffer from the lack of a complete set of observations.

3.6 VERIFICATION OF QUALITATIVE NOWCASTS AND WARNINGS

Most descriptive or worded nowcasts and severe weather warnings cannot be assessed quantitatively and objectively, as different users of qualitative nowcasts and warnings can, and most likely will, interpret them differently.

Many descriptive forecasts can, in theory, be made more definite. In circumstances where a technical definition underlies a descriptive forecast, the descriptive forecast can be verified by going back to the technical definition. Depending on the nature of that definition (binary, continuous or probabilistic) an appropriate verification strategy can be chosen. If no underlying technical definition is available, verification is inevitably subjective.

3.7 RECOMMENDATIONS ON NOWCAST VERIFICATION

The methodology and metrics of nowcast verification should be carefully chosen to produce information that is meaningful to the user. A two-way dialogue is necessary to ensure that the users obtain the information they require.

As a basic guide for developing nowcast verification, those responsible should prepare the following knowledge and procedures:

(a) Understand the needs of users interested in nowcast verification;

(b) Identify verification methods and attributes that can provide answers to the questions of interest;

(c) Select metrics and graphics that appropriately measure and represent the attributes;

(d) Identify and collect a representative matched set of forecasts and observations;

(e) Compute verification metrics using, for example, free available verification tools and packages such as Model Evaluation Tools and the R verification package;

(f) Depict the verification results in ways that are meaningful to the users;

(g) Make nowcast quality assessments on a routine basis to provide ongoing information about nowcast performance.

Verification methodologies and metrics should be as simple as possible to provide quality nowcast summaries that are meaningful and easy to understand. However, they should not be so simple that they are inappropriate. Metrics that attempt to summarize various forecast attributes into one single composite measure are not encouraged. A sufficient number of metrics should be presented to give an honest and comprehensive summary of the different facets of nowcast performance.

Note also that more sophisticated spatial verification methodologies have recently been developed (which are able to provide more diagnostic information about nowcast performance); these methods can also be explored as an advanced addition to the verification toolbox.

Further reading

Methods

Brooks, H.E. and C.A. Doswell, 1996: A comparison of measures-oriented and distributions-oriented approaches to forecast verification. *Weather Forecasting,* 11:288–303.

Brown, B.G., R. Bullock, C.A. David, J.H. Gotway, M.B. Chapman, A. Takacs, E. Gilleland, K. Manning and J. Mahoney, 2004: New verification approaches for convective weather forecasts. Presentation at the Eleventh Conference on *Aviation, Range, and Aerospace Meteorology, American Meteorological Society, Hyannis*, Massachusetts, 4–8 October.

Ebert, E., 2005: Verification of nowcasts and very short range forecasts. Presentation at the World Weather Research Programme International *Symposium on Nowcasting and Very Short Range Forecasting, Toulouse, 5–9 September*.

Jolliffe, I.T. and D.B. Stephenson (eds), 2012: *Forecast Verification: A Practitioner's Guide in Atmospheric Science.* Second edition. Chichester, United Kingdom, John *Wiley and Sons, Ltd.*

Mailier, P.J., I.T. Jolliffe and D.B. Stephenson, 2006: Quality of Weather Forecasts: Review and Recommendations. *Royal Meteorological Society Report*, https://www.rmets.org/quality-weather-forecasts-review-and-recommendations.

Mason, S.J. and A.P. Weigel, 2009: A generic forecast verification framework for administrative purposes. *Monthly Weather Review*, 137:331–349.

Murphy, A.H., 1993: What is a good forecast? An essay on the nature of goodness in weather forecasting. *Weather Forecasting*, 8, 281–293.

Murphy A.H. and E.S. Epstein, 1989: Skill scores and correlation coefficients in model verification. *Monthly Weather Review*, 117:572–581.

Murphy, A.H. and R.L. Winkler, 1987: A general framework for forecast verification. *Monthly Weather Review*, 115:1330–1338.

Nurmi, P., 2003: Recommendations on the Verification of Local Weather Forecasts (at ECWMF Member States). *European Centre for Medium-range Weather Forecasts Operations Department*, October 2003, http://www.cawcr.gov.au/projects/verification/Rec_FIN_Oct.pdf.

Stanski, H.R., L.J. Wilson and W.R. Burrows, 1989: Survey of Common Verification Methods in Meteorology. Second edition. *Research Report No. MSRB 89-5*. Australian Atmospheric Environment Service Forecast Research Division.

Stephenson, D.B, B. Casati, C.A.T. Ferro and C.A. Wilson, 2008: The extreme dependency score: A non-vanishing measure for forecasts of rare events. *Meteorological Applications,* 15:41–50.

World Meteorological Organization Joint Working Group on Forecast Verification Research website, www.cawcr.gov.au/projects/verification.

Preparing datasets

World Meteorological Organization, 2010: *Manual on the Global Data-processing and Forecasting System* (WMO-No. 485). (Updated 2015). Geneva.

———, 2014: *Forecast Verification for the African Severe Weather Forecasting Demonstration Projects* (WMO-No. 1132). Geneva.

Objective and subjective verification

Brooks, H.E., M. Kay and J.A. Hart, 1998: Objective limits on forecasting skill of rare events. In: *Nineteenth Conference on Severe Local Storms*, Minneapolis, 14–18 September. American Meteorological Society.

Kain, J.S., M.E. Baldwin, P.R. Janish, S.J. Weiss, M.P. Kay and G.W. Carbin, 2003: Subjective verification of numerical models as a component of a broader interaction between research and operations. *Weather Forecasting*, 18:847–860.

Thornes, J.E. and D.B. Stephenson, 2001: How to judge the quality and value of weather forecast products. *Meteorological Applications*, 8:307–314.

Additional references

Meteorological Applications, 2008, 2013: Special issues, http://onlinelibrary.wiley.com/doi/10.1002/met.v15:1/issuetoc, http://onlinelibrary.wiley.com/doi/10.1002/met.2013.20.issue-2/issuetoc.

World Meteorological Organization, 2000: *Guidelines on Performance Assessment of Public Weather Services* (WMO/TD-No. 1023). Geneva.

———, 2015: *Seamless Prediction of the Earth System: From Minutes to Months* (WMO-No. 1156). Geneva.

CHAPTER 4. TRAINING

Nowcasting is very important for ground transportation, aviation, the public and industry, and is also a very complex cognitive task for the forecaster. Many kinds of weather that depend on the climate, the season and the special conditions at a particular location belong to nowcasting. The forecaster has to perform many tasks in parallel: continuous monitoring of the present weather situation and consideration of the likely developments over the coming hours; evaluation of many kinds of observations and forecast products and the placing of all this information into a logical and consistent context – all under significant time pressure. Although products of high quality exist that are generated automatically, monitoring them for quality will remain necessary at least for a few years. However, nowcasting not only contains the need to generate scientifically correct products but also implies the challenge to explain to the customer how to use these products. Only continuous training both in meteorology and in communication can provide the basis for successful nowcasting. A comprehensive description of competency is available in *Guide to the Implementation of Education and Training Standards in Meteorology and Hydrology* (WMO-No. 1083), Volume I – Meteorology, Chapter 1.3 (WMO, 2012). In the document, "Implementation Guidance of Aeronautical Meteorological Forecaster Competency Standards" (www.wmo.int/pages/prog/amp/pwsp/documents/AnnexIV_Aeronautical_Met_Forecaster_Competencies.pdf) further information about required competencies can be found. A WMO Guide to Competency is in preparation and will be published in 2017.

To address this training challenge, trainers must rely on both high scientific expertise and social and pedagogical competencies. These requirements are discussed in detail in *Guidelines for Trainers in Meteorological, Hydrological and Climate Services* (WMO-No. 1114) (WMO, 2013*b*).

For optimal nowcasting, skilled forecasters and trainers in many meteorological disciplines are necessary, which is usually impossible for one training institute. However, at many National Meteorological Services, training institutions and partner universities, personnel with special expertise are available. The synergy of networking will yield more efficient nowcasting training.

In section 4.1, forecaster competencies for successful nowcasting are summarized, the recommended training process for the competencies is described and networking opportunities for nowcasting training are discussed.

4.1 FORECASTER SKILLS DURING THE NOWCASTING PROCESS

This topic is addressed in other chapters of the present guidelines. In Chapter 1, observations and their potential for nowcasting are explained. Chapter 2 contains nowcasting techniques and systems and Chapter 5 describes nowcasting applications. Readers considering forecaster training should also refer to these chapters as they are relevant for successful nowcasting. In the present chapter the nowcasting process and the required training fields will be summarized, together with optimal training conditions (for example, in respect to equipment, available products and training staff). However, if the conditions are suboptimal the training will have to be adapted accordingly. The nowcasting process often consists of two steps.

(a) Early warning

This phase is to develop the forecaster's sensitization. Which significant weather will likely occur and where during the next 6 hours?

(i) The forecaster needs good background knowledge in atmospheric physics and skills in the interpretation of relevant meteorological parameters and how to use these within the present synoptic context. For example, surface observations can inform about significant weather and its movement and development. Temperature and dew point suggest the type of air mass. The wind speed and direction give forecasters hints to convergences, gusts and wind shear. Surface pressure and tendencies show hints to dynamical processes.

(ii) The forecaster should know how to use numerical model products; for example, for diagnosing dynamical forcing, atmospheric layering and precipitation formation, and wind shear and gusts. In many services these parameters are automatically derived. However, the forecaster should always be aware of the typical strengths and weaknesses of NWP and verify forecast products against observations, measurements and remote sensing products for the most reliable forecasts.

(iii) Ensemble products and probabilistic forecasts are important to better consider the uncertainties of NWP products. The forecasters can select different kinds of ensemble forecasts – different models, different model runs of the same model with the same lead time, runs with slightly disturbed initial fields (for example, as offered by the European Centre for Medium-range Weather Forecasts). In some weather services, ensemble prediction system products are used especially for nowcasting following additional modifications to parameterization. It should be ensured that the forecaster is trained to deal with probability forecasts and the interpretation of ensemble prediction system results, for example, threshold excess (gusts, precipitation amount) or the likelihood of impact weather (thunderstorms, hail, snow, freezing precipitation, low visibility or fog).

(iv) Model Output Statistics (MOS) can be a useful tool for early warning in relation to probabilities of impact weather in different regions. However, the forecaster should be made aware of typical MOS product errors – for example, the smoothing of extreme weather events by MOS.

(v) Forecasters should be familiar with remote sensing data (satellite, radar, lightning), including their strengths and weaknesses and how to apply them during particular weather situations. Intense training on how to avoid misinterpretations is recommended.

(vi) Forecasters should be trained in conceptual models and how they can be applied for early warning – for example, conceptual models for cyclogenesis, fronts and mesoscale convection.

(b) Nowcasting

Nowcasting is a continuous cycle of weather and product monitoring (automatic guidance and issued nowcasting products or warnings).

(i) Forecasters should be thoroughly instructed in using conceptual models also for nowcasting (for example, rapid cyclogenesis, types of fronts, split front, instant occlusion, convection during summer and winter from small to mesoscale). For example, the physical background, relevant parameters and examples (in relation to satellite products) for many conceptual models are discussed in detail in http://www.eumetrain.org/satmanu/index_conc.html.

(ii) Forecasters should be trained in the efficient combination of different data sources (observations and measurements, vertical profiles (AMDAR), remote sensing, NWP and ensemble products). In some services, automatically derived guidance is available for nowcasting (discussed in section 2.4). However, training should ensure that forecasters are aware of the performance of such guidance, depending on the weather situation and on the location or area.

(iii) Forecasters should also be trained to explain nowcasting products, that is, to show customers how they can be applied.

4.2 TRAINING PROCESS

4.2.1 Identification of learning needs and specification of learning outcomes

This includes identifying the priority training contents and the expected competencies to be acquired by the training. Questionnaires, investigations of data banks or contacting focal points are methods for identifying the learning needs. The chosen content and the method of training should be directly related to the learning outcomes, in other words, what the students should be able to do after the training for optimal nowcasting.

Learning outcomes should be directly aligned with the assessment methods chosen. Learning outcomes are discussed in more detail in section 4.5.

4.2.2 Determination of learning solutions

Learning solutions cannot be considered independently from the constraints of the situation. The availability of qualified personnel is often the main challenge. This relates not only to the trainers but also the trainees. The workload and the course length should be planned according to the available time during the forecasters' work schedule. The training venue equipment is especially relevant for classroom training. However, the conditions at the participants' work places should also be taken into account and replicated, when practical. Blended approaches that use both e-learning and classroom experiences should be considered to expand the learning opportunities. We distinguish here three training formats, or learning solutions. However, other solutions include on-the-job training, coaching and mentoring.

Online

Online training can include both self-directed online learning resources to be used by individuals in their own preferred time frames, and synchronous, or live, events led by instructors. For synchronous online events, technical assistance should be provided for guidance and for solving technical problems (preferably within minutes). The relatively high number of participants is a big advantage of synchronous online training, allowing a fast and flexible dissemination of information and avoiding travel costs. This could enable more weather services to meet the requirements of WMO and ICAO. On the other hand, the provision of online training is challenging and requires special training, involving as it does the monitoring and evaluating of the activities of many participants and the ability to offer help rapidly. Online training is applicable for many learning activities, but some participants may feel that they do not receive sufficient feedback without having contact with others.

Blended

This is a mixture of online and face-to-face training, sometimes followed by a "wrap-up". The close contact among the students and between students and trainers yields the most intense work experience. After the online training, during which participants can gain critical skills and reach similar knowledge levels, the face-to-face phase gives more time for practically oriented nowcasting and the students can receive individual guidance.

Pure face-to-face

This training technique is only applicable if the participants possess similar and advanced prior knowledge of the subject.

4.2.3 Design and development of learning activities and resources

The design of training and learning activities and resources for each learning outcome follows in the context of the steps described above. If they are well chosen and successfully completed the student will be able to perform the job tasks in relation to nowcasting.

For the delivery of training, many different methods can be chosen. In the light of training time, equipment, number of students, learning needs and training solutions chosen, the trainer should use and vary as many different media and training activities as possible to make the training engaging for the students and to achieve optimal retention rates. Passive learning, such as listening or reading, should be reduced to a minimum to increase trainees' activation and assimilation of information. Discussions and exercises, preferably as group work and simulations, should be used as often as possible. If the students are asked to present the results of their work in exercises, the training will be more effective.

4.2.4 Deliver training and manage learning experiences

The challenges for the trainer in maintaining an effective learning environment are:

(a) To keep his/her knowledge in different areas of nowcasting up to date;

(b) To stay focused on the programmed content and learning outcomes, that is, the content that is relevant for nowcasting, while remaining responsive to individual needs;

(c) To help the trainees learn and understand in an optimal way;

(d) To provide quality feedback on learning progress;

(e) To help the trainees remember as much as possible and apply acquired knowledge accordingly.

