Chapter 2
Precipitation Measurement

Abstract Observations of rainfall are often required as part of the flash flood warning process. The main measurement techniques which are used are raingauges, weather radar and satellite precipitation estimation. Each approach has its own advantages and limitations and the methods are complementary to some extent, providing information at different spatial and temporal scales. This has therefore led to the increasing use of multi-sensor precipitation estimates which combine the strengths of each approach and use information from other sources, such as lightning detection systems and atmospheric models. Here an introduction is provided to these techniques and to the more general topic of estimating the uncertainties in the observed values.

Keywords Raingauge • Weather radar • Satellite precipitation estimate • Multi-sensor precipitation estimate • Meteorological observations

2.1 Introduction

Prolonged or heavy rainfall is often the main cause of debris flows and flash floods in rivers and urban areas, and can be a key factor for dam breaks and other types of flash flood. Rainfall observations are used in several ways in the flood warning process, including for raising alerts using rainfall depth-duration thresholds and flash flood guidance methods and as direct inputs to flood forecasting models (see Chaps. 8–11).

The most widely used monitoring techniques are raingauges, weather radar and satellites. Weather radar networks are typically operated by National Meteorological Services (NMS) together with a core national network of raingauges and other meteorological instrumentation (e.g. Fig. 2.1). Additional raingauges are often operated by river basin management, hydropower, water supply, flood warning and other authorities and as part of community-based flood warning schemes. By contrast, geostationary, polar and low-earth orbit satellites are operated by a range

K. Sene, *Flash Floods: Forecasting and Warning*, DOI 10.1007/978-94-007-5164-4_2,

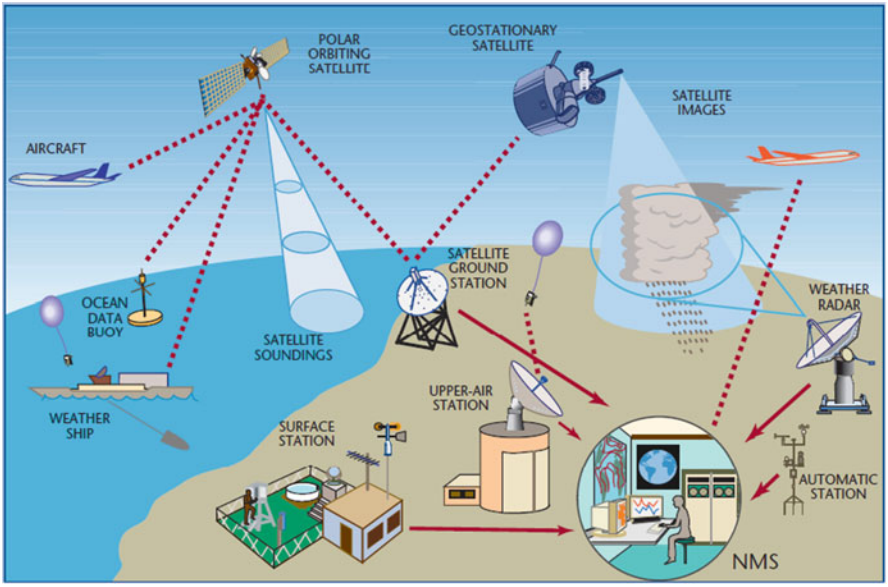

Fig. 2.1 Illustration of the Global Observing System, which is a fundamental component of World Meteorological Organisation (WMO) programmes and services. Data are collected from satellites, hundreds of ocean buoys, aircraft, ships and some 10,000 land-based stations. Within countries, the National Weather Service makes observations using manned and automatic instruments of temperature, precipitation, wind speed and direction, atmospheric pressure and other characteristics of the "weather". The observations, forecasts and products developed from these data are sent around the world every day, using the Global Telecommunication System (World Meteorological Organisation 2006, courtesy of WMO)

of international, national and private sector organisations for telecommunications, earth observation and other applications.

In countries where radar observations are available, these are usually used in preference to satellite-based estimates due to the higher spatial and temporal resolutions which are possible. However, satellite observations are often used to infill gaps in radar coverage and to assist with the post-processing of outputs. Raingauge observations are also widely used to check and adjust the outputs from weather radar and satellite-based systems, as well as being a primary source of observations. The choice of which approach to use in a particular flash flood application then depends on the spatial coverage at the location(s) of interest, past performance, organizational policy, budgets and other factors. Satellite precipitation estimates are also increasingly used in flash flood guidance applications in regions where the radar or raingauge coverage is poor or non-existent (see Chap. 8).

Of these three main approaches, one key difference is that raingauges record values at a point on the ground surface, whereas weather radar and satellite systems observe rainfall remotely either from a side-view or above. Raingauge observations are therefore often spatially averaged before use in flash flood warning applications whilst, for radar and satellite observations, some additional processing is required to infer values at the ground surface. The complementary nature of these techniques has therefore led to the increasing use of multi-sensor precipitation estimates (MPE) which aim to combine the best features of each approach. Here, the term ‘precipitation’ is used to describe all forms of liquid or solid water in the atmosphere, such as rain, snow, hail, sleet, drizzle and graupel. The latest methods also make use of other observation systems such as GPS humidity sensors, wind profilers and lightning detection systems, together with the outputs from Numerical Weather Prediction models.

This chapter provides an introduction to these techniques. The topic of measurement uncertainty is also discussed, with particular reference to weather radar observations. For example, in operational use, information on the spatial and time-varying structure of errors can help to decide how much credence to attach to observations, particularly when used as inputs to a flood forecasting model or a multi-sensor approach. As discussed in Chap. 12, there is also the potential to adopt a more risk-based approach to issuing flood warnings, based on a combination of the probability and consequences of flooding.

Later chapters discuss the related topics of telemetry systems (Chap. 3) and verification techniques for rainfall observations and forecasts (Chap. 4). More generally, the topic of precipitation measurement is an active area for research with many international and national initiatives underway, as illustrated by the examples in Chap. 12. It is also worth noting the role that the World Meteorological Organisation (WMO) plays in defining technical standards and producing guidelines, and some key publications in this area include World Meteorological Organisation (2000, 2007, 2008, 2011). Further information is provided in the many texts on this topic, including those by Strangeways (2007), Michaelides et al. (2008) and Testik and Gebremichael (2010).

2.2 Raingauges

2.2.1 Background

Raingauges are perhaps the most widely used approach for measuring rainfall. Gauges may be installed specifically for flood warning purposes, or for a range of water resources, agricultural and other applications. Most weather stations also include at least one raingauge and in some cases raingauges are installed at river gauging sites.

For manually operated (non-recording) raingauges, the rainfall depth is typically measured in a graduated cylinder at a fixed time each day by volunteers or paid observers; for example, the Community Collaborative Rain, Hail and Snow network (CoCoRaHS) network in the USA has more than 10,000 active observers (http://www.cocorahs.org/). A similar number report on weather conditions, snowfall and other parameters in the National Weather Service Cooperative Observer Program (http://www.nws.noaa.gov/om/coop/).

Fig. 2.2 Examples of raingauges at a weather station in the UK (*left*) and an IFLOWS installation in the USA (*right*). Integrated Flood Observing and Warning (IFLOWS) systems are widely used in flood warning systems in the eastern USA (e.g. see Box 6.1) and have similar origins to the ALERT protocol discussed in Chap. 3; here, the gauge is situated at the top of the structure, which also houses a data logger and telemetry equipment

In some applications, a larger storage gauge is operated alongside the manual gauge to provide a check on the cumulative daily totals over longer periods, such as at monthly intervals. These types of gauge are also useful in remote areas, where daily access is not possible. In some circumstances – for example, in post-event analyses following a major flash flood event – buckets, discarded containers and other receptacles may also provide a useful guide to the amount of rainfall which has fallen.

For automated gauges, a wider range of techniques is used. For example, for tipping bucket raingauges (e.g. Fig. 2.2), the principle of operation is that wedge-shaped 'buckets' on a lever arm alternately fill, causing the lever to tip, allowing the water to drain away and the second receptacle to take its place. The mechanism is calibrated to tip when a given volume of water has been collected, expressed as a depth of rainfall. Each tip then generates an electrical signal suitable for recording by an electronic data logger and, if required, conversion by a modem into a form suitable for telemetry transmission (see Chap. 3). Typically, when gauges are purchased, the recording depth is chosen according to the anticipated rainfall intensities at the gauge location. For example, 0.2 or 0.5 mm gauges are widely used in flood warning applications.

Another automated approach to measuring rainfall is to use instruments which rely on the weight or depth of water collected. For example, vibrating wire, strain gauge or load-cell approaches are typically used in weighing raingauges, and electrodes or floats to record depths. Drop-counting devices (or disdrometers) are also widely used in calibration studies for weather radars and in an increasing number of other applications. Typically these use optical or laser transmitters and receivers a short distance apart which detect the number, size and/or velocity of droplets and other types of precipitation passing through the beam (e.g. Fig. 12.1). Alternatively, in impact types, a piezoelectric sensor is used to count the number of droplets striking the surface, together with the impact forces to provide an indication of the size of each drop. A related approach is to design the gauge so that the size of passing into the instrument is almost independent of rainfall intensity, so that only the number needs to be counted.

Impact types, in particular, form a small, low-maintenance device with no moving parts and are increasingly used in road weather information systems and urban areas. Microwave-based systems with a range of kilometres also show promise as a way of estimating the path-averaged rainfall and are discussed in Chap. 12. Another solid-state option is a hot-plate gauge which consists of two heated plates, upward- and downward- facing, which are designed to measure both snow water equivalent and rainfall. The precipitation rate is estimated by 'calculating the power required to either melt or evaporate snow or to evaporate rain on the upward-facing plate, compensated for wind effects by subtracting out the power on the lower, downward-facing plate' (Rasmussen et al. 2011).

For flash flood applications, automated gauges are generally preferred if budgets allow, typically using 1-, 5- or 15-min recording intervals. However, it is worth noting that manually operated gauges are used successfully in many community-based flood warning systems, supported by a network of volunteer observers (e.g. Box 1.2). Low-cost automated raingauge and weather station instruments are also increasingly used by weather enthusiasts, with the web-based outputs providing another potentially useful source of information to national meteorological and hydrological services.

The choice of the type and make of gauge to use depends on a number of factors, including performance, cost, reliability, maintenance requirements, organisational standards and the level and quality of vendor support. However, a 2008/2009 World Meteorological Organisation survey of techniques for measuring solid precipitation at automatic weather stations (Nitu and Wong 2010) suggested that, at that time, the most common type of instrument in use in national meteorological and hydrological services was the tipping bucket raingauge (approximately 83% of responses). The next most widely used option was the weighing raingauge (16%) and, across all types, the most common reporting intervals were either 1-min or hourly. However, wide variations were reported in terms of manufacturers and gauge orifice areas, capacity, sensitivity and other factors. The survey also focused on national services and the preferred types may differ in local and regional organisations.

2.2.2 Interpretation of Observations

As with other types of instrumentation, there are some limitations on the accuracy of observations from a raingauge. In addition to the calibration and electromechanical issues associated with each type, a number of other factors can be important. For example, during high winds, errors often occur due to local distortions of the wind field around the gauge, and splashing sometimes occurs in heavy rainfall.

Wind effects from nearby buildings, hills and trees may also affect readings and low-lying gauges are also potentially at risk from being submerged by flood waters.

To assess and reduce wind-related problems, so-called ‘reference gauges’ are sometimes installed, in which the gauge is located in a mesh-covered pit with the opening at ground level. Also, in colder climates, snowfall can affect readings or even block or cover the instrument, although this can be overcome to some extent by adding an electrical heater to the gauge and/or a wind shield or snow fence. Maintenance issues sometimes also cause problems; for example, with vegetation growing around the gauge, or grass cuttings, sand, insects or falling leaves blocking the instrument.

To help to avoid these issues, many countries have national standards for the installation and operation of raingauges and for assessing the uncertainty in outputs. These are typically based on international guidelines and the findings from intercomparison experiments (e.g. World Meteorological Organisation 2008; Sevruk et al. 2009; Vuerich et al. 2009). Some examples of the types of siting criteria which are used include maximum heights above the ground and minimum distances to obstacles of a given type or height, such as trees or buildings. However, for flood warning applications, for reasons of cost, practicality, security and other factors, compromises are sometimes made compared to the ideal installation. There may also be technical reasons for installing raingauges at greater heights above ground level than standard and accepting the resulting reductions in accuracy; for example in locations where extensive snow cover is a regular occurrence or flooding is a potential risk.

When measurements are received via a telemetry system, these are typically screened for outliers through comparisons with historical maximum values and readings from nearby gauges. Suspect values are then flagged for further investigation. In multi-sensor systems (see Sect. 2.5), other types of observations are often used as part of this quality control process, such as those from weather radar, satellite, or lightning detection systems. For example, this may help to confirm that an unusually high value could have been due to a storm, or that a long period of zero values was due to the gauge being frozen or blocked by snow. For flood warning applications in particular, a key requirement is to identify and remove or correct anomalous values in near real-time without unintentionally removing genuine extreme observations. Empirical corrections are also widely used to help to compensate for wind-effects and other types of error (e.g. World Meteorological Organisation 2009).

In many cases, spatial estimates of rainfall are required from a network of raingauges; for example, to help with weather radar signal processing (see Sect. 2.3) and for some types of flood forecasting models (see Chap. 5). The methods used range from simple Thiessen polygon and inverse distance approaches to surface fitting techniques such as Kriging and spline and multiquadric approaches (e.g. Creutin and Obled 1982; Tabios and Salas 1985; Seo 1998; Goovaerts 2000; Daly 2006). For the more complex approaches, the analyses are often performed with the assistance of digital terrain models and Geographic Information System (GIS) tools. Some techniques also provide an estimate of the uncertainty arising from the spatial averaging process.

Although it is difficult to generalize, simpler techniques are usually used primarily in low-lying or flat terrain and/or where rainfall events are typically reasonably extensive and homogeneous, such as with widespread frontal storms. By contrast, the more complex techniques tend to perform better in complex terrain particularly if additional variables such as elevation or aspect are included in the analysis, such as with co-Kriging approaches. Geostatistical approaches are also widely used in weather radar raingauge adjustment schemes (see Sect. 2.3). However, for all methods, the density of the raingauge network is a key factor which determines the accuracy of the results, particularly for convective events.

By contrast, schemes which require expert judgement or interactive computer processing – such as isohyetal techniques – are rarely used in flash flood warning applications due to the lack of time for manual inputs. However they are widely used in post-event analyses of flash flood events due to the greater accuracy which is sometimes possible. Another practical challenge can arise when the records from several organisations need to be combined, perhaps using the outputs from different types of gauges using different reporting intervals and quality control standards. This typically requires extensive studies to decide how best to combine the data from the sources available.