4.2.5 Assessment of learning and evaluation of the learning process

Feedback is a critical element of teaching and the quality and quantity of feedback is the greatest predictor of learning. The positive effects of this element are highlighted in a meta-analysis of learning by Hattie (2009). The terms assessment and evaluation are often used in similar ways. In the following usage, the assessment refers to measurement of learning, and evaluation to the measurement of the quality of the training.

Assessment of learning

Assessment is a measure of what the students have learned, for example, by testing knowledge and skill gains. Learning should be assessed against the required learning outcomes. The assessment of skills is best done through observations of practice exercises, such as in simulations or role playing. We distinguish five different categories of assessment that can be applied in training of nowcasting:

(a) Initial assessment is used for identifying the prior knowledge and selection of participants;

(b) Formative assessment is used during the training itself by providing feedback that could lead to changes in performance;

(c) Summative assessment can be used for determining if the required knowledge and skills have been obtained by the training;

(d) Criterion-referenced assessment is used for comparing individuals against standards, for example, job competencies;

(e) The norm-referenced assessment is only applicable if a comparison of an individual with a normative group is required and possible.

To ensure effective results, training processes and assessments should be directly related to the intended learning outcome, that is, the forecaster should be able to perform accurate and timely nowcasting. The articles of Bloom et al. (1956), Shane (1981) and Clark (1999) contain detailed explanations about Bloom's Taxonomy. This framework defines learning outcomes in terms of the level of cognitive processing required (Anderson and Krathwohl, 2001). Effective training for nowcasting skills will require learning outcomes at all levels of Bloom's Taxonomy. In other words, training participants will need opportunities to practice skills, receive feedback, and to be assessed on their attainment of these skills to assert that the training was successful for them. If nowcasting training does not achieve most of the learning outcomes it cannot be considered successful.

Evaluation of training

For the assessment of trainers, five dimensions have been identified that characterize those that are successful (Hattie, 2003). Such trainers can: identify essential aspects of their subject; guide learning through classroom interactions; monitor learning and provide feedback; attend to affective attributes; and influence student outcomes.

Evaluation is a method of measuring the worth of a learning opportunity; for example, whether the learning opportunity met its objectives and has impacts for the participants' performance in the workplace. It can answer questions such as "Were the learning methods appropriate for improving skills?", "Was the content relevant for nowcasting?", "Is the performance of nowcasting improved?". In Esterby-Smith (1994), four categories of training evaluation are specified. Kirkpatrick (1994) describes four levels of student evaluation (see also http://www.ct.gov/ctdn/lib/ctdn/ttt_14_m5_handouts2.pdf and *Guidelines for Trainers in Meteorological, Hydrological and Climate Services* (WMO-No. 1114), Chapter 8 (WMO, 2013*b*).

Guidance has been developed by WMO on how to evaluate the quality of training delivered in the context of the Organization's work. These recommended practices may already be met if an institution has national accreditation as a provider of vocational training, or can demonstrate that it carries out its training activities in accordance with the requirements of the International Organization for Standardization's Learning services for non-formal education and training – Basic requirements for service providers, ISO 29990:2010, or WMO.

4.3 NETWORKING

Without international cooperation it would be almost impossible for a particular training institute to deliver training in nowcasting that fulfils the requirements according to WMO. A lot of excellent training material and many skilled and experienced trainers and training managers are available. A selection of training bodies and projects will be described in this subsection.

World Meteorological Organization

The Organization is one of the most important sources to obtain guidance on training delivery, training organization, assessment, how to fulfil the requirements for an institute's training events and its personnel, and how an institute or its training events may become accredited. WMO also offers training and material for instructors.

The concept of the WMO Global Campus is being developed in a feasibility study that will be completed in June 2019. Its purpose is to assist WMO Regional Training Centres and national meteorological training centres to collaborate, coordinate and share more effectively to increase the availability of quality learning opportunities. A catalogue of training events and learning resources will help meteorological and hydrological services choose learning opportunities and training managers to find eligible trainers. The WMO Global Campus will provide quality assurance criteria that should be used as guidelines for training activities. The quality criteria fall into the three categories of product, processes and organization.

Community for the Advancement of Learning in Meteorology (CALMet)

The purpose of CALMet is to offer a platform to share experiences, expectations, ideas and strategies in meteorology education and training. Current activities and outcomes from workshops and online forums can be found at CALMet Commons (www.calmet.org). Trainers and training managers can receive help for solving training issues by using the available forums.

EUMETNET Working Group on Education and Training – EUMETCAL

EUMETCAL (www.eumetcal.eu), the education and training project of EUMETNET, is a European virtual organization for meteorological training with the following objectives:

(a) Promote and share evolving technologies and methodologies for the development of training activities and assist member States' organizations to address their training needs with advanced learning;

(b) Provide information about education and training activities;

(c) Respond to the training needs of EUMETNET NHMSs;

(d) Provide a forum for creating and exchanging training resources and implementing activities related to all meteorological aspects;

(e) Provide a mechanism whereby EUMETNET NHMSs collaborate to enhance their training capabilities on a long-term basis, with solid cooperation.

Several organizations provide resources that can be very useful for those conducting nowcast training. Below are four key examples to consider:

(a) WMO: The link www.caem.wmo.int/moodle/ leads to learning resources of aeronautical meteorology that can be also used for nowcast training. The link http://etrp.wmo.int/moodle/ contains resources for instructors and training managers. Additional assistance in education and training, also in relation to nowcasting, can be found in https://public.wmo.int/en/resources/training;

(b) EUMETSAT: The link http://www.eumetsat.int/website/home/Data/Training/index.html will lead the reader to training courses and a training library;

(c) European Meteorological Training (EUMETRAIN) (www.eumetrain.org): An international training project sponsored by EUMETSAT, offers training material (manuals, interactive training modules, case studies, online teaching and courses) and training support in the field of satellite meteorology;
(d) Cooperative Program for Operational Meteorology, Education and Training MetEd (COMET MetEd) (https://www.meted.ucar.edu/): Online training resources are available for all fields of meteorology, hydrology and climatology and for different target groups.

Further reading

Anderson, L.W. and D.R. Krathwohl (eds), 2001: *A Taxonomy for Learning, Teaching, and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives*. Complete edition. New York, Longman.

Bloom, B.S. (ed.), M.D. Engelhart, E.J. Furst, W.H. Hill and D.R. Krathwohl, 1956: *Taxonomy of Educational Objectives: The Classification of Educational Goals. Handbook I: Cognitive Domain*. New York, Longman.

Brown, P.C., H.L. Roediger III and M.A. McDaniel, 2014: *Make It Stick: The Science of Successful Learning*. Harvard University Press/Belknap.

Clark, D.R., 1999: Bloom's Taxonomy of Learning Domains, (updated 2015), http://www.nwlink.com/~donclark/hrd/bloom.html.

Dave, R.H., 1970: Psychromotor levels. In: *Developing and Writing Behavioral Objectives* (R.J. Armstrong, ed.). Tucson, Arizona, Educational Innovators Press.

Easterby-Smith, M., 1994: *Evaluating Management Development, Training and Education*. Brookfield, Vermont, Gower Publishing.

Hattie, J.A., 2003: Teachers make a difference. What is the research evidence? Presented at the Building Teacher Quality: What Does the Research Tell Us? Australian Council for Educational Research Annual Conference, Melbourne, 19–21 October.

Hattie, J.A., 2009: *Visible Learning: A Synthesis of over 800 Meta-analyses Relating to Achievement*. Oxford, Routledge.

Hattie, J.A. and H. Timperley, 2007: The Power of Feedback. *Review of Educational Research*, 77(1):81–112.

International Organization for Standardization, 2010: *Learning Services for Non-formal Education and Training – Basic Requirements for Service Providers*. ISO 29990:2010.

Kirkpatrick, D.L., 1994: *Evaluating training programs: The four levels.* San Francisco, Berrett-Koehler.

Krathwohl, D.R., B.S. Bloom and B.B. Masia, 1956: *Taxonomy of Educational Objectives: The Classification of Educational Goals. Handbook II: The Affective Domain*. New York, David McKay Company.

Shane, H.G., 1981: *Significant writings that have influenced the curriculum*: 1906–1981. *Phi Delta Kappan*, 62(5):311–314.

World Meteorological Organization, 2012: *Guide to the Implementation of Education and Training Standards in Meteorology and Hydrology, Volume I – Meteorology* (WMO-No 1083). Geneva.

———, 2013*a*: *Guide to the Implementation of a Quality Management System for National Meteorological and Hydrological Service*s (WMO-No. 1100). Geneva.

———, 2013*b*: *Guidelines for Trainers in Meteorological, Hydrological and Climate Services* (WMO-No. 1114). Geneva.

CHAPTER 5. APPLICATIONS

In contrast to NWP model development, which requires a deep examination of meteorological processes and underlying physics and mathematics, the development and design of nowcasting systems is more tailored to the specific needs of different types of users. Nowcasting plays a role in almost all sectors of the society, for traffic, power generation, warnings issued by authorities, and for the general public. The following sections are intended to give an overview of the current standard of knowledge with respect to these application areas.

5.1 AVIATION

An important aspect in nowcasting is the early detection of and the issuing of warnings to the aviation community of weather hazards (for example, thunderstorms, hail, tornadoes and icing) and the rapid dissemination of this information to end users.

5.1.1 Wind-shear detection

Particularly threatening to aircraft and the leading cause of aviation-related human fatalities are downbursts that occur on small scales, called microbursts, that have outflow speeds of >25 metres per second over distances of <4 kilometres. Pilots undergo aircraft simulator training to learn how to fly through microbursts, but due to the rapidly evolving nature of these phenomena and limited visual clues, accidents still occur.

Automated detection and nowcasting systems have been developed to alert air traffic controllers and pilots to the presence of wind shear over the runways. The least expensive of the horizontal wind-shear detection systems is the Low Level Wind-shear Alert System (LLWAS), which measures the horizontal wind speeds and directions using a set of strategically spaced surface anemometers that are optimally sited along the runways to obtain high-resolution calculations of wind shear from all angles. The wind-shear values exceeding specific thresholds over specific parts of the runway(s) are automatically relayed to the air traffic control tower for dissemination by controllers to pilots on approach or take-off.

A more expensive and accurate horizontal wind-shear alert system is obtainable from a Terminal Doppler Weather Radar (TDWR) located near the runways, or more typically at 10–15 kilometres from the airport. The TDWR provides information on rainfall rate, but more importantly, as a Doppler radar with high-resolution data spacing (150 metres), it is able to detect and quantitatively measure radial wind speeds associated with microbursts. Algorithms have been developed that automatically calculate the Doppler radial wind shear and render the shear measurements and location of the wind shear on a geographical situational display in the air traffic control tower for controllers to view and relay to pilots. Installation of LLWAS and TDWRs have reduced the number of wind-shear-related accidents and fatalities to zero over all the major airports in the United States. These automated systems have also been installed or are being installed in other countries around the world (for example, Burundi; Hong Kong, China; Dakar, Senegal; and Entebbe airport in Uganda).

Vertical wind shear is not always associated with convective activity. Profilers are key instruments for monitoring changes in vertical wind shear as they collect continuous vertical profiles of the total wind with high update frequencies. Profiler measurements are included in automated wind-shear detection systems at airports where nearby terrain has substantial impact on the airport weather (for example, the Juneau Airport Wind system (JAWS) running at Juneau Alaska Airport; the Hong Kong, China, Windshear and Turbulence Warning System (WTWS) running at the Hong Kong, China, International Airport).

5.1.2 Hail, tornado and thunderstorm detection

Lightning poses a significant threat to ground crew operations. Radar reflectivity thresholds are commonly used in automated techniques to indicate lightning within a storm, and then extrapolation techniques are applied to nowcasting to predict when these storms will reach the airport. Potentially more accurate, and less expensive, other techniques use arrays of lightning sensors to monitor the build up of electric fields and nowcast the lightning occurrence. The Rapidly Developing Thunderstorm product used in Europe and Africa is an example of an automated nowcasting system that combines satellite, lightning and storm extrapolation techniques to produce automated thunderstorm nowcasting products. Recently, effort has been directed at running NWP models that assimilate lightning data to provide location-specific nowcasting of lightning occurrence. The AutoNowcaster expert system combines radar, satellite, lightning, surface, soundings and NWP instability fields to detect and nowcast thunderstorms and nowcast lightning occurrence within a specified distance of ground operations.

The Consolidated Storm Prediction for Aviation is a blended system of radar observations with rapid update cycle, high-resolution (4 kilometres) NWP forecasts that is run operationally for the United States Federal Aviation Administration. It is a 0–8-hour nowcasting system that provides nowcasting of thunderstorm intensity and echo tops for enroute planning and weather avoidance. Other aviation nowcasting systems, such as the Convective Nowcasting Oceanic system blends polar orbital and GEO satellite observations with global model forecasts to produce 0–2-hour nowcasting of thunderstorm hazards (turbulence, icing and lighting) along aviation routes over the oceans.

Radar algorithms exist to automatically detect hail. Satellite data has been used as proxies in the identification of potential for hail. However, there are no automated operational techniques available for the aviation community that will produce nowcasting, watches or warnings for hail. The responsibility still resides with national weather service forecasters to alert the air traffic control and terminal area managers.

5.1.3 Visibility and fog detection

Nowcasting and displaying operationally significant changes in visibility, ceiling height and the onset or dissipation of fog continues to be a challenge. One and two dimensional fog models are being tested in various places throughout the world, but operational prediction is still problematic and the accuracy is not yet at the level needed for aviation operations. Most operational NWP models have low skill and significant biases in predicting low visibilities less than 3 miles (below the visual-flying-range limit for aviation), compared to the prediction of ceiling height restrictions, due to the lack of physics in the model for depicting visibility reductions. Multispectral satellite imagery could be useful in the detection of low cloud, fog and areas with likely reduced visibilities, but do not provide prediction of the onset and dissipation of fog. Automated aviation applications for nowcasting fog employ blended systems that combine surface station visibility and ceiling height measurements with NWP model forecasts to produce very short-term detection and nowcasting products. One nowcasting system that has shown improved accuracy in the United States and is used operationally by United States National Weather Service forecasters, aviation forecasters, and airline meteorologists is a system that ingests surface sensor data in four different NWP models and provides a consensus forecast of the time that low clouds and fog will clear the approach runways of an airport.

5.1.4 Icing detection

Inflight icing has been a factor in aircraft accidents and can create significant disruption of flight operations. Two systems are run in the United States to diagnose and forecast icing conditions, the Current Icing Product and the Forecasting Icing Product, respectively. These algorithms combine numerical model output with satellite imagery, radar reflectivity, surface observations and pilot reports to identify and predict likely locations for in-flight icing conditions. Research has shown that dual-polarization radars have potential for detecting icing over a wide variety of weather conditions. A radar icing algorithm combines dual-polarization radar fields with

NWP model temperature profiles to detect elevated icing hazard regions and produces an in-flight icing hazard index. An additional icing detection system called the Icing Remote Sensing System has been developed that consists of a K-band radar, microwave profiling radiometer and ceilometer. This combination of instruments also has a high success rate in detecting icing conditions.