More generally, when developing a catchment averaging scheme, observations from manually-read gauges are often included in the analysis since network densities are usually higher than for telemetered gauges. Although values are typically only available on a daily basis, they can provide an indication of storm total rainfall, and sometimes reveal spatial variations in rainfall which could be incorporated into a real-time averaging scheme, such as rain-shadow areas and influences from elevation or aspect. Other factors which are sometimes considered include indicators which describe the influence of features such as the slope, inversion-height characteristics, storm-directions, coastal influences, and types of event (frontal, orographic, convective etc.). Again, a GIS-based approach is widely used for these types of analyses; for example interpreting real-time observations by reference to a grid-based precipitation climatology (e.g. Daly et al. 1994; Zhang et al. 2011).

If archived weather radar observations are available, these can provide a useful comparison, and might in some cases lead to the decision to use radar-rainfall estimates as input to any flood forecasting component. For example, time sequences of radar images for major storms sometimes show consistent patterns for storm tracks, speeds and scales, and indicate areas of orographic enhancement. Comparisons with observations for individual raingauges or on a catchment-wide basis might then suggest giving a greater weighting to some gauges. Where budgets allow, experimental studies using dense networks of raingauges are also useful for investigating the spatial distribution of rainfall and developing catchment averaging techniques (e.g. Krajewski et al. 2003; Villarini et al. 2008; Volkmann et al. 2010).

However, for flash flood applications, one challenge is that the gauge densities required are often higher than for many other applications. The requirements vary between types of flash flood and some examples are provided in later chapters. Also, a more general issue is that, due to access difficulties and lower population densities, the spatial coverage of gauges is often poor at high elevations with – at best - only a few real-time gauges available, such as at major reservoirs and experimental sites. In these situations, another approach to assessing the adequacy of the gauge coverage is to investigate the likely impacts of the resulting uncertainties on forecasting model performance at the lead times of interest. For example one possibility is to compare the model performance - with and without data assimilation - using different choices of raingauges and averaging schemes, including any non-telemetered gauge records available. There have been many studies of this type although results tend to be specific to individual catchments, models and applications (see Chaps. 8–12).

2.3 Weather Radar

2.3.1 Background

Radar technology was first introduced operationally in the 1930s as a way of tracking aircraft. Experimental trials for meteorological applications began soon after the Second World War when it was realized that the interference from rainfall could be useful as a way of remotely observing precipitation. One of the first national systems was the WSR-57 network in the USA for which the first radars were installed in 1959. Many other countries soon followed although, due to cost and other factors, there are still a number with just a few sites serving major airports or population centres, or none at all.

Where a network is available, the resulting rainfall intensity images are widely used in flash flood applications; for example to track the progress of thunderstorms. The precipitation estimates are also used as a basis for short-range rainfall forecasting (or nowcasting; see Chap. 4) and as an input to real-time flood forecasting models and flash flood guidance approaches (see Chaps. 5 and 8). Meteorological services are also increasingly using weather radar outputs as part of the data assimilation process for mesoscale and convective-scale forecasting models (see Chap. 4).

The basic principle of operation is that an electromagnetic (microwave) signal is transmitted and the backscattered energy is recorded from rainfall and other objects. Magnetron or klystron transmitters are normally used. The signals are transmitted in pulses with the time delay – or 'listening' time – between transmissions much longer than the time of the pulse itself. If precipitation is encountered, the power of the reflected signal can be related to the range and a parameter called the radar reflectivity factor which depends on the drop size distribution. With certain key assumptions (see later), the reflectivity can then be related to the rainfall intensity at the ground surface whilst the time delay between transmission and reception provides an indication of the range.

The signal is transmitted from an antenna dish which is typically rotated at a few revolutions per minute and protected from the elements by a radome. The antenna is normally mounted on a steel or concrete tower, with key equipment kept in one or more nearby buildings (e.g. Fig. 2.3).

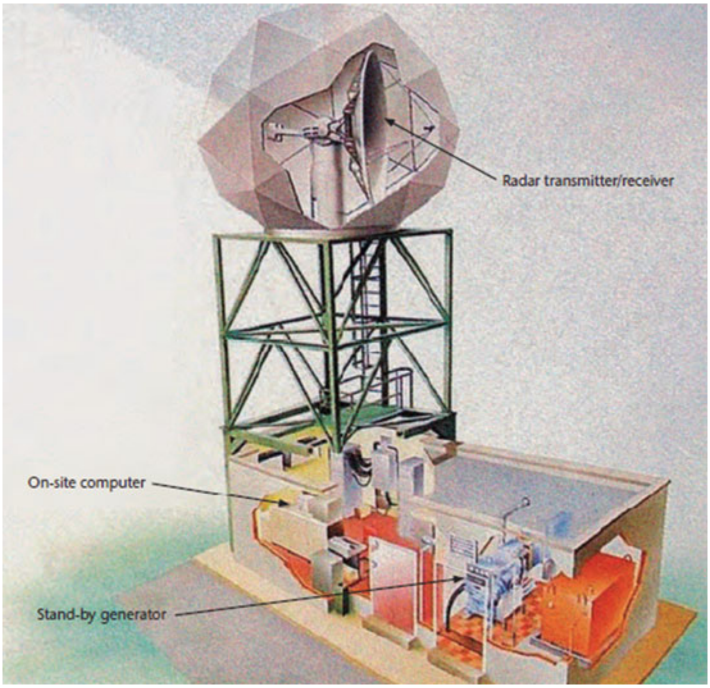

Fig. 2.3 View of the internal workings of a weather radar (Met Office 2009; Contains public sector information licensed under the Open Government Licence v1.0)

To provide an indication of rainfall and wind variations with altitude, several scanning angles are typically used with a full-volume scan completed over a period of several minutes. Beam angles typically range from horizontal or slightly above the horizontal to several degrees or more, and slightly negative angles are sometimes used in mountainous areas to view precipitation below the elevation of the instrument. In some systems, the scanning strategy can be adjusted depending on the current atmospheric conditions; for example, by using a faster rotation rate with more scan elevations for a rapid assessment of heavy rainfall, or a slower rate with fewer scan elevations to increase the sensitivity for wind profiling in clear-air.

The transmitting frequency used is normally in the C- or S-band, with wavelengths of about 5 and 10 cm respectively (e.g. Fig. 2.4). S-band instruments have a longer range and suffer less from signal attenuation in rainfall at a given range; however, they usually cost significantly more than C-band devices and are less sensitive to lighter rainfall. To provide an indication, the price of a modern C- or S-band instrument and associated infrastructure is typically of the order of one-million dollars or more, although costs continue to reduce as the technology improves.

At the network design stage, in addition to cost considerations, the choice of sites, wavelength, beam width, scan angles and other design features is typically made on the basis of detailed studies of a number of factors (e.g. Leone et al. 1989;

Fig. 2.4 Example of a Met Office C-band weather radar in the UK (*left*) and a NOAA/National Weather Service S-band (NEXRAD) radar in the USA (*right*) (Met Office 2009: Contains public sector information licensed under the Open Government Licence v1.0, and courtesy: National Oceanic and Atmospheric Administration http://www.erh.noaa.gov/)

World Meteorological Organisation 2008). These typically include site access considerations, local topography and typical storm and rainfall characteristics in a region (scale, locations, intensities etc.), and the intended applications (e.g. flood warning, aviation, weather forecasting). In some cases this includes field experiments using raingauge, satellite, drop-size (disdrometer) and other observations. Risk-based or multi-criteria analyses are also increasingly used to assess the suitability of a network for each proposed application; for example in terms of the coverage in urban areas or for catchments which have a high flood risk.