The accumulation of ice on taxiways, runways and aircraft due to freezing precipitation also greatly impacts the safety and efficiency of aviation. The Weather Support to Deicing Decision Making system, developed in the United States by the National Center for Atmospheric Research (NCAR) Research Applications Laboratory, is a real-time, operational system run at airports that provides aviation users with current and short-term forecasts of weather conditions, including the liquid-equivalent snowfall rate during winter storms. The system combines radar reflectivity information with precipitation rate from a network of surface precipitation gauges and uses a cross-correlation tracking algorithm to produce 60-minute nowcasting of precipitation rate on the ground. The system also provides alert information when icing conditions (freezing drizzle, freezing rain, freezing fog, and frost) are observed. Displays at the operational facilities of the airport show the detection and nowcasting products, giving airport operations personnel the ability to observe and monitor changing weather conditions in real time.

5.2 ROADS

Most of the European road maintenance services use a maintenance decision support system to trigger alarms. But the requirement to obtain additional nowcasting information about the character of the expected weather event and about the reliability of the information gained is increasing (Table 5.1). One aim is to increase the preparedness of the road management units (road winter services) and to consider more effectively the environmental and economic aspects (less salt, less cost). Thus, detailed and timely forecasts for special meteorological events (snowfall, freezing drizzle, drifting snow, wind gusts, fog and other causes of reduced visibility, black ice and storm) are required, including the exact starting time of the event and its estimated duration.

In recent years, road maintenance agencies worldwide have shifted from reactive to proactive strategies for snow and ice control, such as anti-icing. Compared to traditional methods for snow and ice control (for example, de-icing and sanding), anti-icing leads to decreased applications of chemicals and abrasives, decreased maintenance costs, improved level of service, and lower accident rates. Reliable road weather nowcasting on high temporal and spatial resolution are the key to a successful anti-icing programme, as the pavement surface temperature dictates the timing for anti-icing applications and the appropriate application rate.

The basic impulse for an immediate start of operations (spreading, ploughing, etc.) is given by the parameter precipitation and its intensity. Precipitation may occur in form of rainfall, snowfall, or a combination of both, which may end in black ice formation at a certain temperature level. The most critical situations arise when the road conditions are not apparent and are changing rapidly at a local scale.

5.3 MARINE

To forecast marine weather phenomena, variables and parameters, marine forecasters are required to diagnose past and present conditions to produce analyses and short-term forecasts. Marine forecasters are required to issue forecasts and warnings for hazardous weather phenomena, variables and parameters (Table 5.2), including spatial extent, onset and cessation, duration, and intensity and its temporal variations.

Warnings and forecasts of different weather phenomena and parameters should be in accordance with the *Manual on Marine Meteorological Services* (WMO-No. 558), Volume I – Global Aspects, and Volume II – Regional Aspects, and/or national standard operating procedures.

Table 5.1. Required nowcasting parameters and their resolutions

Nowcasting parameter	*Importance for nowcasting of road conditions*	*Time increment/ spatial resolution*	*Temporal resolution (accuracy*)*
Total precipitation	Very	15–30 min/≤1 km	15 min
Precipitation type	Very	15–30 min/1 km	15 min
Radiation fluxes	Very	30 min/1 km	30–60 min
Temperature (2 m above ground)	Very	60 min/1 km	60 min (RMSE <2K)
Dew point temperature (2 m above ground)	Very	60 min/1 km	60 min
Temperature (surface, pavement)	Very	60 min/1 km	30 min (RMSE <2K)
Relative humidity (2 m above ground)	Moderately	60 min/1 km	60 min
Wind speed and wind direction (10 m above ground)	Very	60 min/1 km	30–60 min (RMSE <2 m/s)
Cloud cover (especially low clouds)	Very	30 min/1 km	30–60 min
Fog	Very	30 min/1 km	30–60 min

* RMSE: Root mean squared error.

Marine forecasters should ensure that forecasts of weather parameters and phenomena are consistent (spatially and temporally) across boundaries of the area of responsibility as far as practicable, whilst maintaining meteorological integrity. This will include monitoring forecasts and warnings issued for other regions, and liaison with adjacent regions as required.

Table 5.2. Required weather phenomena, parameters and variables for marine forecasting and warnings

Nowcasting parameter	*Routine marine forecasting*	*Hazardous phenomena*
Wind	Directional variability, speed and wind gusts	Wind hazards
Sea state	Waves or multiple swell systems	Unusual and hazardous wave/ current conditions
Precipitation	Associated horizontal visibilities	Heavy precipitation with poor horizontal visibility
Fog or mist	Associated horizontal visibilities	Poor horizontal visibility
Other types of visibility obscuration (smoke, dust, haze, sandstorms, duststorms, blowing snow, volcanic ash/rock)	Associated horizontal visibility	Poor horizontal visibility
Sea-ice state	Freezing spray or precipitation, snowfall Icing on vessels or structures	Exceptional and rapidly changing sea-ice conditions Icebergs
Synoptic situation for tropical, sub-tropical, temperate and polar climate zones as required	Major weather systems, anticyclones, low-pressure systems, fronts, thunderstorms, downburst/microburst, squalls or gust fronts, hail, tornadic/water spout activity	Tropical cyclones and their movement Storm-induced abnormal water (sea) levels: sea-level and storm-surge harbour seiches

To communicate meteorological information to internal and external users, marine forecasters should (a) ensure that all forecasts and warnings are disseminated via the authorized communication channels to user groups; (b) provide marine weather briefings as necessary and provide consultation to meet specific user needs; (c) make use of forecasts and warnings of meteorological parameters, variables and phenomena to describe their impact on marine operations, safety of life and property – including the coastal environment and population.

5.4 HYDROLOGY

For hydrological forecasts, precipitation inputs are of major importance, since the accuracy of calculation of discharge forecast depends on the accuracy not only of analysed but also of predicted precipitation sums. A nowcasting system used for applications in hydrology should feature the following characteristics:

(a) *High spatial and temporal resolution of the precipitation fields*

One kilometre resolution or higher is recommended if the density of rain gauge data and the coverage with radar data allow for it. For large catchment areas, a coarser resolution or simplified precipitation field might be used as well, but the latter should always be derived from fields with higher resolution.

(b) *High update frequency of the nowcasting fields*

Small rivers can rise in a remarkably short period of time, and therefore a 5-minute update frequency – as is provided by certain nowcasting systems – is optimal; however, 15–minute updates are sufficient in most cases. The precipitation fields should be made available to the forecasters as soon as possible; a delay (for example, caused by late data transmission from rain gauges and their transfer) of greater than 10–15 minutes could result in late warnings.

(c) *Probabilistic nowcasting of precipitation*

Precipitation forecasts are often subject to uncertainties, especially in convective situations, and there is increasing need for probabilistic information, that is, an ensemble of scenarios allowing hydrologists to better assess the spread of the predicted precipitation sums.

Flash floods are among the most deadly disasters affecting most countries in the world. The Flash Flood Guidance System (www.wmo.int/pages/prog/hwrp/flood/ffgs/index_en.php) is a hydrometeorological modelling system implemented through a global programme of WMO in various developing regions in the world. It combines near-real-time remote sensing of rainfall amounts by satellite (or radar if available) with data from geographical information systems and NWP precipitation fields to provide guidance on the potential of flash floods over small basins for the 6 hours to come. It is a diagnostic tool for NMHS forecasters of information on the hydrological state of small basins to be used alongside other data and tools (nowcasting and forecasting) to develop warnings for flash floods.

5.4.1 Landslides

Landslides are, in the majority of cases, triggered by heavy or prolonged rainfall episodes, also aggravated by contributing factors such as deforestation. These episodes either take the form of an exceptional short-lived event, such as the passage of a tropical cyclone or even the rainfall associated with a particularly intense thunderstorm, or of a long-duration rainfall event with lower intensity, such as the cumulative effect of monsoon rainfall in South Asia. Although the characteristics of rainfall are critical to the initiation of slope failure, currently no system provides a real-time global overview of rainfall conditions that may trigger landslides. Such a system requires fine-scale precipitation information that is available continuously in time and space. Conventional ground-monitoring networks for precipitation information are largely inadequate for this purpose, particularly in many developing countries, due to insufficient hydrometeorological networks, long delays in data transmission, and the lack of data sharing in many transboundary river basins. As a result, altitude has been used as an approximate surrogate for precipitation to help stratify landslide hazards because few regions with complex terrains have a well-maintained precipitation monitoring network (Sidle and Ochiai, 2006). The National Aeronautics and Space Administration Tropical Rainfall Measuring Mission multi-satellite precipitation analysis product provides an opportunity to evaluate how rainfall attributes affect the spatial distribution and timing of landslides in regions that suffer from scarce in situ data (Hong et al., 2006). The co-occurrence of satellite precipitation and landslide reports may serve as a valuable indicator for characterizing the spatio-temporal distribution of landslide-prone areas to establish a global rainfall-triggered landslide climatology (Kirschbaum et al., 2012*a*).

Considerable efforts have been made to understand the triggers for landsliding in natural systems mainly based on rainfall intensity and duration (see, for example, Caine, 1980; Brand et al., 1984; Larsen and Simon, 1993; Ahmad, 1995; Corominas and Moya, 1999). Other techniques that can be used to try to understand rainfall triggers include:

(a) Actual rainfall techniques, in which measurements of rainfall are adjusted for potential evapotranspiration and then correlated with landslide movement events;

(b) Hydrogeological balance approaches, in which pore water pressure response to rainfall is used to understand the conditions under which failures are initiated;

(c) Coupled rainfall–stability analysis methods, in which models for pore water pressure response and slope stability are coupled to try to understand the complexity of the system;

(d) Numerical slope modelling, in which finite-element (or similar) models are used to try to understand the interactions of all relevant processes.

5.5 GENERAL PUBLIC

5.5.1 General public nowcasting requirements

Population and economic growth have increased the number of lives at risk to severe weather and the financial impacts resulting from severe storms. Meanwhile, the modernization of societies means that meteorological information is now indispensable to people’s daily lives. Compared to the more specific and narrower requirements for nowcasting products in specialized areas (such as roads, hydrology and marine), requirements of general-public nowcasting bring a wider variety of expectations on nowcasting products, not only on severe weather phenomena but also on different kinds of elements that are relevant to safety, health, daily life, tourism and entertainment.

There are distinct characteristics of demand and application of general-public nowcasting compared to the specialized areas discussed previously, such as wide coverage on weather phenomena and meteorological variables, diverse capabilities in weather-information-dependent decision-making, and with different conditions of receiving and accessing meteorological information. Despite the increasingly sophisticated demands on general-public nowcasting, from the perspective of protecting lives and livelihoods the most important information from nowcasting for the public is the warning of severe weather.

5.5.2 Categories of nowcasting products

Based on the characteristics of nowcasting products, 0–6-hour products for public interests can be considered in four categories: (a) severe weather warning; (b) nowcasting of meteorological elements; (c) nowcasting of meteorological indexes; (d) information on observations. The rapid expansion of technology in today's society provides more sophisticated data delivery mechanisms that provide specific information, guidance, and decision-support tools for the general public. However, ways of achieving timely reception and easy access to nowcasting information for the general public may differ from place to place due to diverse infrastructure conditions and economic status. Table 5.3 lists typical 0–6-hour nowcasting products for general-public purposes and ways to deliver and access them.

Table 5.3. Typical 0–6-hour nowcasting products for the general public

Forecast category	*Parameters*	*Temporal resolution/update/ upgrade frequency*	*Spatial resolution*	*Delivery/access*
Warning in signal flags	Typhoon/hurricane Torrential rainfall Lightning Hail Gust wind Tornado (in the United States) Fog Road icing Heatwave Cold wave Haze Duststorm	3 hours (generally) Upgrade depends on the weather evolution	Impact area within city/ town/county	Television/radio/ Internet/ Mobile phones Public transport and public screens Typhon/wireless alarm buzzer
Meteorological elements	Precipitation T2m Rh2m Wind 10 metres Visibility Cloud cover	60 minutes	1–3 km in city 5–10 km in rural environment	Television/radio/ Internet/ Mobile phones Public transport and public screens
Meteorological indices	Air-quality index PM2.5/PM10 CO/NO_2/SO_2 UV-index Pollen index	60 minutes	10–50 km	Television/radio/ Internet/ Mobile phones Public transport and public screens
Observations	Satellite/radar echo/ lightning images (for typhoon/convections)	<10 minutes	Impact areas: 5 km in city	Internet Mobile phones
	Precipitation/T2m/Rh2m/ Wind 10 m	10 minutes	10–20 km in rural environment	
	Visibility/Cloud cover	10 minutes	10–50 km	
	PM2.5/PM10	10 minutes	10–50 km	

Notes:
PM2.5/10: Atmospheric particulate matter having diameter of less than 2.5 or 10 micrometres.
T2m: Temperature at 2 metres.
Rh2m: Relative humidity at 2 metres.

5.5.3 **Outreach and education on nowcasting products**

Adequate application of nowcasting products and correct response to the warnings could significantly contribute to the optimization of protective measures and reduction of losses due to disasters. Therefore, public outreach and education is a critical component of nowcast applications, especially in the transition from the “text-based” traditional way of nowcasting products to evolve into the digital/image age. The fundamental elements for public outreach and education are (a) what the warnings of different grades (in signal flags) mean; (b) what their corresponding risks/hazards and impacts would be; (c) what kinds of proper actions should be taken for safety. Also, the uncertainties within nowcasting information for different weather phenomena and for meteorological elements should be included in public outreach and education.

5.6 CIVIL PROTECTION

Severe weather-related events (for example, floods, storms and droughts) often threaten lives and property and can lead to serious economic losses, despite the rapid development in modern technologies. Civil protection from natural disasters may require an enhanced organization, predominantly in the awareness and preparedness of the general public. Moreover, civil protection operations are only successful when rescue teams are well coordinated, which is strongly dependent on accurate real-time information (weather situation, alerts, and the like). Warning and alerting are essential parts of emergency management. Timely and appropriate warning and alerting of authorities, emergency response organizations and the general public of impending hazards can significantly contribute to the optimization of protective measures and the reduction of disaster losses. Within the United Nations International Strategy for Disaster Reduction, early warnings have a special status. Within the system of warning and alerting, three decision-making processes are relevant:

(a) The definitions of thresholds and criteria for warnings, as well as the ongoing monitoring and early detection of hazards that might exceed a given threshold level (for example, precipitation, thunderstorms, hail or pollutant concentrations) that trigger a warning;

(b) The organization responsible for the warning dissemination specifying the content of the warning message and the mode of disseminating the warning (for example, siren, media announcements, SMS or alarm) to inform the target audience;

(c) The reaction to the warning.