For individual radars, the practically useful detection range depends on a number of factors, including the local topography and the elevation of the instrument, but is typically about 200–300 km for C-band devices and more for the S-band. However, due to the curvature of the earth, at the maximum range the beam is typically at a considerable altitude even for the lowest scan angle. The spatial resolution also decreases due to the spread of the beam. For example, “a nominal 1° beam spreads to 0.9, 1.7 and 3.5 km at ranges of 50, 100, and 200 km, respectively”, with a beam at an elevation of 0.5° approximately 4km above the Earth’s surface at a range of 200km (World Meteorological Organisation 2008). For quantitative estimates of rainfall intensity – rather than images – the practically useful range is therefore less than the maximum detection range and can vary significantly between seasons due to atmospheric and other influences.

In operational use, the backscattered power is usually related to rainfall using a power law relationship between reflectivity and rainfall rate or intensity (Marshall and Palmer 1948). Typically the parameters in the relationship are calibrated based on comparisons of raingauge and radar estimates of rainfall, and in some cases from more detailed investigations using disdrometers and other meteorological instrumentation. The resulting relationships are then optimized for typical storm conditions in a region. When the drop size distribution varies from these conditions the outputs may under- or over-record rainfall; for example in exceptionally heavy rainfall or light drizzle. However, in some systems, it is possible to select alternative coefficients depending on the time of year or the operator's view on the most appropriate form to use in the prevailing conditions; for example by choosing stratiform, convective or tropical rainfall options.

Since the 1970s, instruments have increasingly been equipped with Doppler capability such that it is nowadays a standard feature in most networks. The resulting variations in phase or frequency between successive pulses then allow an estimate to be derived for the velocity of hydrometeors in the pulse volume (rain, snow, hail etc.). Since this depends on both the size and type of object, this can help to discriminate between rainfall and other types of precipitation, and false echoes such as those from aircraft, birds, insects and ground clutter.

A more recent development has been to retrofit existing radars with dual polarization capability and to make this standard for new instruments. This is sometimes referred to as a dual-pol. approach and falls within the more general category of polarimetric or multi-parameter approaches. Here, rather than just using a single plane (usually, but not always, horizontal), the microwave pulse is transmitted with both horizontal and vertical polarization and the characteristics of the reflected signal are recorded in both planes. As discussed in Box 2.1, this allows a number of additional parameters to be calculated which provide further information on the type and intensity of precipitation, and greatly assist with the quality control of observations. This approach has recently started to be used operationally in a number of national weather radar networks, including those in the USA, UK, France and Japan.

The operational use of X-band radars – which have a wavelength of about 3 cm and a range of about 30–60 km or more – is another recent development, although they have been used in research for many years. One limitation is the shorter range and greater signal attenuation from rainfall than for C- and S-band instruments. However, a major attraction is the lower cost and greater sensitivity to rainfall. It is also easier to find suitable locations for new installations; for example, a typical diameter for the antenna dish is of the order 1 m compared to about 10 m for an S-band radar. Some typical applications are to support heavy rainfall and flood warnings near major population centres and for rainfall detection in regions with complex terrain, thereby supplementing and 'filling gaps' in the national network coverage. Some locations where this approach is used or under development include parts of the USA, Japan (see Box 10.1) and Denmark (e.g. Pedersen et al. 2007; Maki et al. 2010; McLaughlin et al. 2009). Another development is the use of adaptive or 'agile' scan strategies to focus monitoring effort on the areas of most rapid storm development (see Chap. 12).

In some cases, mobile C- and X-band radars are also used in flash flood applications, and are typically transported on a truck to be installed where needed for a few weeks or months (see Box 9.1 for example). In the USA significant investments are also being made in a new generation of solid state phased array radars, as discussed in Chap. 12. More generally, information on the types of instruments used internationally is sparse but some trends can be deduced. For example, in the National Weather Service NEXRAD network, S-band Doppler dual polarisation devices are the standard approach (see Box 2.1). The situation in Europe is more mixed, with a database of information for 30 countries (http://www.knmi.nl/opera/) indicating 32 S-band, 162 C-band and 2 X-band instruments, of which 170 were Doppler equipped and 38 used dual polarization (database version 1.18; 1 June 2012).

By contrast, in the first feedback from a World Meteorological Organisation survey, with responses from 66 countries – including the USA and parts of Europe – 11 countries stated that they presently had no weather radar systems (Sireci et al. 2010). Of the 48 countries which provided detailed information, the top three applications were for nowcasting, large scale weather monitoring and flood warning. Also, there was a roughly equal split between magnetron and klystron transmitters, but overall only 7% of instruments were said to have dual polarization capability. However, since the time of that survey, dual polarization upgrades have been completed in several of the countries surveyed.

Box 2.1 Dual Polarization Weather Surveillance Radar, USA

The National Weather Service has operated a network of weather surveillance radars since the 1940s and Table 2.1 summarises some key historical developments (NOAA 2010). The most recent change is the upgrade to dual polarization (dual-pol or polarimetric) capability. The basis of the technique is that microwave pulses are transmitted in both the horizontal and vertical planes, rather than just the horizontal. Modifications to the existing fleet of 159 radars were made to the antenna hardware and by providing additional signal and post-processing software, without affecting the existing scanning strategies, data resolution or reflectivity and velocity algorithms.

The availability of reflected power and phase information in two planes allows several new parameters to be calculated in addition to the reflectivity factor for horizontal polarization Z_h. These include (Ryzhkov et al. 2005; Scharfenberg et al. 2005; Schlatter 2010):

- The differential reflectivity (Z_{DR}) which is a measure of the log of the ratio of the reflected horizontal to vertical power returns. Z_{DR} is approximately zero dB for spherical hydrometeors and becomes positive when these are horizontally oriented and – much less frequently – negative when vertically oriented (e.g. in an electrical field). It provides an indication of the presence of hail and of the median rain drop shape and hence size
- The specific differential phase (K_{DP}) which is the mean rate of change of the differential phase per kilometre, where the differential phase is a measure

(continued)

Box 2.1 (continued)

Table 2.1 Some key developments in the weather surveillance radar network in the USA

Date	Description
1947	US Basic Radar Network started, based on converted radars from World War 2
1959	S-Band Weather Radar Surveillance network started (WSR-57 radars)
1971	First Doppler radar installed at the National Severe Storms Laboratory (NSSL)
1976	Installation of local C-band radars (WSR-74C) and additional S-band radars (WSR-74S)
1976–1979	Field tests of 4 Doppler radars as part of the Joint Doppler Operational Project
1984	First research trials of dual polarization radar at NSSL
1990–1997	Installation of the NEXRAD network of 159 S-Band Doppler radars (WSR-88D)
2002–2003	Joint POLarization Experiment at NSSL on dual polarization techniques (JPOLE)
2011–2012	Upgrade of the NEXRAD network to dual polarization

of the shifts (or lag) between horizontal and vertical phases; for example, due to passing through rainfall. The differential phase is near zero for spherical objects and higher for horizontally-oriented objects, with the magnitude of the change also increasing with particle concentration. It is useful for distinguishing between precipitation and other echoes, for identifying regions of high liquid content even in the presence of hail, and for estimating rain-rate

- The correlation coefficient (CC or ρ_{HV}) between horizontally and vertically polarized power returns. This is typically higher (close to 1.0; perfect correlation) for meteorological echoes that are fairly uniform in shape and size, such as rain and snow, and lower for more irregular shapes, such as clear air returns (blooms) caused by concentrations of birds and insects, and ground clutter. It is extremely useful for differentiation of precipitation vs. non-precipitation targets and for identifying melting layers, giant hail and airborne tornadic debris

In particular, some advantages of using the differential phase parameter include its immunity to radar calibration errors, attenuation in precipitation, and partial blockage of the radar beam (Ryzhkov et al. 2005). Various other correlation parameters can also be estimated between transmitted and reflected components although their relationship to precipitation characteristics is less well understood.