Weather services face the challenge of issuing improved weather warnings for the general public at a high update frequency and with more precise geographical specification. To satisfy all these requirements, an analysis and nowcasting system cannot be restricted to weather stations but needs to be operated on a high-resolution grid. A grid of 1 kilometre is a sufficiently high resolution to reproduce slope inclinations on the sidewalls of major valleys. The nowcasting system should take into account, as far as possible, all available data sources (NWP model results, station data, radar data (also with 1 kilometre spatial resolution), satellite data, radio soundings, etc.) and use them to construct physically consistent analyses of atmospheric fields.

False alarms cause financial losses and may result in people losing their confidence in weather services and civil protection authorities. The availability and reliability of weather information directly affects the quality of warnings and thus the efficiency of security measures to mitigate damage to life or property (see Figure).

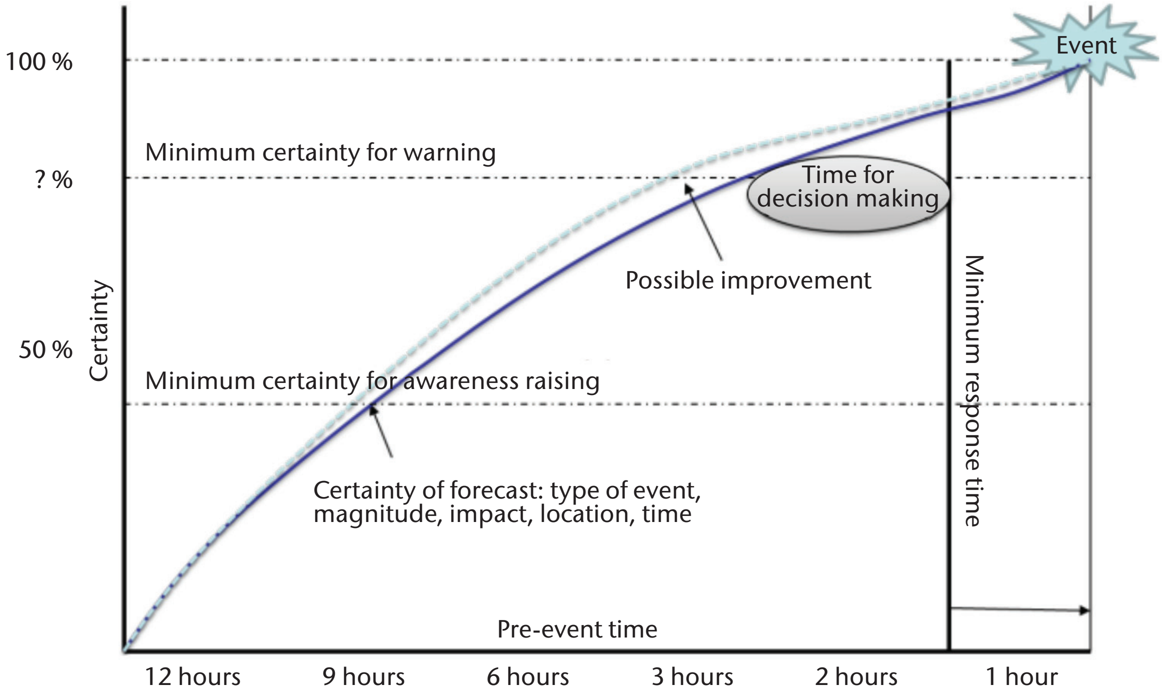
5.7 RENEWABLE ENERGY

Wind and solar power are presently considered as the sources of renewable energy with the best chance of competing with fossil-fuel energy production in the near future.

However, the optimum integration of electricity produced by future wind turbines and solar-power plants demands an accurate wind- and solar-energy potential availability, evaluation and forecast. What happens when these conditions are not met? As an example, if the uncertainty level in the estimates of mean wind were 10%, this could lead to a 30% error in power production.

Long-term averages based mainly on historical measurement data are usually used for the resource assessments of sites being considered for the installation of wind farms or solar power plants. Once this is done, forecasting tools are applied for short-term information – 1 to 72 hours in advance depending on the usage – on the production.

Different timescales have to be considered for renewable energy production forecasting. For very short-term prediction (from 30 minutes to 3 hours), persistence forecasting is presently used in the case of wind energy based on the simple assumption that the wind speed will not change



General illustration of the relation between the quality of forecasts, pre-warning time, response time and time for decision-making

Source: Mileti and Sorensen (1990)

dramatically in the very short term. The situation is different – and more difficult – for solar energy, where extremely rapid changes in the local cloud cover may induce dramatic changes in the output of the individual power plant.

These very short-term predictions are much more difficult in complex terrain where the topography may dramatically decrease the accuracy of the prediction (turbulence effects, local wind conditions, etc.). In addition, harsh weather conditions (for example, icing) are a further weather-dependent source of potential failures for energy production and distribution.

Nowcasting techniques, along with the use of NWP models, and in combination with post-processing techniques such as downscaling and the online assimilation of in situ and regional ground-based or remote-sensing measurements may add substantial value to short-time forecasts.

References/further reading

Aviation

Aviation Weather Center, inflight icing diagnosis and prediction products, http://www.aviationweather.gov/adds/icing.

Cooperative Program for Operational Meteorology, Education and Training MetEd (COMET MetEd), ASMET 7 aviation-related training module: Forecasting Fog for Aviation – Kenya Case Study, https://www.meted.ucar.edu/asmet/e_africa_a7.

———, Nowcasting for Aviation in Africa, https://www.meted.ucar.edu/avn_int/nowcasting.

Cornman, L.B., R.K. Goodrich and C.S. Morse, 1998: A fuzzy-logic method for improved moment estimation from Doppler spectra. *Journal of Atmospheric and Oceanic Technology*, 15:1288–1306.

Donovan, M., E. Williams, C. Kessinger, G. Blackburn, P.H. Herzegh, R.L. Bankert, S.D. Miller and F.R. Mosher, 2008: The identification and verification of hazardous convective cells over oceans using visible and infrared satellite observations. *Journal of Applied Meteorology and Climatology*, 47:164–184.

Fujita, T.T. and H.R. Byers, 1977: Spearhead echo and downburst in the crash of an airliner. *Monthly Weather Review*, 105:129–146.

Fujita, T.T. and F. Caracena, 1977: An analysis of three weather-related aircraft accidents. *Bulletin of the American Meteorological Society*, 58:1164–1181.

Goodrich, R.K., C. Morse, L.B. Cornman and S.A. Cohn, 2002: A horizontal wind and wind confidence algorithm for Doppler wind profilers. *Journal of Atmospheric and Oceanic Technology*, 19:257–273.

International Civil Aviation Organization, 2005: *Manual on Low-level Wind Shear*. Doc 9817 AN/449. Montréal, Quebec.

Kessinger, C., M. Donovan, R. Bankert, E. Williams, J. Hawkins, H. Cai, N. Rehak, D. Megenhardt and M. Steiner, 2008: Convection diagnosis and nowcasting for oceanic aviation applications. In: *Remote Sensing Applications for Aviation Weather Hazard Detection and Decision Support* (W.F. Feltz and J.J. Murray, eds). Proceedings of SPIE, 7088(08).

McCarthy, J., J.W. Wilson and T.T. Fujita, 1982: The Joint Airport Weather Studies Project. *Bulletin of the American Meteorological Society*, 63:15–22.

Morse, C.S., R.K. Goodrich and L.B. Cornman, 2002: The NIMA method for improved moment estimation from Doppler spectra. *Journal of Atmospheric and Oceanic Technology*, 19:274–295.

Mueller, C., T. Saxen, R. Roberts, J. Wilson, T. Betancourt, S. Dettling, N. Oien and J. Yee, 2003: NCAR Auto-Nowcast system. *Weather and Forecasting*, 18:545–561.

Pinto, J., W. Dupree, S. Weygandt, M. Wolfson, S. Benjamin and M. Steiner, 2010: Advances in the consolidated storm prediction for aviation (CoSPA). Paper presented at the Fourteenth Conference on Aviation, Range and Aerospace Meteorology, American Meteorological Society, Atlanta, 18–21 January.

Rasmussen, R., M. Dixon, S. Vasiloff, F. Hage, S. Knight, J. Vivekanandan and M. Xu, 2003: Snow nowcasting using a real-time correlation of radar reflectivity with snow gauge accumulation. *Journal of Applied Meteorology*, 42:20–36.

Roberts, R.D. and J.W. Wilson, 1989: A proposed microburst nowcasting procedure using single-Doppler radar. *Journal of Applied Meteorology*, 28:285–303.

Shun, C.M. and S.S.Y. Lau, 2000: Terminal Doppler Weather Radar (TDWR) observation of atmospheric flow over complex terrain during tropical cyclone passages. In: *Microwave Remote Sensing of the Atmosphere and Environment II*. Proceedings of SPIE 4152(42), doi:10.1117/12.410622.

Wilson, J.W., R.D. Roberts, C.K. Kessinger and J. McCarthy, 1984: Microburst wind structure and evaluation of Doppler radar for airport wind shear detection. *Journal of Applied Meteorology*, 23:898–915.

Low-level wind-shear alert systems

Keohan, C., 2007: Ground-based wind shear detection systems have become vital to safe operations. *International Civil Aviation Organization Journal*, 62(2):16–20, https://www.icao.int/publications/journalsreports/2007/6202_en.pdf.

Terminal Doppler weather radar

Massachusetts Institute of Technology Lincoln Laboratory, https://www.ll.mit.edu/mission/aviation/faawxsystems/tdwr.html.

Roads

Carmichael, C.G., W.A. Gallus, B.R. Temeyer and M.K. Bryden, 2004: A winter index for estimating winter roadway maintenance costs in the Midwest. *Journal of Applied Meteorology*, 43:1783–1790.

Chen, D., T. Gustavsson and J. Bogren, 1999: The applicability of similarity theory to a road surface. *Meteorological Applications*, 6:81–88.

Cooperative Program for Operational Meteorology, Education and Training MetEd (COMET MetEd) Weather and Road Management module, http://meted.ucar.edu/dot/index.htm.

Crevier, L.P. and Y. Delage, 2001: METRo: A new model for road-condition forecasting in Canada. *Journal of Applied Meteorology*, 40:2026–2037.

Delage, Y., 1974: A numerical study of the nocturnal atmospheric boundary layer. *Quarterly Journal of the Royal Meteorological Society*, 100:351–364.

———, 1997: Parameterising sub-grid scale vertical transport in atmospheric models under statically stable conditions. *Boundary-Layer Meteorology*, 82:23–48.

Delage, Y. and C. Girard, 1992: Stability functions correct at the free convection limit and consistent for both the surface and Ekman layers. *Boundary-Layer Meteorology*, 58:19–31.

Federal Highway Administration (FHWA), 2004: *Clarus – America's 21st Century Surface Transportation Weather Observing and Forecasting System.* Publication No. FHWA-HOP-04-037. Road Weather Management Program, Office of Transportation Operations.

Haiden, T., A. Kann, C. Wittmann, G. Pistotnik, B. Bica and C. Gruber, 2011: The Integrated Nowcasting through Comprehensive Analysis (INCA) system and its validation over the eastern Alpine region. *Weather and Forecasting*, 26:166–183.

Hertl, S. and G. Schaffar, 1998: An autonomous approach to road temperature prediction. *Meteorological Applications*, 5:227–238.

Jacobs, W. and W.E. Raatz, 1996: Forecasting road-surface temperatures for different site characteristics. *Meteorological Applications*, 3:243–256.

Mailhot, J., S. Bélair, R. Benoit, B. Bilodeau, Y. Delage, L. Fillion, L. Garand, C. Girard and A. Tremblay, 1998: Scientific Description of RPN Physics Library – version 3.6. Quebec, Recherche en Prévision Numérique, Meteorological Service of Canada.

Meirold-Mautner, I., Y. Wang, A. Kann, B. Bica, C. Gruber, G. Pistotnik and S. Radanovics, 2010: Integrated nowcasting system for the Central European area: INCA-CE. In: *Data and Mobility, Advances in Intelligent and Soft Computing (J.* Düh, H. Hufnagl, E. Juritsch, R. Pfliegl, H.K. Schimany and H. Schönegger, eds), 81:107–114. Berlin, Springer, doi:10.1007/978-3-642-15503-1_10.

Norrman, J., 2000: Slipperiness on roads – an expert system classification. *Meteorological Applications*, 7:27–36.

Office of the Federal Coordinator for Meteorology (OFCM), 2002: Weather Information for Surface Transportation: A National Needs Assessment Report. Report No. FCM-R18-2002. Silver Spring, Maryland, OFCM.

Permanent International Association of Road Congresses (PIARC), 2010: *Snow and Ice Databook*. Quebec, Winter Service, PIARC, http://www.piarc.org/en/order-library/6727-en-Snow%20and%20ice%20databook,%202010.htm.

Rayer, P.J., 1987: The Meteorological Office forecast road surface temperature model. *Meteorological Magazine*, 116:180–191.

Sass, B.H., 1992: A numerical model for prediction of road temperature and ice. *Journal of Applied Meteorology*, 31:1499–1506.

———, 1997: A numerical forecasting system for the prediction of slippery roads. *Journal of Applied Meteorology*, 36:801–817.

Shao, J., J.E. Thornes and P.J. Lister, 1993: Description and verification of a road ice prediction model. *Transportation Research Record*, 1387:216–222.

Standing International Road Weather Conference (SIRWEC), proceedings 1984 to 2016 (every second year), www.sirwec.org.

Thornes, J.E., 1995: A comparative real-time trial between the UK Met. Office and ocean routes to predict road surface temperature. *Meteorological Applications*, 7:27–36.

Thornes, J.E. and D.B. Stephenson, 2001: How to judge the quality and value of weather forecast products. *Meteorological Applications*, 8:307-314.

White, S.P., J.E. Thornes and L. Chapman, 2006: A Guide to Road Weather Systems. SIRWEC, http://www.sirwec.org/documents/rwis_web_guide.pdf.

Wikelius, M.J., E.J. Fleege, J.L. Rockvam and R. Bamford, 1996: Integrated state-wide road/weather information system in Minnesota. Presented at the *Fourth International Symposium on Snow Removal and Ice Control Technology,* Reno, Nevada, 11–16 August, Transportation Research Board.

Ye, Z., C. Strong, L. Fay and X. Shi, 2009: Cost Benefits of Weather Information for Winter Road Maintenance. Final report. Montana State University College of Engineering for Iowa Department of Transportation, https://westerntransportationinstitute.org/wp-content/uploads/2016/08/4W1576_Final_Report.pdf.

Marine

Ad hoc Task Team on Marine Competency Requirements, 2014: Marine Weather Forecasters Competence Standards Framework (updated 2016), Intergovernmental Oceanographic Commission of UNESCO, http://www.ioc-unesco.org/index.php?option=com_oe&task=viewDocumentRecord&docID=13093.