Based on extensive field trials (Ryzhkov et al. 2005; Scharfenberg et al. 2005), some key benefits which have been found include significant improvements to

(continued)

Box 2.1 (continued)

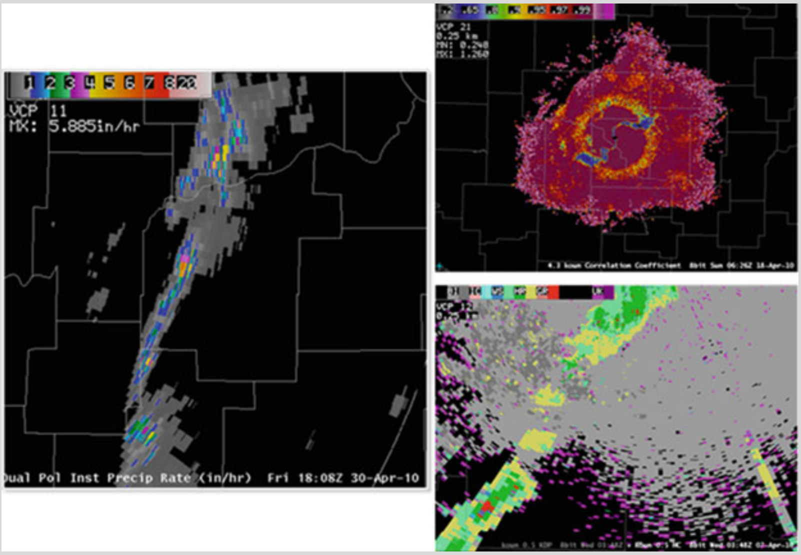

Fig. 2.5 Some examples of outputs from a dual polarization radar in Oklahoma. From the top right clockwise: Melting Layer Detection Algorithm outputs clearly showing a bright-band ‘ring’; Hydrometeor Classification Algorithm outputs (HR = heavy rain, GR = graupel, WS = wet snow, IC = Ice Crystals, UK = Unknown); Dual-Pol QPE outputs showing the instantaneous precipitation rate in inches/hour (NOAA/National Weather Service; Schlatter 2010)

radar data quality and rainfall estimates, and an improved ability to distinguish rainfall echoes from other types of return, such as those caused by anomalous propagation and non-hydrometeors. For example Zrnic and Ryzhkov (1999) note that polarimetry has the potential to:

- Improve quantitative precipitation estimation
- Discriminate hail from rain and possibly gauge hail size
- Identify precipitation type in winter storms (dry/wet snow, sleet, rain)
- Identify electrically active storms
- Identify biological scatterers (birds, insects) and their effects on wind measurements; and
- Identify the presence of chaff and its effects on precipitation measurements

Other benefits include the ability to identify airborne tornadic debris and to provide qualitative improvements in precipitation estimates.

For the NEXRAD dual-polarization upgrades, in addition to the three base products described above, three new algorithms were made available (e.g. Fig. 2.5):

(continued)

Box 2.1 (continued)

- Melting Layer Detection Algorithm – which detects the melting layer based on reduced values for the correlation coefficient CC
- Hydrometeor Classification Algorithm – which makes a best guess of the dominant hydrometeor type for every beam elevation angle, using the following classification scheme: light/moderate rain, heavy rain, hail, 'big drops', graupel, ice crystals, dry snow, wet snow, unknown
- Dual-Pol QPE – an advanced precipitation estimation algorithm making use of dual-polarization parameters

2.3.2 Interpretation of Observations

As with any other type of instrumentation, there are a number of strengths and limitations with weather radar observations.

For flash flood applications, the most obvious advantage is the ability to observe precipitation over an extensive area, including catchments which have no raingauges. However, there is the intrinsic physical limitation that – for each scan angle – values are recorded above rather than at the ground surface, with the beam width and minimum detection height increasing with distance from the radar. Even the lowest beam may therefore overshoot some forms of precipitation, such as low-level orographic rainfall. Some other potential issues include blockage and ground clutter from mountains, buildings, wind farms and other obstacles, plus sea clutter for some sites. Also, for fast-developing storms, significant changes to precipitation and wind fields can occur in the time that it takes to perform a full volume scan.

To help to overcome some of these issues, when a network of radars is operated, the processed outputs are normally combined into a mosaic or composite image to make best use of all of the observations available. This is sometimes the only product available but in some cases single site raw and/or processed values are provided; for example to users who wish to use their own post-processing algorithms. Composite outputs are usually processed from the original polar scans to a grid-based format. For example, rainfall intensity values might be provided as 5-min accumulations on a 1 km grid around radar sites but with the resolution decreasing to 2 km and then 5 km at greater distances (although the values used differ between organisations). For multi-sensor precipitation products (see Sect. 2.5), the inclusion of other types of outputs is also being explored, such as military radars, the Doppler radars which are often used at major airports, and the privately-operated C- and X-band radars used by television stations in some countries.

To assist with interpreting outputs, maps of coverage are often produced and in some cases are made publicly available. For example, Fig. 2.6 shows one of the reflectivity products available from the national weather radar network in the USA.

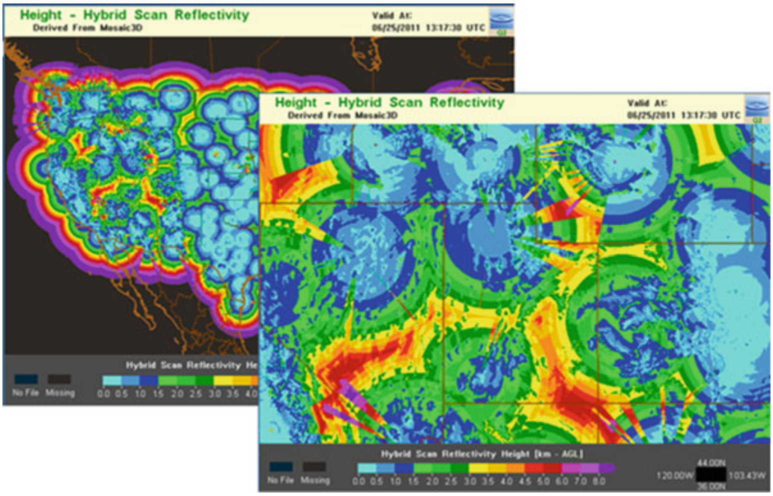

Fig. 2.6 Example of outputs for the hybrid scan reflectivity height (HSRH) from the US weather radar network on 25 June 2011. The *zoomed-in area* shows details for parts of Utah, Nevada and Colorado illustrating the gaps in coverage in these mountainous states. HSRH is the height of the lowest non-missing single radar hybrid scan reflectivity at each NMQ grid cell and has units of kilometres above ground level, where the NMQ product is discussed in Box 2.3 (http://nmq.ou.edu/)

Simpler pre-defined clutter maps or masks are also widely used to provide an indication of the maximum useful range. These are typically based on a one-off digital terrain model analysis taking into account topography, obstacles (buildings, wind farms etc.) and – in some cases – beam power distributions for standard atmospheric conditions. Long-term average values of the reflectivity may also reveal fixed artefacts in the observations and variations in performance in different seasons.

There are a number of other potential issues with the coverage and accuracy of observations and some key points are summarized in Table 2.2 and illustrated in Figs. 2.5 and 2.7. In some cases these issues also present opportunities; for example, for the study of insects and bats (in the emerging field of aeroecology) or to derive near-surface humidity estimates for data assimilation in atmospheric models, based on variations in propagation times to the locations of known ground clutter, such as nearby hills (e.g. Weckworth et al. 2005).

However, where possible corrections are usually applied to filter out or take account of these influences. The various stages in the analysis typically include signal-processing and quality control, hydrometeor classification and product generation (e.g. Collier 1996; Bringi and Chandrasekar 2001; Meischner 2004; World Meteorological Organisation 2008; Villarini and Krajewski 2010).

For example, one approach which has been widely introduced since the 1990s is to improve estimates for the surface precipitation using assumed values for the Vertical Profile of Reflectivity (VPR). Typically use is made of mean (climatological)

Table 2.2 Some factors which can affect the accuracy of weather radar observations of precipitation, in addition to uncertainties in rainfall-reflectivity relationships and physical limitations (ground clutter, range-related issues etc.)

Type	Item	Description
Hardware-related	Mechanical or electrical	Antenna pointing errors, electronic stability issues, downtime for maintenance or repair, signal interference from external sources
	Radome attenuation	Attenuation of the reflected signal due to wetting of the radome. A hydrophobic coating is often used to reduce this effect and correction algorithms are increasingly applied (e.g. storm emission-based approaches)
Atmospheric	Aeroecology	Reflections from concentrations of birds, bats and/or insects, sometimes called blooms or bloom echoes
	Anomalous propagation/ducting	Curvature of a beam due to variations in refraction arising from air temperature and humidity gradients, in some cases causing the beam to strike the ground. Sometimes referred to as anaprop
	Clear-air echoes	Minor influences on backscattered radiation due to variations in refractivity due to turbulence, inversions, wind shear etc.
Precipitation	Evaporation	Evaporation of precipitation beneath the lowest beam elevation
	Orographic enhancement	Low-level rainfall arising from topographic influences beneath the lowest scan height
	Snow and hail	Increased reflectivity from hail in convective storms and the 'bright-band' effect where snowflakes turn to rain; for example in some winter, stratiform conditions (e.g. Fig. 2.5)
	Updrafts/downdrafts	Influences on fall velocities from updrafts and downdrafts, particularly in convective storms
	Wind shear	Horizontal advection of precipitation, particularly beneath the lowest beam, with the effect most apparent for drizzle and light rainfall

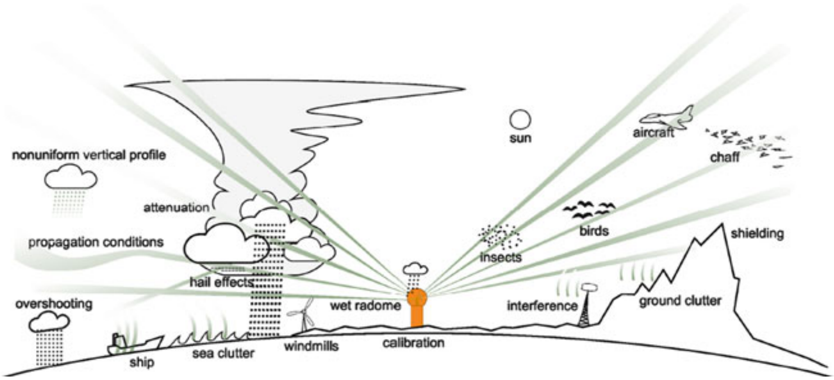

Fig. 2.7 Phenomena affecting radar data quality (Holleman et al. 2006 and OPERA, a project and operational service of EUMETNET EIG)

or parameterized values for the radar site or real-time estimates based on profiles measured near to the radar or averaged across parts of the scan volume. Profiles are typically applied on an area-wide or pixel-by-pixel basis, sometimes distinguishing between different types of precipitation (e.g. Fig. 2.9 in Box 2.3). In some cases, satellite observations and the outputs from atmospheric models are used as part of the correction process, such as for estimates of the freezing level and wind fields. In some systems, conceptual or statistical models are used to help to account for orographic and other local effects beneath the lowest beam elevation.

More generally, telemetered raingauge observations are widely used in adjusting radar outputs. Views differ on the best approach to use and, in some organisations, whether real-time adjustments should be made at all. For example, where the raingauge coverage is sparse, adjustments can degrade rather than improve rainfall estimates in ways that are not easily anticipated. The technique also tends to work better for widespread frontal events where rainfall is relatively uniform, rather than for convective events. The main choices are to apply adjustments in real-time, or to use typical bias and other correction factors derived over the past few days or more (e.g. Wood et al. 2000; Gjertsen et al. 2004). In some cases, hybrid versions are used which combine aspects of both approaches.

The adjustments are typically expressed in the form of functions of the ratio between radar and raingauge values at and around coincident grid-squares. This could be as simple as a single mean-field value applied across the whole domain, or range-dependent or spatially-varying estimates. In the latter case, spatial interpolation techniques which are used include inverse distance, Kalman filter, Kriging, multiquadric and Bayesian approaches (e.g. Wilson and Brandes 1979; Todini 2001; Moore 1999; Seo and Breidenbach 2002). Some options for deciding on the best approach to use include analyses of past performance and field trials using dense networks of raingauges at experimental sites.

The use of raingauge data is sometimes described as bias-correction of radar observations. However there are also errors in raingauge observations and, in some adjustment schemes, an allowance is made for these uncertainties. More generally, raingauge-adjusted outputs can be regarded as a form of multi-sensor precipitation product, using just two observation systems. A next step beyond that is to use additional types of observations such as those from satellites and lightning detection systems, and this topic is discussed in Sect. 2.5.

2.3.3 Weather Radar Products

The outputs from a weather radar network are typically made available as a suite of products to meet the needs of a range of end users; for example, providing estimates for rainfall rates, wind speeds and directions, and other parameters. Boxes 2.1 and 2.3 show several examples of the types of output available. In some organisations, products are made available for several different stages in the processing of outputs, such as the following examples for rainfall rate:

- Single site – the raw reflectivity outputs; users then need to apply their own quality control and signal processing algorithms, including raingauge adjustments if applicable and the conversion from polar to grid coordinates
- Mosaic Level I – a basic quality controlled rainfall composite product, with no real-time raingauge adjustments, although possibly including weekly (or other) bias adjustments
- Mosaic Level II – as for Level I but including real-time raingauge adjustments and more sophisticated correction procedures
- Mosaic Level III – as for Level II but inspected by an experienced forecaster and – if appropriate – adjusted before distribution to end users
- Multi-sensor – automated products which use raingauge, satellite, lightning and other observations, and atmospheric model outputs, to improve estimates (see Sect. 2.5)

Here the different levels of output provided are just for illustration and the terminology used varies widely between organisations. For example, the following WMO classification is often adopted: Level I (primary data or instrument readings), Level II (meteorological variables and processed data) and Level III (derived meteorological parameters) (World Meteorological Organisation 2007). Typically several products are made available for parameters such as rainfall, wind profiles, and cloud top heights, together with newer types of products from dual polarization radars, where available. Increasingly outputs include data quality indices or other estimates for the uncertainty in outputs (see Box 2.2).