World Meteorological Organization, 2012: *Manual on Marine Meteorological Services* (WMO-No. 558). Geneva.

Hydrology

Basist, A., G.D. Bell and V. Meentemeyer, 1994: Statistical relationships between topography and precipitation. *Journal of Climate*, 7:1305–1315.

Benoit, R., P. Pellerin, N. Kouwen, H. Ritchie, N. Donaldson, P. Joe and E.D. Soulis, 2000: Toward the use of coupled atmospheric and hydrologic models at regional scale. *Monthly Weather Review*, 128:1681–1706.

Chen, F. and J. Dudhia, 2001: Coupling an advanced land surface-hydrology model with the Penn State-NCAR MM5 Modeling System. Part I: model implementation and sensitivity. *Monthly Weather Review*, 129(4):569–585.

Daly, C., R.P. Neilson and D.J. Phillips, 1994: A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *Journal of Applied Meteorology*, 33:140–158.

Duan, Q., S. Sorooshian and V.K. Gupta, 1992: Effective and efficient global optimization for conceptual rainfall-runoff models. *Water Resources Research*, 28(4):1015–1031.

Entekhabi, D. and P.S. Eagleson, 1989: Land surface hydrology parameterization for atmospheric general circulation models including subgrid scale spatial variability. *Journal of Climate*, 2(8):816–831.

Fekete, B.M., C.J. Vörösmarty, J.O. Roads and C.J. Willmott, 2004: Uncertainties in precipitation and their impacts on runoff estimates. *Journal of Climate*, 17(2):294–304.

Goovaerts, P., 2000: Geostatistical approaches for incorporating elevation into the spatial interpolation of rainfall. *Journal of Hydrology*, 228:113–129.

Guan, H., J.L. Wilson and O. Makhnin, 2005: Geostatistical mapping of mountain precipitation incorporating autosearched effects of terrain and climatic characteristics. *Journal of Hydrometeorology*, 6:1018–1031.

Gupta, H.V., H. Kling, K.K. Yilmaz and G.F. Martinez, 2009: Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. *Journal of Hydrology*, 377:80–91.

Haiden, T., M. Kerschbaum, P. Kahlig and F. Nobilis, 1992: A refined model of the influence of orography on the mesoscale distribution of extreme precipitation. *Hydrological Sciences Journal*, 37:417–427.

Janál, P. and M. Starý, 2012: Fuzzy model used for the prediction of a state of emergency for a river basin in the case of a flash flood – Part 2. *Journal of Hydrology and Hydromechanics*, 60(3):162–173.

Jasper, K., J. Gurtz and H. Lang, 2002: Advanced flood forecasting in Alpine watersheds by coupling meteorological observations and forecasts with a distributed hydrological model. *Journal of Hydrology*, 267:40–52.

Jasper, K. and P. Kaufmann, 2003: Coupled runoff simulations as validation tools for atmospheric models at the regional scale. *Quarterly Journal of the Royal Meteorological Society*, 129:673–692.

Kahl, B. and H.P. Nachtnebel, 2008: Online updating procedures for flood forecasting with a continuous rainfall-runoff-model. In: *Flood Risk Management: Research and Practice* (P. Samuels, S. Huntington, W. Allsop and J. Harrop, eds). CRC Press.

Kann, A. and T. Haiden, 2005: The August 2002 flood in Austria: Sensitivity of precipitation forecast skill to area size and duration. *Meteorologische Zeitschrift*, 14:369–377.

Kiefer Weisse, A. and P. Bois, 2001: Topographic effects on statistical characteristics of heavy rainfall and mapping in the French Alps. *Journal of Applied Meteorology*, 40:720–740.

Kling, H. and H. Gupta, 2009: On the development of regionalization relationships for lumped watershed models: The impact of ignoring sub-basin scale variability. *Journal of Hydrology*, 373:337–351.

Komma, J., C. Reszler, G. Blöschl and T. Haiden, 2007: Ensemble prediction of floods – catchment non-linearity and forecast probabilities. *Natural Hazards and Earth System Sciences*, 7:431–444.

Kunstmann, H. and C. Stadler, 2005: High resolution distributed atmospheric-hydrological modeling for Alpine catchments. *Journal of Hydrology*, 314:105–124.

Kyznarová H. and P. Novák, 2009: CELLTRACK – Convective cell tracking algorithm and its use for deriving of life cycle characteristics. *Atmospheric Research*, 93:317–327.

Nash, J.E. and J.V. Sutcliffe, 1970: River flow forecasting through conceptual models – Part I. A discussion of principles. *Journal of Hydrology,* 10(3):282–290.

Novák P. (2007): The Czech Hydrometeorological Institute's severe storm nowcasting system. *Atmospheric Research*, 83(2–4):450–457.

Šálek, M., L. Březková and P. Novák, 2006: The use of radar in hydrological modelling in the Czech Republic – case studies of flash floods. *Natural Hazards and Earth System Sciences*, 6:229–236.

Stanzel, P., B. Kahl, U. Haberl, M. Herrnegger and H.P. Nachtnebel, 2008: Continuous hydrological modelling in the context of real-time flood forecasting in alpine Danube tributary catchments. *IOP Conference Series: Earth and Environmental Science*, 4:012005.

Starý, M. and B. Tureček, 2000: Operative control and prediction of floods in the River Odra basin. In: *Flood Issues in Contemporary Water Management* (J. Marsalek, W.E. Watt, E. Zeman and F. Sieker, eds). NATO Science Series, Volume 71, Series 2: Environment security, Kluwer Academic Publishers.

The Nurture Nature Center, Social Science – Focus on Floods, Annotated Bibliography of Hazard and Flood-related Articles, http://socialscience.focusonfloods.org/bibliography/.

Wood, S.J., D.A. Jones and R.J. Moore, 2000: Accuracy of rainfall measurement for scales of hydrological interest. *Hydrology and Earth System Sciences*, 4(4):531–543.

Landslides

Ahmad, R., 1995: Landslides in Jamaica: Extent, significance and geological zonation. In: *Environment and Development in Small Island States: The Caribbean* (D. Barker and D.F.M. McGregor, eds). Kingston, The Press, University of the West Indies.

Baum, R.L., J.W. Godt and W.Z. Savage, 2010: Estimating the timing and location of shallow rainfall-induced landslides using a model for transient, unsaturated infiltration. *Journal of Geophysical Research*, 115:F03013, doi:10.1029/2009JF001321 (corrected 2013: doi: 10.1002/jgrf.20100).

Borga, M., G.D. Fontana and F. Cazorzi, 2002: Analysis of topographic and climatic control on rainfall-triggered shallow landsliding using a quasi-dynamic wetness index. *Journal of Hydrology*, 268:56–71.

Brand, E.W., J. Premchitt and U.B. Phillipson, 1984: Relationship between rainfall and landslides in Hong Kong. In: *Proceedings of the Fourth International Symposium on Landslides* (Toronto, 16–21 September). Ontario, Canadian Geotechnical Society.

Caine, N., 1980: The rainfall intensity-duration control of shallow landslides and debris flows. *Geografisca Annaler*, 62A:23–27.

Cannon, S.H., 1988: Regional rainfall-threshold conditions for abundant debris-flow activity. In: *Landslides, Floods, and Marine Effects of the January 3–5, 1982, Storm in the San Francisco Bay Region, California*. Reston, Virginia, US Geological Survey (*US Geological Survey Professional Paper* 1434).

Cannon, S.H. and S.D. Ellen, 1985: Rainfall conditions for abundant debris avalanches in the San Francisco Bay region, California. *California Geology*, 38(12):267–272.

Centre for Research on the Epidiology of Disasters (CRED): Emergency Events Database – the International Disaster Database, http://www.emdat.be/.

Chleborad, A.F., R.L. Baum and J.W. Godt, 2006: Rainfall Thresholds for Forecasting Landslides in the Seattle, Washington, Area – Exceedance and Probability. US Geological Survey open-file report 2006-1064. Reston, Virginia, US Geological Survey.

Corominas, J. and J. Moya, 1999: Reconstructing recent landslide activity in relation to rainfall in the Llobregat River basin, Eastern Pyrenees, Spain. *Geomorphology*, 30:79–93.

Croizer, M.J., 1986: *Landslides: Causes, Consequences and Environment*. London, Croom Helm.

Dahal, R.K. and S. Hasegawa, 2008: Representative rainfall thresholds for landslides in the Nepal Himalaya. *Geomorphology*, 100:429–443, doi:10.1016/j.geomorph.2008.01.014.

Ferrari, E. and P. Versace (eds.), 2015: *Monitoring, Modelling and Early Warning of Extreme Events Triggered by Heavy Rainfall*. Proceedings of the Fifth International Workshop on Hydrological Extremes, MED-FRIEND project, University of Calabria, Cosenza, Italy, 26–28 June 2014.

Gabet, E.J., D.W. Burbank, J.K. Putkonen, B.A. Pratt-Sitaula and T. Ojha, 2004: Rainfall thresholds for landsliding in the Himalayas of Nepal. *Geomorphology*, 63:131–143.

Galewsky, J., C.P. Stark, S. Dadson, C.C. Wu, A.H. Sobel and M.J. Horng, 2006: Tropical cyclone triggering of sediment discharge in Taiwan. *Journal of Geophysical Research*, 111:F03014, doi:10.1029/2005JF000428.

Glade, T., M. Crozier and P. Smith, 2000: Applying probability determination to refine landslide-triggering rainfall thresholds using an empirical “antecedent daily rainfall model”. *Pure and Applied Geophysics*, 157:1059–1079.

Godt, J.W., R.L. Baum and A.F. Chleborad, 2006: Rainfall characteristics for shallow landsliding in Seattle, Washington, USA. *Earth Surface Processes and Landforms*, 31:97–110, doi:10.1002/esp.1237.

Guzzetti, F., S. Peruccacci, M. Rossi and C.P. Stark, 2008: The rainfall intensity–duration control of shallow landslides and debris flows: An update. *Landslides*, 5:3–17, doi:10.1007/s10346-007-0112-1.

Guzzetti, F., P. Reichenbach, M. Cardinali, M. Galli and F. Ardizzone, 2005: Probabilistic landslide hazard assessment at the basin scale. *Geomorphology*, 72:272–299.

Hong, Y., R. Adler and G. Huffman, 2006: Evaluation of the potential of NASA multi-satellite precipitation analysis in global landslide hazard assessment. *Geophysical Research Letters*, 33:L22402, doi:10.1029/2006GL028010.

———, 2007: Use of satellite remote sensing data in the mapping of global landslide susceptibility. *Natural Hazards*, 43:245–256, doi:10.1007/s11069-006-9104-z.

Huffman, G.J., R.F. Adler, D.T. Bolvin and E.J. Nelkin, 2010: The TRMM Multi-satellite Precipitation Analysis (TMPA). Satellite Rainfall Applications for Surface Hydrology (M. Gebremichael and F. Hossain, eds). Dordrecht, Springer Verlag.

Huffman, G.J., D.T. Bolvin, E.J. Nelkin, D.B. Wolff, R.F. Adler, G. Gu, Y. Hong, K.P. Bowman and E.F. Stocker, 2007: The TRMM multisatellite precipitation analysis (TMPA): QuaSI-GLOBAL, MULTIYEAR, combined-sensor precipitation estimates at fine scales. *Journal of Hydrometeorology*, 8:38–55.

Iverson, R.M., 2000: Landslide triggering by rain infiltration. *Water Resources Research*, 36:1897–1910.

Jibson, R.W., 1989: Debris flows in southern Puerto Rico. In: *Landslide Processes of the Eastern United States and Puerto Rico* (P. Schultz and R.W. Jibson, eds). Boulder, Colorado, *Geological Society of America special* paper, 236:29–55.

Kirschbaum, D.B., R. Adler, D. Adler, C. Peters-Lidard and G. Huffman, 2012*a*: Global distribution of extreme precipitation and high-impact landslides in 2010 relative to previous years. *Journal of Hydrometeorology*, 13:1536–1551.

Kirschbaum, D.B., R. Adler, Y. Hong, S. Hill and A. Lerner-Lam, 2010: A global landslide catalog for hazard applications: Method, results, and limitations. *Natural Hazards*, 52(3):561–575, doi:10.1007/s11069-009-9401-4.

Kirschbaum, D.B., R. Adler, Y. Hong, S. Kumar, C. Peters-Lidard and A. Lerner-Lam, 2012*b*: Advances in landslide nowcasting: Evaluation of a global and regional modeling approach. *Environmental Earth Sciences*, 66:1683–1696, doi:10.1007/s12665-011-0990-3.

Kirschbaum, D.B., R. Adler, Y. Hong and A. Lerner-Lam, 2009: Evaluation of a preliminary satellite-based landslide hazard algorithm using global landslide inventories. *Natural Hazards and Earth System Sciences*, 9:673–686.

Larsen, M.C. and A. Simon, 1993: A rainfall intensity-duration threshold for landslides in a humid-tropical environment, Puerto Rico. *Geografiska Annaler*, 75:13–23.

Lepore, C., S.A. Kamal, P. Shanahan and R.L. Bras, 2012: Rainfall-induced landslide susceptibility zonation of Puerto Rico. *Environmental Earth Sciences*, 66:1667–1681, doi:10.1007/s12665-011-0976-1.

Liao, Z., Y. Hong, D. Kirschbaum and C. Liu, 2011: Assessment of shallow landslides from Hurricane Mitch in central America using a physically based model. *Environmental Earth Sciences*, 66:1697–1705, doi:10.1007/s12665-011-0997-9.

Nadim, F., O. Kjekstad, P. Peduzzi, C. Herold and C. Jaedicke, 2006: Global landslide and avalanche hotspots. *Landslides*, 3:159–173, doi:10.1007/s10346-006-0036-1.

Nagarajan, R., A. Roy, R.V. Kumar, R.V., A. Mukherjee and M. Khire, 2000: Landslide hazard susceptibility mapping based on terrain and climatic factors for tropical monsoon regions. *Bulletin of Engineering Geololgy and the Environment*, 58:275–287.

National Oceanic and Atmospheric Administration, National Weather Service Climate Prediction Center, http://www.cpc.ncep.noaa.gov.

Petley, D.N., The landslide blog, http://blogs.agu.org/landslideblog/.

Petley, D.N., W.D.O. Crick and A.B. Hart, 2002: The use of satellite imagery in landslide studies in high mountain areas. Presented at the Twenty-third Asian Conference on Remote Sensing (ACRS), Kathmandu, Nepal, 25–29 November, https://www.researchgate.net/publication/228762030_The_use_of_satellite_imagery_in_landslide_studies_in_high_mountain_areas.

Petley, D.N., Dunning, S.A. and N.J. Rosser, 2005: The analysis of global landslide risk through the creation of a database of worldwide landslide fatalities. In: *Landslide Risk Management* (O. Hungr, R. Fell, R. Couture and E. Eberhardt, eds). Amsterdam, A.T. Balkema.

Petley, D.N., G.J. Hearn, A. Hart, N.J. Rosser, S.A. Dunning, K. Oven and W.A. Mitchell, 2007: Trends in landslide occurrence in Nepal. *Natural Hazards*, 43:23–44, doi:10.1007/s11069-006-9100-3.

Sidle, R.C. and H. Ochiai (eds), 2006: *Landslides: Processes, Prediction, and Land Use. Water Resources Monograph series No.* 18. Washington, D.C., American Geophysical Union.

Singhroy, V., K. Molch and M. Bulmer, 2002: Characterization of landslide deposits using SAR Images. In: *Geoscience and Remote Sensing Symposium*, Toronto, 24–28 June. IEEE, doi:10.1109/IGARSS.2002.1024982.

Terlien, M.T.J., 1998: The determination of statistical and deterministic hydrological landslide-triggering thresholds. *Environmental Geology*, 35(2–3):124–130.

Wieczorek, G.F., 1996: Landslide triggering mechanisms. In: *Landslides: Investigation and Mitigation* (K.A. Turner and R.L. Schuster, eds). Transportation Research Board special report No. 247. Washington, D.C., National Academy Press.

Wilson, R.C. and A.S. Jayko, 1997: Preliminary Maps Showing Rainfall Thresholds for Debris-flow Activity, San Francisco Bay Region, California. US Geological Survey open-file report 97-745.

General public

China Meteorological Administration Public Weather Service, http://www.cma.gov.cn/en2014/service.

Duan, Y.X., J.J. Pan and Q.C. LI, 2009: Analysis of public needs for weather services in Beijing. *Journal of Arid Meteorology*, 27(2) [in Chinese].

Hong Kong (China) Public Weather Service, http://www.hko.gov.hk/wservice/tsheet/pubwx.htm.

Met Office, public weather service outputs, http://www.metoffice.gov.uk.

National Oceanic and Atmospheric Administration National Weather Service, http://www.weather.gov.

World Meteorological Organization, 1999: *Guide to Public Weather Services Practices* (WMO-No. 834). Geneva.

Civil protection

Adeola, F.O., 2003: Flood Hazard Vulnerability: A Study of Tropical Storm *Allison* (TSA) Flood Impacts and Adaptation Modes in Louisiana. Quick Response Research Report #162. Boulder, Colorado, Natural Hazards Center.

Brommer, D.M. and J.C. Senkbeil, 2010: Pre-landfall evacuee perception of the meteorological hazards associated with hurricane *Gustav*. *Natural Hazards*, 55(2):353–369.

Cahyanto, I., L. Pennington-Gray, B. Thapa, S. Srinivasan, J. Villegas, C. Matyas and S. Kiousis, 2014: An empirical evaluation of the determinants of tourist's hurricane evacuation decision-making. *Journal of Destination Marketing and Management*, 2(4):253–265.

Cluckie, I.D. and D. Han, 1995: Weather radar information processing in real-time for flood forecasting. In: *Natural Risk and Civil Protection* (T. Horlick-Jones, A. Amendola and R. Casale, eds). London, E. & F.N. Spon.

Cutter, S.L. and C.T. Emrich, 2006: Moral hazard, social catastrophe: The changing face of vulnerability along the hurricane coasts. *The ANNALS of the American Academy of Political and Social Science*, 604:102–112.

Donahue, A., 2012: Disaster risk perception, preferences, and preparedness. University of Connecticut, Department of Public Policy, West Hartford, Connecticut.

Mileti, D. S. and J. H. Sorenson, 1990: Communication of Emergency Public Warnings: A Social Science Perspective and State of-the-art Assessment. Oak Ridge National Laboratory Report ORNL-6609. Oak Ridge, Tennessee.

Morrow, B.H., 2009: Risk Behavior and Risk Communication: Synthesis and Expert Interviews. SocResearch Miami. Final report for the National Oceanic and Atmospheric Administration, Coastal Services Center. Miami, SocResearch.

Phillips, B.D. and B.H. Morrow, 2007: Social science research needs: Focus on vulnerable populations, forecasting, and warnings. *Natural Hazards Review*, 8(3):61–68.

Radford, L.M., 2012: New tropical cyclone warning graphics: Preferences, comments and future suggestions. PhD thesis. The University of Alabama.

Sharples, J.J., R.H.D. McRae, R.O. Weber and A.M. Gill, 2009: A simple index for assessing fire danger rating. *Environmental Modelling and Software*, 24:764–774.

Sorenson, J.H., 2000: Hazard warning systems: Review of 20 years of progress. *Natural Hazards Review*, 1(2):119–125.

Stein, R.M., L. Dueñas-Osorio and D. Subramanian, 2010: Who evacuates when hurricanes approach? The role of risk, information, and location. *Social Science Quarterly*, 91(3):816–834.

Thomalla, F., T. Downing, E. Spanger-Siegfried, G. Han and J. Rockström, 2006: Reducing hazard vulnerability: Towards a common approach between disaster risk reduction and climate adaptation. *Disasters,* 30(1):39–48.

Construction industries/energy

An, S. and N. Cho, 2010: A study on the methods for improving weather information application by analysis the present state in building construction. *Korean Journal of Construction Engineering and Management*, 11(3):89–96, doi:10.6106/KJCEM.2010.11.3.89.

Appelqvist, P., F. Babongo, V. Chavez-Demoulin, A. Hameri and T. Niemi, 2016: Weather and supply chain performance in sport goods distribution. *International Journal of Retail and Distribution Management*, 44(2):178–202, doi:10.1108/IJRDM-08-2015-0113.

Ballesteros-Pérez, P., M. Del Campo-Hitschfeld, M. González-Naranjo and M. González-Cruz, 2015: Climate and construction delays: Case study in Chile. *Engineering, Construction and Architectural Management*, 22(6):596–621, doi:10.1108/ECAM-02-2015-0024.

Chinnadurai, J., V. Venugopal, P. Kumaravel and R. Paramesh, 2016: Influence of occupational heat stress on labour productivity – a case study from Chennai, India. *International Journal of Productivity and Performance Management*, 65(2):245–255, doi:10.1108/IJPPM-08-2014-0121.

De Place Hansen, E. and J. Larsen, 2011: Employment and winter construction: A comparative analysis of Denmark and western European countries with a similar climate. *Construction Management and Economics*, 29(9):875–890, doi:10.1080/01446193.2011.617762.

Dytczak, M., G. Ginda, N. Szklennik and T. Wojtkiewicz, 2013: Weather influence-aware robust construction project structure. *Procedia Engineering*, 57:244–253, doi:10.1016/j.proeng.2013.04.034.

Li, X., K. Chow, Y. Zhu and Y. Lin, 2016: Evaluating the impacts of high-temperature outdoor working environments on construction labor productivity in China: A case study of rebar workers. *Building and Environment*, 95:42–52, doi:10.1016/j.buildenv.2015.09.005.

Mohamed, S. and K. Srinavin, 2002: Thermal environment effects on construction workers' productivity. *Work Study*, 51(6):297–302, doi:10.1108/00438020210441849.

Nguyen, L., J. Kneppers, B. García de Soto and W. Ibbs, 2010: Analysis of adverse weather for excusable delays. *Journal of Construction Engineering and Management*, 136(12):1258–1257, doi:10.1061/(ASCE)CO.1943-7862.0000242.

Srinavin, K. and S. Mohamed, 2003: Thermal environment and construction workers' productivity: some evidence from Thailand. *Building and Environment*, 38(2):339–345, doi:10.1016/S0360-1323(02)00067-7.

Thomas, H. and R. Ellis, 2009: Fundamental principles of weather mitigation. *Practice Periodical on Structural Design and Construction*, 14(1):29–35, doi:10.1061/(ASCE)1084-0680(2009)14:1(29).

Zhao, J., N. Zhu and S. Lu, 2009: Productivity model in hot and humid environment based on heat tolerance time analysis. *Building and Environment*, 44:2202–2207, doi:10.1016/j.buildenv.2009.01.003.

CHAPTER 6. LESSONS LEARNT FROM OLYMPIC EVENTS AND MEMBER SURVEY

6.1 INTRODUCTION

The WMO World Weather Research Programme (WWRP) has conducted many forecast demonstration projects (FDPs) and research development projects (RDPs) (for example, the Mesoscale Alpine Programme (MAP), MAP Demonstration of Probabilistic Hydrological and Atmospheric Simulation of Flood Events, the Hydrological Cycle in the Mediterranean Experiment, Tokyo Metropolitan Area Convection Study for Extreme Weather Resilient Cities project (TOMACS), and the Integrated Nowcasting Comprehensive Analysis – Central Europe project (INCA-CE)). This chapter focuses on the projects associated with the summer and winter Olympic Games as well as the INCA-CE project as they are most relevant to operational nowcasting. These projects were created to advance knowledge, to promote systems and to build capacity. FDPs are real-time demonstrations of state-of-the-art, prototype nowcasting systems and include verification and societal impact components. While there are significant research aspects to both FDPs and RDPs, the latter are primarily focused on advancing the science.

6.2 SERVICE REQUIREMENTS

The FDPs and RDPs are motivated by the extraordinary challenges of nowcasting requirements of sporting events. In general, the safety and security of large groups of athletes and spectators in a high-visibility situation highlights the credibility and reputation of the NMHS. However, the specificity and precision (time and space) of the weather requirements for various sports for a fair competition raise the level of the challenges to uncharted levels, particularly when television schedules and other competition rules can change the decision or warning thresholds on the scale of minutes to days. In summer, sailing competition managers need nowcasts of quasi-constant wind direction in order to set up the race course orientation prior to race start, and may change the orientation during the race. Nowcasting has traditionally focused on heavy precipitation, but even a light drizzle can be hazardous to tennis competitors. In winter, visibility nowcasts precise to 100 metres (approximately two turns for an Alpine downhill event) are required over a 2-kilometre distance. For a fair competition, a nowcast of similar conditions for competition duration (90 minutes) is another challenge. Arguably, winter nowcasting poses a greater challenge than summer. The timescale is the same but the spatial scales are smaller as the weather changes significantly with altitude.

Thus, FDPs and RDPs are organized to respond to the operational service challenges, and participants in projects are attracted by the scientific challenges. From a technology-transfer or research perspective, the projects are a cost-effective way to conduct research. Experts bring their systems and optimize them for the specific project conditions; this removes the necessity for the host or organizer of an event of expending considerable time and effort to import and optimize their own systems. Experts are able to compare similar systems, which is often the most effective way to diagnostically validate and verify their own systems and concepts in a common weather environment.

One of the principal messages is that, with advanced nowcasting capacity, nowcast services in the future will be quite broad and tailored to specific users. The future challenge is whether these services will be delivered through an NMHS or the private sector.

6.3 OBSERVATIONS

High-resolution observations are critical to nowcasts and nowcasting systems. Radars and other leading-edge remote-sensing tools (wind profilers, radiometers, Doppler LIDARs, etc.) are often deployed for the projects. However, high-resolution (at the scale of minutes or seconds) in situ data, using new technology (for example, for visibility or precipitation) are also needed. These are used for analysis to drive nowcasting systems, for interpretation of results, but also for verification and validation. In fact, this is a key feature of FDPs and RDPs, because operational networks are generally designed for synoptic forecasting and are insufficient for nowcasting and validation of nowcasting systems. As systems are expensive to deploy, participants in the projects often take advantage of the opportunity to test them.

Mesonets are usually deployed in a uniform manner (with typical spacings of 10 kilometres between stations), which may not be the best strategy if there is a critical physical feature of prime concern (Joe et al, 2017).

A common issue for nowcasting systems is the need for more information in the boundary layer. High-resolution NWP does not adequately provide enough detail to meet the service need.

6.4 UNDERSTANDING/FORECAST TECHNIQUE

High-resolution and high-sensitivity observations result in new knowledge. Fine-scale features in the atmosphere are revealed that form the basis of greater understanding through pattern recognition and scientific analysis. While high-resolution models help, one can never be certain if they capture the situation and the phenomena. Mo et al (2014) show how a mid-mountain cloud that created conditions unsafe for downhill skiing could form under stable conditions using a combination of observations from in situ sensors, radar, wind profiler and high-resolution NWP. Wilson et al (2010) showed that thunderstorms forming in the mountains west of and advecting into the Beijing basin would grow or die depending on the stability of the atmosphere in the plains area. Teakles et al (2014) needed 1-second data from three wind sensors about 100 metres apart to capture the ebb and flow of the transition from drainage flow to upslope flow. This level of detail was not captured in the high-resolution NWP models, thus demonstrating the value of high-resolution observations and also the level of understanding and interpretation necessary to provide the required nowcasts. The TOMACS project showed that a modelled thunderstorm took on different modes (non-severe to supercell) when the wind shifted by only 10° in the very localized inflow region provided by very high-resolution Doppler LIDAR wind measurements.

6.5 NOWCAST TECHNIQUE, PROCESS AND SYSTEMS

There has been a considerable focus on the use of computer algorithms to produce products to aid the forecaster’s decision-making (Joe et al., 2002; Lakshmanan et al., 2007).

One major lesson learned is that if automated guidance is provided, diagnostic products documenting and supporting the guidance must also be provided. Without this access to the supporting evidence, there is nothing available to the forecaster to judge the quality of the guidance to issue a warning. Autonowcaster provides nowcasts of 35 dBZ thunderstorms but also provides diagnostic interest fields. Variational Doppler Radar Assimilation System provides analysis fields such as temperature-anomaly fields to show cold pools. The Canadian Radar Decision Support system provides cell views to show, in one image, various cell-centric radar products. The Integrated Weighted Model system produces spaghetti plots of model output with data observations for point nowcasts.

One lesson that is often repeated is that for automated guidance or prediction systems to be useful, they need to be constructed with a human-centred design approach. Providing only the “answer” is insufficient, as there is no information with which to judge guidance. There must be commensurate diagnostic products, also automatically generated, that are easily and quickly accessible, otherwise there will be no resource saving (Crandall et al., 2006; Pliske et al., 1997) and the nowcasting products will not be useful. Therefore, a high level of expertise in the fine-scale details of the weather (mesoscale meteorology) also requires a high-level knowledge of the weakness and strengths of the automated guidance systems (including high-resolution NWP) and also in rapid decision-making in short-time frame situations.

Another lesson is that radar algorithms to detect severe events, such as mesocyclone or downburst, have to be configured with a high probability of detection because the phenomena are rare, distinct features of short duration that should not be missed. Also, being rare, normal statistics (of the central tendency of a distribution) do not apply as the phenomena are inherently at the tail of the distribution. One is not interested in skill scores that optimize hits versus misses, as this results in being mediocre or average at best, which is not acceptable for warning purposes.

Nowcast systems are now being developed for point nowcasting, without remote sensing data, with high-resolution (1 minute) in situ observations and outputs from multi-models for continuous weather variables. This opens up the possibility of developing nowcasting systems for NMHSs that do not possess radars through the upgrading of an existing weather station to collect high temporal data (1 minute) and to use globally available NWP output.