From a hydrological perspective, perhaps the best approach to deciding whether to use raingauge or radar-based estimates of rainfall is to compare the outputs over a number of rainfall events, ideally over a period of several years, both in terms of rainfall and when used as an input to flood forecasting models. For example, some meteorological services now maintain archives of radar observations dating back a decade or more. In some countries, long-term reanalyses of outputs are also planned or underway taking account of the impacts of changes in raingauge networks and radar hardware and signal-processing techniques during the analysis period

Box 2.2 Uncertainty Estimates for Weather Radar Products

For real-time operation, it is often useful to provide an indication of the uncertainty in weather radar products. For example, this information can be used when combining the outputs from multiple instruments to form a mosaic or composite, particularly in locations where this involves observations from more than one organization or country. Probabilistic outputs are also potentially useful for input to flood forecasting models (see Chap. 12) and in guiding the generation of ensembles in nowcasting approaches (see Chap. 4). Other potential applications include "validation of radar and rain gage data merging procedures, testing of various methods for computation of mean areal precipitation, and sensitivity analysis of rainfall-runoff models" (Krajewski and Georgakakos 1985).

Perhaps the most widely-used approach to date has been to provide data quality flags or indices as an indication of performance (e.g. Holleman et al. 2006; Einfalt et al. 2010). Values are typically presented on a scale of 0 to 1, 100 or 255 with associated metadata describing any vertical profile of reflectivity or other corrections applied. This information provides a guide on the confidence to attach to outputs and can be used in algorithms which combine the outputs from multiple sites into composite or mosaic products. It is also potentially useful when deciding whether to assimilate weather radar data into Numerical Weather Prediction models.

Both static (global) and dynamic (real-time) indices are used. Typically values are derived on a pixel-by-pixel basis, with static estimates based on physical limitations such as range, ground clutter, and beam height, or long-term (climatological) observations. By contrast, real-time values are typically based on pre-defined thresholds or confidence limits linked to reflectivity observations and possibly other information, such as satellite observations.

For example, following a Europe-wide survey, Norman et al. (2010) proposed three levels of complexity relying on: reflectivity and some global quality factors (level 1); incorporating 'climatological' data such as frequency of detection or clutter maps (level 2); and using additional dynamic information such as the height of the freezing level from Numerical Weather Prediction models (level 3). It was noted that users may wish to receive three types of quality information: the likelihood of an echo being from a hydrometeor, the quality of the reflectivity measurements, and the quality of the conversion of these values to a rainfall intensity at the ground surface.

Data quality indices also provide an indication of the uncertainty in outputs but there are some limitations with this approach. An alternative is to derive direct estimates for the error covariance matrix or simplified representations of it, such as an ensemble estimate. This approach aims to represent

(continued)

Box 2.2 (continued)

both the spatial and temporal relationships in the uncertainties in the precipitation field, although there are still numerous factors to understand about the error structure (e.g. Krajewski and Smith 2002). However, for flash flood warning applications, one potential advantage of deriving quantitative estimates of uncertainty is that – when used as input to a flood forecasting system – this can potentially assist in taking risk-based decisions based on a combination of probability and consequence, such as whether to operate a flood control gate or evacuate a residential area. However, this is a developing research area and is discussed further in Chap. 12.

There have been numerous off-line (simulation) studies of the uncertainties in weather radar observations, using stochastic, error decomposition and other approaches. Simulations of this type and practical experience generally suggest that the spatial sampling error 'decreases with increasing area size, increasing time period, increasing *(rain)* gage density, and increasing rainfall amount' (Wilson and Brandes 1979, reported by Krajewski et al. 2010). However, for real-time use, rather than trying to combine individual sources of error, with assumptions about their spatial and temporal inter-relationships, another approach is to derive an estimate for the overall error by comparisons with raingauge observations (e.g. Ciach et al. 2007; Germann et al. 2009; Mandapaka and Germann 2010). This can also be extended to include a consideration of the uncertainties in the raingauge observations themselves, and in satellite and other observation systems if using a multi-sensor approach (see Sect. 2.5).

(e.g. Delrieu et al. 2009; Moulin et al. 2009; Krajewski et al. 2010). The simulated values aim to reflect the current operational performance of the network and are potentially of great use in developing flood forecasting models and for other hydrological applications.

For real-time use, when radar outputs are used as inputs to a flood forecasting model, a number of other factors usually need to be considered. Typically these include the need to establish a reliable means of delivery (e.g. leased line, high-speed broadband), a service level agreement (or similar), data archiving facilities, and round-the-clock support arrangements. In some cases, additional software is required for receiving, viewing and post-processing the radar outputs and several systems are commercially available. If possible, a system of version control should also be established to notify end users of any significant changes in hardware or signal processing algorithms which might affect flood forecasting applications.

Many research studies have also been performed to compare the various weather radar products and analysis techniques which are available, and to share both observations and best practice. For example, in Europe, approximately 30 countries participate in the OPERA programme of EUMETNET (http://www.knmi.nl/opera/).

Similarly, for a World Meteorological Organisation intercomparison experiment, a prioritized list of Quantitative Precipitation Estimation (QPE) issues cited in the project concept document (http://www.wmo.int/) included:

- Ground Clutter and Anomalous Propagation
- Vertical Profile of Reflectivity
- Partial Occultation
- Reflectivity Bias Calibration (Monitoring)
- Attenuation Correction/Handling
- Minimize Impact of DSD (*Drop Size Distribution*) Variability
- Gauge Adjustment (function of density)
- Consistent verification and Data Quality Metrics
- Uncertainty/Scale/Probability Concepts

2.4 Satellite Precipitation Estimates

2.4.1 Background

Satellite observation systems have transformed many aspects of natural hazard monitoring since they were first introduced in the 1960s. For meteorological applications, some quantities which can be measured or inferred include (World Meteorological Organisation 2008):

(a) The temperature profile, and the temperature at the cloud top and at the surface of the sea and land
(b) The humidity profile
(c) The wind at cloud level and at the ocean surface
(d) Liquid and total water and precipitation rate
(e) Net radiation and albedo
(f) Cloud type and height of cloud top
(g) Total ozone
(h) The coverage and the edge of ice and snow

For flash flood applications, the images provided are typically used to help forecasters track the progression of frontal systems, tropical cyclones and other major features. However, as discussed in Chaps. 8–11, due to spatial resolution issues the quantitative use of satellite precipitation estimates has been limited to date except in regions with sparse raingauge coverage and no weather radar networks. More generally, though, satellite observations play an important role in data assimilation for Numerical Weather Prediction models (see Chap. 4) and in producing multi-sensor precipitation products (see Sect. 2.5). As discussed in Chaps. 3 and 12, observations of soil moisture, snow cover and land use are also potentially useful as inputs to distributed rainfall-runoff models.

The two main types of satellite system use geostationary and low earth or polar orbits. For meteorological observations, international coordination is provided by the Coordination Group for Meteorological Satellites (CGMS) which provides both design and operational support; for example by facilitating the temporary relocation of geostationary satellites in case of problems with any individual spacecraft (http://www.cgms-info.org/).

Geostationary satellites are placed into an orbit chosen to maintain a fixed position relative to a point on the ground, with an orbital height of about 36,000 km. For meteorological applications, approximately six satellites are required to provide complete coverage up to latitudes of about 55°, although polar-orbiting satellites need to be used as well for a full global coverage (World Meteorological Organisation 2007). Images are typically provided every 15–30 min in the visible, water vapour and infrared bands at a spatial resolution of 1–4 km. In some systems there is also the option to use a faster rapid-scanning mode to focus on smaller areas on the earth surface. Some satellites also include additional sensors for monitoring carbon dioxide, ozone and other constituents and for space observations.