For model point nowcasts, the nearest model point is not always the best one to use, particularly in complex terrain. One must pick points with similar slopes and orientation to the sun.

The INCA system produces products directly to decision-makers, bypassing NMHS forecasters. This also shifts the meteorological analysis and decision-making to the end user, requiring them to develop expertise. This is a paradigm shift of significant proportions as it challenges the notion of authoritative voice of experts and expertise.

Proficiency in forecasting does not necessarily translate into nowcasting proficiency and vice versa. Decision-making in short-term, stressful nowcasting situations is a personal skill and an art that still confounds the most experienced nowcaster. Training via weather-event simulation, classroom training and pre-games trials are used to prepare the nowcaster. There is no substitute for "on-the-job training" for both learning and for decision-making.

One of the most significant challenges is that there is a gap in the 6–12-hour lead time range. The predictability of precipitation systems is scale dependent. The larger scales can be predicted with skill up to about 6 hours and can be as low as 20 minutes for small scale features.

The heavy focus on data and automation led to the Phoenix experiment (McCarthy et al., 2007). The explicit question was how well could a forecaster do without technology and only data. The implicit question was whether the new model technologies actually contribute to forecasters' ability or whether they encourage the attitude "belief in technology/technology is the answer". The results demonstrate that expertise and data are the critical factors.

6.6 TECHNOLOGY TRANSFER AND SOCIETAL IMPACTS

Users are unlikely to have expert knowledge of nowcasting technologies. Surveys have revealed that there is often a misunderstanding of the process of nowcasting. This is in part due to the limited definition based primarily on time and also the overuse of the term "warning" (for example, there are "early warning systems" for climate applications).

Transfer of new technology into an existing operational programme is a social process. Experienced adults are self-motivated, learn on their own, and if the technology is relevant, early adopters will naturally migrate to new systems that appear to provide benefits. Little formal training materials need to be provided. Simulation tools and on-the-job learning are much more effective.

Direct interaction with end users and decision-makers (for example, Alpine downhill course managers) with nowcasters promoted successful rapid technology transfer. Trust in the products and in each other was identified as the key factor. This also promoted new ways of looking at the weather, promoted new knowledge and focused the nowcasts.

For participants in such projects, it is an inexpensive and very effective way to conduct research. Proponents of the systems are the best to demonstrate them. Analysis of data takes time, results need to be digested and decisions made about which technology to adopt and how to introduce it within the context of an NHMS. The tangible benefits to operations are often realized about 10 years later but there are also details that immediately benefit the host NMHS, particularly in data quality and mesoscale meteorological knowledge. National projects have been developed to accelerate the technology transfer process (Golding et al, 2016; Joe et al, 2017).

Societal impact studies are very difficult to conduct effectively given the limited duration of FDPs. Engaging users, and winning their trust and confidence on new products takes time. Longer-duration "test-bed" projects may provide a better tool to engage "early adopters". Careful choice of technology and planning is needed as the expectations of end users for continuity and technology transfer need to be managed. It is recommended that NMHSs may be better served if FDPs and test-bed projects fall under the joint management of GDPFS, the Public Weather Services (PWS) Programme and WWRP, as there may be significant technology transfer impacts.

6.7 VERIFICATION

There are two categories of tests required for establishing relationships – statistical, quantitative and objective; and diagnostic, qualitative and causal. There has been a significant effort to promote statistical verification through workshops and research activities to deal with developing techniques and metrics to capture phasing errors (time and space differences) and for extremes. These are relevant to nowcasting. However, they are in their infancy and still suffer from violating the "law of large numbers".

Real-time verifications have been trialled and new statistics have been successfully introduced to a broader community. Similarly to automated guidance, diagnostic tools are needed to understand the significance of the verifications. However, diagnostic verification (causal) is most critical to nowcast technique developers.

6.8 LESSONS LEARNT FROM THE PUBLIC WEATHER SERVICES PROGRAMME MEMBER SURVEY

The WMO CBS at its fourteenth session (Dubrovnik, Croatia, 25 March–2 April 2009) requested the PWS Programme to continue assisting Members to improve their national PWS programmes by providing guidance on the application of new technology and scientific research in data acquisition and use, especially for nowcasting and multi-hazard warnings.

As part of the mandate of the PWS Programme, the CBS Open Programme Area Group on PWS Expert Team on Services and Products Innovation and Improvement (ET-SPII) was tasked to survey Members on existing nowcasting systems. A draft questionnaire for Members was compiled by ET-SPII during and following its 2012 meeting. Following additional review and input, including those from the president of the Commission for Instruments and Methods of Observations, the finalized questionnaire was distributed to NMHSs via the GDPFS annual survey early in 2014.

The results of this survey are intended to provide information on the variety, strengths and weaknesses of nowcasting systems used in the WMO community. This will allow those Members who are contemplating the development of nowcasting systems to benefit from the experience of others.

The analysis of the results of this survey is presented for those Members striving to develop effective and sustainable nowcasting services, using the principles outlined in *The WMO Strategy for Service Delivery and its Implementation Plan* (WMO-No. 1129).

Based on the results of this survey, it is recommended to adopt a “building-block approach” when developing a nowcasting solution. The stages of such an approach are outlined below. Stages 1 to 3 consider only data sourced externally to an NMHS. After these initial, basic stages, consideration can be given to additional elements, given appropriate resources and funding. This should provide an NMHS with the needed guidance on what to focus on in its planning.

Basic system:

Stage 1 – Using externally sourced satellite products;

Stage 2 – Using externally sourced global NWP;

Stage 3 – Additional sources of external data.

Advanced system:

Stage 4 – Developing an internal surface observations network;

Stage 5 – Expanding the surface network;

Stage 6 – Developing radar capability;

Stage 7 - Expanding and calibrating a radar network;

Stage 8 – Local NWP, other data and towards an integrated nowcasting system.

Based on the survey, it is recommended that NMHSs planning to develop and maintain a nowcasting capability should consider the following six elements:

(a) Evaluating user needs and decisions;

(b) Linking service development and delivery to user needs;

(c) Evaluating and monitoring service performance and outcomes;

(d) Sustaining and improving service delivery;

(e) Developing skills needed to sustain service delivery;

(f) Sharing best practice and knowledge.

The ET-SPII concluded their survey with the following recommendations:

(a) Members should develop nowcasting services and systems according to the principles defined in *The WMO Strategy for Service Delivery and its Implementation Plan* (WMO-No. 1129);

(b) In particular, Members should engage with users, understand their requirements and incorporate these needs into the development and evolution of nowcasting services. This might be via user groups, surveys or other forms of feedback;

(c) With knowledge of these user needs, Members should be fully aware of the particular problem they need to address with a nowcasting service (such as heavy rain in sensitive areas bringing flooding);

(d) NMHSs should plan to meet users’ needs in a sustainable fashion, supporting the infrastructure the service requires. Members should consider the elements which comprise a nowcasting capability as part of a broader, end-to-end service, considering the need for the skills and resources required to build and maintain the service, and ensure it remains aligned to user needs;

(e) When planning nowcasting services, consideration should be given to the many advantages (and some disadvantages) of sharing capabilities and data with other organizations, including neighbouring NMHSs;

(f) Partnerships should be formed with other NMHSs that can offer advice, experience and shared capabilities for nowcasting.

These recommendations have been integrated into the recommendations set out in Annex A.

Further reading

Crandall, B., G. Klein and R.R.Hoffman, 2006: *Working Minds: A Practitioner's Guide to Cognitive Task Analysis*. Cambridge, MA, MIT Press.

Golding, B.W., S.P. Ballard, K. Mylne, N. Roberts, A. Saulter, C. Wilson, P. Agnew, L.S. Davis, J. Trice, C. Jones, D. Simonin, Z. Li, C. Pierce, A. Bennett, M. Weeks and S. Moseley, 2014: Forecasting capabilities for the London 2012 Olympics. *Bulletin of the American Meteorological Society*, 95:883–896.

Joe, P., S. Belair, N.B. Bernier, J.R. Brook, D. Brunet, V. Bouchet, W. Burrows, J.P. Charland, A. Dehghan, N. Driedger, C. Duhaime, G. Evans, A.-B. Filion, R. Frenette, J. de Grandpré, I. Gultepe, D. Henderson, A. Herdt, N. Hilker, L. Huang, E. Hung, G. Isaac, D. Johnston, C.-H. Jeong, J. Klaassen, S. Leroyer, H. Lin, M. MacDonald, J. MacPhee, Z. Mariani, T. Munoz, J. Reid, A. Robichaud, Y. Rochon, K. Shairsingh, D. Sills, C. Stroud, L. Spacek, Y. Su, N. Taylor, J.M. Wang, J. Vanos, J. Voogt, T. Wiechers, S. Wren, H. Yang and T. Yip, 2017: The Environment Canada Pan and ParaPan American Science Showcase Project. Submitted to *Bulletin of American Meteorological Society*.

Joe, P., M. Falla, P. Van Rijn, L. Stamadianos, T. Falla, D. Magosse, L. Ing and J. Dobson, 2002: Radar data processing for severe weather in the National Radar Project of Canada. Paper 4.3. Twenty-first Conference on Severe Local Storms, American Meteorological Society, San Antonio, 12–16 August.

Lakshmanan, V., T. Smith, G. Stumpf and K. Hondl, 2007: The Warning Decision Support System–Integrated Information. *Weather and Forecasting*, 22(3):596–612.

McCarthy, P.J., D. Ball and W. Purcell, 2007: Project PHOENIX – optimizing the machine–person mix in high-impact weather forecasting. Twenty-second Conference on Weather Analysis and Forecasting/Eighteenth Conference on Numerical Weather Prediction, American Meteorological Society, Park City, UT, 25–29 June.

Mo, R., P. Joe, G.A. Isaac, I. Gultepe, R. Rasmussen, J. Milbrandt, R. McTaggart-Cowan, J. Mailhot, M. Brugman, T. Smith and B. Scott, 2014: Mid-mountain clouds at Whistler during the Vancouver 2010 Winter Olympics and Paralympics. *Pure and Applied Geophysics*, 171(1-2):157–183.

Pliske, R., D. Klinger, R. Hutton, B. Crandall, B. Knight and G. Klein, 1997: Understanding skilled weather forecasting: Implications for training and the design of forecasting tools. Technical Report No. 1L/HR-CR-1997-003, for Armstrong Laboratory, Brooks AFB, Texas, Klein Associates Inc.

Teakles , A., M. Ruping, C.F. Dierking, C. Emond, T. Smith, N. McLennan and P. Joe, 2014: Realizing user-relevant conceptual model for the ski jump venue of the Vancouver 2010 Winter Olympics. *Pure and Applied Geophysics*, 171(1-2):184–207.

Wilson, J., Y. Feng, M. Chen and R.D. Roberts, 2010: Nowcasting challenges during the Beijing Olympics: Successes, failures, and implications for future nowcasting system. *Weather and Forecasting*, 25:1691–1714.

ANNEX A. RECOMMENDATIONS FOR SUCCESS IN BUILDING NOWCASTING CAPABILITIES IN DEVELOPING COUNTRIES

(a) Plan in advance and consult with experts (WMO and others) on your equipment needs before purchasing an expensive system.

(b) Define and plan the reception (archiving, storage and bandwidth) of necessary datasets for the forecasting process via, for example, Internet and the WMO Information System.

(c) If an NMHS cannot afford expensive instrumentation, it should at least start by obtaining access to satellite data or surface station or global model outputs, which are efficient low-cost nowcasting systems.

(d) Plan how the necessary maintenance, provision of spare parts for and repair of the equipment and systems will be supported.

(e) Plan how to develop the expertise and technical support staff within the NMHS who will be needed to keep the equipment, hardware and software updated, calibrated and operational.

(f) Develop a plan for incorporating VSRF and nowcasting in the operational setting. Document the process to make it sustainable.

(g) Develop guidelines for local forecasters based on nowcasting guidelines provided by WMO.

(h) Despite automated nowcasting techniques, forecasters should still play a vital role in nowcasting.

(i) Decide on the best sustained approach for training forecast staff; consider international and online training activities, events and available materials.

(j) Provide training on all aspects of the nowcasting process, from technical support staff to forecasters to end users.

(k) Determine and understand the end users’ requirements.

(l) Cooperate with neighbouring countries on a regional scale.

(m) Strive for rapid integrated display systems to visualize different datasets in real time.

ANNEX B. ADVANTAGES AND LIMITATIONS OF DIFFERENT TYPES OF UPPER-AIR OBSERVATION INSTRUMENTS

Instrument	*Advantages*	*Limitations*
Radiosondes	Good quality and simultaneous presence of temperature, wind, moisture and pressure measurements (moisture with marginal accuracy, all other variables with good accuracy). Excellent vertical resolution (provide full resolution data from just above ground to heights of up to 30 km).	Low temporal resolution (over two thirds of the stations make observations at 0000 UTC and 1200 UTC, some stations make observations once per day). Poor horizontal resolution (only over populated areas; in ocean areas radiosonde observations are taken by few ships that sail mainly in the North Atlantic).
AMDAR/ TAMDAR	Good temporal and vertical resolution of atmospheric profile in the vicinity of airports (reports are taken during takeoff and landing). Coverage includes data-sparse areas such as over the oceans and in places where there is little or no RADOB* data. Accurate complimentary upper-air data and, in many cases, first-hand data from the lower atmosphere.	Vertical profiles of wind and temperature are limited to airports having suitably equipped aircraft and are limited at some times (little during night time). Slightly worse quality than radiosonde. AMDAR data are collected in collaboration with national domestic and international airlines and are not available in many countries because of the data collection costs to the respective airline companies.
Radars/wind and temperature profilers	High vertical and temporal resolution with a good accuracy as cost-effective enhancements to RADOB* data. Especially useful in making observations at times between balloon-borne soundings (sub-hourly). Very usable high-quality data from low or mid-troposphere, especially in mountainous and coastal regions. Good for wind shear, turbulence and phenomena not detected by other observations.	Possible echo contamination, data available only in populated areas (no data over oceanic, sparsely populated and polar regions). The high cost of installation and maintenance compared to that required for an radiosondes sounding system. The difficulty to obtain the necessary frequency bands limits operational implementation.
* RADOB: Report of ground radar weather observation.		

ANNEX C. GUIDELINES FOR RADAR ATTRIBUTES

When purchasing a radar there are many attributes to consider that depend on the desired use of the instrument. The major consideration is the radar wavelength since it significantly affects cost and capability. There are three wavelengths to consider when purchasing an instrument for operational use: S-band (~10 cm), C-band (~5 cm) and X-band (~3 cm). For most operational purposes, the width of the radar beam should not be more than about 1° in order to obtain high-resolution, pencil-thin radar beams that can target a range of precipitation features. The longer the wavelength the greater antenna size required to obtain a 1° beam. This contributes to the higher cost of S-band radars. Table C indicates the recommended radar wavelength for specific applications.

Table C. Suitability of radar wavelength for specific applications, where 1 is best and 2 is second best. * indicates attenuation of the radar signal by moderate and heavy rain that would limit the useful radar range of coverage to roughly 30 km

Radar application	*S-band*	*C-band*	*X-band*
Heavy rain	1	2	*
Severe convective storms	1	2	*
Snow estimation and nowcasting	1	1	1
Part of national network	1	2	*
Gap filler radar in national network	NA	1	1
Mobile research radar	NA	1	2

General radar specifications

Any newly purchased radar should have Doppler capabilities and it is highly recommended to have dual polarization. A dual-polarization radar needs to be capable of rotating while pointed vertically as this is an important step in keeping the radar well calibrated and producing high-quality precipitation estimates. As mentioned above, the beam width should not be greater than about 1°, unless data collections are to be undertaken at ranges <50 kilometres from the radar. Radar sensitivity is discussed below.

Radar range

While a great advantage of radar is to observe precipitation over large areas, the usefulness of radars for nowcasting is limited to radar ranges below 230 kilometres and depending on some phenomena such as downbursts and shallow snow storms that are produced by cold air flowing over warm bodies of water to less than 100 kilometres. The buyer of radar should not be swayed by claims that a particular radar can see to ranges of 400 kilometres or more. Because of the Earth’s curvature, the radar beam is more than 4 kilometres above the ground at 200 kilometres, and 13 kilometres above ground at 400 kilometres, thus dramatically reducing its usefulness to detect and nowcast high-impact weather close to the ground at longer ranges.

Clear-air echo

Radars can detect return from insects over land areas at any location in the world, provided the air temperature is >10° C. Most modern radars have sufficient sensitivity to observe insect return to ranges between 50 and 150 kilometres, depending on the depth of the boundary layer and number of insects. Bragg scatter echo mentioned in section 2.5.1 is best observed with S-band radar. Manufactures often provide software and display that threshold weaker returned signals, thus limiting the ability to see “clear-air” features and very light snowfall. Thus, the buyer of a new radar needs to be aware of radar sensitivity and request the ability to observe the weaker signals.

ANNEX D. AUTOMATED NOWCASTING SYSTEMS

(References cited in this annex are listed at the end of Chapter 2.)

Thunderstorm Identification Tracking Analysis and Nowcasting (TITAN)

Originally developed by Dixon and Wiener (1993), TITAN is a cell-tracking-based algorithm in which the precipitation area is selected according to a defined threshold (around 35 dBZ) and approximated by an ellipse (and its parameters). The important parameters for the cell-tracking algorithm are the reflectivity-weighted centroid, the volume, and the size and shape of the storm area. TITAN cell-tracking algorithm is part of a larger software package with the same name. The TITAN package is an entire software system that not only supports storm tracking and forecasting, but has also been expanded to include radar correction of analysis and climatology aspects.

Storm cell identification and tracking (SCIT)

Another cell-tracking algorithm that is widely used and originally published by Johnson et al. (1998). SCIT has some similarities with TITAN in its capabilities for tracking identified storm cells. The tracking process is carried out directly as a function of distance between cells instead of the minimization of a cost function as in TITAN, whereas the identification is more complex than the simple threshold selection of TITAN; the identification works with several (the default is seven) reflectivity thresholds for the cell detection. SCIT is integrated in the Warning Decision Support System – Integrated Information (WDSS-II).

Thunderstorm radar tracking (TIT) algorithm

The TRT algorithm is the operational cell-tracking nowcasting system used by Météo Swiss. Originally presented in Hering et al. (2004), it has continuously evolved with the addition of new features. As for the previously introduced cell-tracking algorithms, it also identifies convective cells, in this case by means of an adaptive thresholding scheme, allowing cells to be detected and tracked in different stages of their evolution. As for the previous algorithms, this algorithm implements splitting and merging of observed cells. Merge is defined when a storm track terminates in the projected area of another storm, when it is concluded that the storm did not terminate but merged to form a larger storm. For splits, the algorithm searches for storm tracks that have no history. If the centroid of such a storm is lying within a forecast ellipse of an already existing storm, then it is concluded that the storm is not new but that a split has taken place.

Fuzzy logic algorithm for storm tracking (FAST)

This recently developed cell-tracking algorithm (Jung and Lee, 2015) has an important difference with respect to the previous ones mentioned, which is the use of fuzzy logic to discriminate some storm tracking based on the statistic of some parameters.

Other cell-tracking algorithms extensively used in the nowcasting community are CELLTRACK (Novak, 2007), TRACE3-D (Handwerker, 2002) and RAD2-3 (Rigo and Llassat, 2004), among others.

McGill algorithm for precipitation nowcasting by Lagrangian extrapolation (MAPLE)

This algorithm was developed at McGill University, Canada, and uses statistical techniques on past radar images to predict the future location and intensity of reflectivity and future quantitative precipitation. It is an algorithm developed by Germann and Zawadzki (2002) that uses the variational echo tracking technique (Laroche and Zawadzki, 1994) to estimate the motion field of precipitation and a modified semi-Lagrangian backward scheme for advection. The latest observation is advected to the future up to 6 hours. This nowcasting tool has been applied in several locations such as the Republic of Korea and Switzerland, among others.

Continuous tracking radar echoes by correlation (Co-TREC)

This extrapolation algorithm is included in several nowcasting systems such as S-PROG (Berenguer, 2005), CELLTRACK (Novak, 2007) and RainCast (Schmid et al., 2000), among others. It is an extension of TREC (Rinehart and Garvey, 1978) by applying the continuity equation as a smooth constraint to filter the noisy displacement vectors obtained by maximizing the correlation between consecutive radar echoes. Different advection schemes can be applied after the motion vectors have been obtained, but a semi-Lagrangian backward scheme is the one recommended, in accordance with Germann and Zawadzki (2002), to avoid changes in the power spectrum of the advected reflectivity field.

Apart from the application of these two algorithms to obtain the displacement motion of the latest observation, optical flow is currently one of the most extended techniques to determine these vectors. These three techniques are carried out in the physical space, but an attempt to determine the motion vectors in the frequency space was formulated by Ruzanski et al. (2011) in the CASA nowcasting system.

Integrated Nowcasting through Comprehensive Analysis (INCA)

INCA has been developed for use in mountainous terrain (Haiden et al., 2011). Analysis and nowcasting fields include temperature, humidity, wind, precipitation amount and type, cloudiness, and global radiation. The nowcasting part employs classical correlation-based motion vectors derived from previous consecutive analyses. In the case of precipitation, the nowcast includes an intensity-dependent elevation effect. After 2–6 hours of forecast time the nowcast is merged into an NWP forecast provided by a limited-area model, using a predefined temporal weighting function.

Auto-nowcast (ANC) system

The main reference for this system is Mueller et al. (2003), but this is a highly complex nowcasting system developed in the United States by NCAR and operationally installed by the Meteorological Development Laboratory. The ANC system is a sophisticated complete nowcast system that uses a data-fusion technique to optimize the use of meteorological data in nowcasting and very short range forecasting. It produces 0–1-hour thunderstorm nowcasting predictor fields derived from combining information from observation-based feature detections (such as radar, satellite and surface networks), NWP, and human forecaster input. The software applications in the ANC environment include algorithms for identifying boundary-layer convergence zones, boundary–storm interactions, cumulus cloud detection and growth, boundary-relative shear profile, boundary-relative updraft strength, and storm trends and tracks. A fuzzy-logic application is used to allow the user to combine the weighted outputs from the various analysis algorithms to produce time- and space-specific forecasts of thunderstorm initiation, growth and decay. The nowcast predictor fields, especially thunderstorm initiation, growth and decay generated by ANC can be used as guidance by the forecasters in their warning decisions.

NowCastMIX – AutoWARN at Deutscher Wetterdienst

NowCastMIX is an expert system for the warning guidance -process input to AutoWARN. Every 5 minutes the forecaster receives warning areas for the next at Deutscher Wetterdienst that has been developed as a pre hour. For customers, specified warning products are offered, adapted for smart phones, tablets and Internet. Information is issued about thunderstorms and connected weather phenomena (hail, gusts, intensity of precipitation), heavy rain, snowfall intensities and freezing rain. The forecaster is able to check and adapt the warning guidance.

(a) The following data sources are processed:

  (i) Radar-based cell tracking;

  (ii) Regions of risk of high-impact weather – CellMOS;

  (iii) Precise lightning-strike monitoring;

  (iv) 3-D-radar scan and vertically integrated liquid water;

  (v) Radar-based precipitation quantities – analyses and forecasts;

  (vi) Real-time station reports;

  (vii) NWP-Consortium for Small-scale Modelling-DE (COSMO-DE) (near-storm environment estimates).

(b) The post-processing of the data contains four steps:

  (i) Gridded analysis: 1x1 km over Germany and a buffer zone to the West;

  (ii) Fuzzy logic: Storm severity assessment (gusts, hail, rain) and cell motion;

  (iii) Clustering: Grouping cells and optimizing properties in space and time to reduce rapid fluctuations;

  (iv) Polygon generation and forward integration of warning areas up to +60 minutes.

(c) For the final step, AutoWARN, the following data sources are combined:

  (i) NowCastMIX (integrated nowcasting product, 1x1 km);

  (ii) Combination of observations/measurements;

  (iii) ModelMIX (MOS, NWP-ensemble, post-processed data, 1 km).

Canadian Airport Nowcasting (CAN-NOW) System

The CAN-Now system is a nowcasting or short-term weather forecast system developed by Environment and Climate Change Canada. It was originally tested at Toronto airport and its use is recommended for major airports. The system uses several sources of information such as numerical model data, pilot reports, ground in situ sensor observations (precipitation, icing, ceiling, visibility and wind), on-site remote sensing (such as vertically pointing radar and microwave radiometer) and off-site remote sensing (satellite and radar). The output provides information such as ceiling, visibility, as well as precipitation rate and type to help decision-makers such as pilots, dispatchers or air-traffic controllers to make plans with increased margins of safety. A combination of previously developed nowcasting systems are integrated in CAN-Now such as the Integrated Weighting System (Huang, 2011), Adaptive Blending of Observations and Models (Bailey et al., 2009) and Environment Canada's Canadian Radar Decision Support based on the scheme developed by Bellon and Austin (1986). For severe weather applications, this system identifies cells, their properties (area, intensity, mesocyclone, downbursts) and tracks them into the future.

Short-range Warnings of Intense Rainstorms in Localized Systems (SWIRLS)

The second version of this nowcasting system, SWIRLS-2, is a quantitative precipitation forecast (QPF) system comprised of a family of nowcasting subsystems responsible for the ingestion of various types of conventional and remote-sensing observation data, and execution of a rich bundle of nowcasting algorithms, as well as product generation, dissemination and visualization via different channels. A summary of some capabilities of this system can be found in Li and Lai (2004). SWIRLS-2 concentrates on heavy precipitation events and takes advantage of the combination of an area tracker (an adapted version of CO-TREC) and a cell-tracking algorithm (GTrack, similar to TITAN). SWIRLS is used in combination with a rapid-update cycle NWP component to extend the QPF to 24 hours ahead.

These are state-of-the-art operational nowcasting tools, but research is being carried out to extend their capabilities. The main focus seems to be on the uncertainty associated with the growth and decay of precipitation, and also on the local errors due to diurnal cycle or changes in the wind gust due to orography or small-scale effects. The majority of these systems are deterministic, but the actual trend is to introduce the previously studied uncertainties by means of stochastic perturbations, Bayesian framework, and the like. For this reason, the last operational nowcasting system introduced is a probabilistic one widely used in many countries, for example Australia, Belgium and the United Kingdom of Great Britain and Northern Ireland.

Short-term Ensemble Prediction System (STEPS)

STEPS is the improved quantitative radar precipitation estimating and forecasting system based on S-PROG (Seed, 2003). It was jointly developed by the Australian Bureau of Meteorology and the United Kingdom Met Office (Bowler et al., 2006). The basic idea is to decompose the rainfall field into a sum of k different levels (the “cascade”), with each level representing features of a particular scale, and to consider the evolution of these levels separately. This decomposition is made of both NWP and radar extrapolated fields and, at the same time, a correlated noise with specific properties is added. STEPS blends these three decomposed fields giving different weights depending on the scale and lead time. Once the blending is done, the different levels are added up again, obtaining a final reflectivity field. The ensemble is obtained by generating different correlated noise fields (stochastic process).

ANNEX E. TYPES OF FORECASTS AND VERIFICATION METHODS

Nature of forecast	*Events*	*Verification methods*	*Recommendations*
Deterministic:			
Continuous	Precipitation amounts	Visual, continuous	The scatterplot is one of the simplest but most useful ways of evaluation. Forecast bias is measured by the mean error. Good accuracy measures are the mean absolute error and the root mean squared error. The mean absolute percentage error may be useful in cases where forecast errors increase as the observations get larger (for example, quantitative precipitation forecasts).
Dichotomous (binary, yes/no)	Occurrence of fog, hail, tornado	Visual, dichotomous	To measure accuracy, the hit and false alarm rates are appropriate in most situations, but they should always be used together; the proportion correct should be avoided. The base rate (event probability) should always be quoted. The frequency bias is useful to detect systematic over/underforecasting. However, severe weather occurrences are rare events, and the number of forecasts and observations of severe weather may be small. More useful in this case is the extreme dependency index (EDI).

Multi-category	Precipitation type (rain, shower, snow, freezing rain)	Visual, multi-categorical	The easiest way to evaluate is via a contingency table showing the frequency of forecasts and observations in the various bins. There are fewer statistics that summarize the performance of multi-category forecasts. However, any multi-forecasts with multiple categories can be reduced to a series of binary forecasts using thresholds.
Probabilistic	Probability of heavy precipitation	Visual, probabilistic, ensemble	The use of the Brier score alone without decomposition is not recommended. Reliability diagrams provide useful summaries of forecast performance and also give information on the resolution (and sharpness) of a forecast system. The receiver operating characteristic (ROC) curve and the area under it are also powerful assessment tools that are closely linked with economic value and other quality assessment metrics for binary forecasts.

Spatial distribution	Heavy rain, thunderstorms	Spatial, object based, dichotomous	The main motivation for spatial methods is to help account for the double penalty problem and to provide diagnostic of high-resolution forecasts for users. Neighbourhood (fuzzy) methods using fractions skill scores and binary MSE skill scores give credit to "close" forecasts. The method for object-based diagnostic evaluation (MODE) evaluates attributes of identifiable features. Field verification evaluates distortion and displacement (phase error).

For more details see *Forecast Verification for the African Severe Weather Forecasting Demonstration Projects* (WMO-No. 1132) (https://www.wmo.int/pages/prog/www/Documents/1132_en.pdf) and the WMO Joint Working Group on Forecast Verification Research website www.cawcr.gov.au/projects/verification.

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