Currently the main meteorological geostationary satellites are those within the NOAA GOES, European Meteosat and Japanese MTSAT (formerly GMS) programmes, together with those operated by India, China and the Russian Federation. For example, the GOES and Meteosat programmes include 2–3 primary satellites each. These are all operated by national or international agencies with data made available to national meteorological and hydrological services for use in weather forecasting and other applications. Since the 1970s, a number of replacement satellites have been launched within these programmes, with each upgrade providing additional functionality, resolution and reliability. The instrumentation used typically includes imagers and sounders. Data collection and distribution systems are often also included and are widely used for the telemetry of hydrological and meteorological data (see Chap. 3).

Polar and Low Earth Orbit (LEO) satellites by contrast are operated at much lower altitudes and therefore normally provide higher resolution observations, but move relative to a fixed location on the ground. For example, polar orbits typically have an altitude of 800–1000 km with an orbital time of about 100 min. Global coverage is then provided over a number of orbits. For a single satellite, the orbits used often mean that the time for which a location is visible in each day is quite limited, with intervals of much as 1–3 days for some low earth orbits. For example, one estimate suggested that, for US satellites alone, the 3-hourly coverage averages about 80% of the earth's surface for latitudes of up to 50° (Huffman et al. 2007) although this continues to improve. However, most meteorological satellites are placed into sun synchronous polar orbits so that the satellite passes twice over a given location on the equator at approximately the same time each day.

Microwave instruments are often carried on polar orbiting satellites for humidity, soil moisture and other observations. Several military, civil and commercially operated systems provide information which is potentially useful for natural hazard-related applications, or intended specifically for weather forecasting, such as those within the NOAA-N, NASA Aqua, European MetOp and NASA NPP programmes. The sensors carried vary between systems but some examples include the Special Sensor Microwave Imager Sounder (SSMIS; successor to SSM/I), Advanced Microwave Sounding Unit (AMSU), Microwave Humidity Sounder (MHS) and – for visible and infrared observations – the Advanced Very High Resolution Radiometer (AVHRR).

The outputs from research satellites are potentially also useful although do not necessarily have the same standards of availability and quality control as for operational satellites. For flash flood applications, one programme of particular interest is the joint US/Japanese Tropical Rainfall Measuring Mission, or TRMM (http://trmm.gsfc.nasa.gov/; http://www.eorc.jaxa.jp/TRMM/). This was the first satellite to carry a space-borne precipitation radar and this operates on the same principle as ground-based instruments although using the shorter K_u-band (wavelength ~2 cm) to provide a lightweight instrument and low power consumption.

The satellite was launched in 1997 for an anticipated 3–5 years although the mission was subsequently extended beyond 2010 due to the value of the information provided. It operates in an equatorial orbit at an altitude of approximately 400 km and with a path between about 35°N to 35°S, with 16 orbits per day and an orbital time of about 90 min. The horizontal resolution of the radar observations is approximately 5 km and the outputs have been used in numerous research studies and some operational applications. The satellite also carries visible and infrared scanning, microwave imager (TMI), lightning imaging and radiated energy instruments. It will be replaced by the more advanced Global Precipitation Measurement (GPM) mission constellation of satellites (Hou et al. 2008) which is potentially of great interest for flash flood applications (http://pmm.nasa.gov/GPM/) and is described in Chap. 12.

2.4.2 Interpretation of Observations

To interpret satellite observations, numerous corrections need to be applied for instrumental, atmospheric and other factors. Table 2.3 shows some examples of the types of derived outputs which are used in meteorological applications, in addition to the raw radiance and imagery outputs. Due to limitations on the coverage, accuracy and resolution of individual sensors, products are often based on the outputs from several sensors.

Precipitation products form another category and again are often derived from a combination of the outputs from different sensors and systems (e.g. World Meteorological Organisation 2000; Scofield and Kuligowski 2003; Vasiloff et al. 2007; Gebremichael and Hossain 2009; Sorooshian et al. 2011). In general terms, in addition to the TRMM radar-based approach (see previous section), the main types of technique include:

- Infrared/visible-based estimates – algorithms which typically make use of geostationary observations of cloud-top brightness temperatures and cloud extent

Table 2.3 Some examples of the types of satellite-based products which are used in meteorological applications (categories based on World Meteorological Organisation 2007)

Category	Typical inputs	Examples of products
Cloud characteristics	Visible, infrared	Cloud top temperatures, types, heights, masks etc.
Atmospheric temperature and humidity soundings	Infrared, microwave	Vertical profiles of air temperature and humidity
Atmospheric motion winds	Sequences of cloud, water vapour or ozone images or fields	Estimates for wind speeds and directions at various levels
Land and sea surface temperatures	Infrared (cloud-free), radiometers, microwave (sea temperatures)	Estimates with various spatial resolutions and coverages
Snow and ice	Visible, infrared, microwave	Spatial coverage, plus snow depth estimates for active microwave instruments
Vegetation	Visible, infrared	Vegetation type and growth, leaf area index etc.
Ocean surface	Microwave (active), scatterometer	Sea-level (altimetry), significant wave height, wind intensity etc.

and morphology to estimate rainfall intensity. A key assumption is that rainfall intensities at the ground are greater for deeper formations, which reach higher altitudes and hence lower temperatures. This assumption applies primarily to convective clouds and is less valid for other types, such as cirrus, stratiform and orographic cloud, and for situations with appreciable wind-shear of cloud tops. In addition to images at a given time, life-history approaches are sometimes used to provide information on the stage of development of a cloud system based on a sequence of images. Products of this type started to become available operationally soon after the first geostationary satellites were launched in the 1970s

- Microwave-based estimates – algorithms which use passive microwave observations from polar orbiting satellites to infer the water and ice content of cloud formations based on emissions of cloud water. This technique generally works best over the oceans where there is a sharp contrast with the background levels of radiation. Over land, a different approach is used, which is to observe the masking effect of cloud on brightness temperatures. This works best in situations where there are significant amounts of cloud ice particles present, and less well for warmer orographic cloud, for example. The first operational products of this type were based on the SSM/I sensor, which was first flown in the 1980s and has since been joined by a number of other systems (AMSU, TMI etc.; see previous section)

Of these two approaches, microwave techniques generally provide more accurate estimates of precipitation but less frequently and at a lower spatial resolution. For a given location on the ground, the best temporal and spatial resolutions currently achieved are typically 15 min/4 km for geostationary satellite-based precipitation products and 3-6 h/15 km for passive microwave-based products (Vasiloff et al. 2007). However, the performance depends on a number of factors, including the choice of sensors, the signal processing algorithms used, and atmospheric conditions (e.g. Sorooshian et al. 2011).

Regarding signal processing, a wide variety of techniques has been developed, including physically-based, conceptual and data-driven methods, used either alone or in combination. Combined, merged or 'data fusion' products are also increasingly available which combine the strengths of different approaches. Typically these take advantage of the higher frequency of geostationary observations and the greater accuracy of polar-orbit based observations (e.g. Heinemann et al. 2002; Huffman et al. 2007; Kidd et al. 2008; Box 2.3). For example, one widely used approach is to use cloud tracking or advection schemes based on geostationary observations to 'infill' missing periods in microwave-based observations (e.g. Joyce et al. 2004).

Some algorithms also make use of the outputs from atmospheric models, such as for the wind field and relative humidity (e.g. Scofield and Kuligowski 2003). Products have also been developed which combine satellite observations and real-time or recent raingauge observations (e.g. Xie and Arkin 1996; Tian et al. 2010). In research studies, the TRMM space-borne precipitation radar has also proved to be a valuable tool for evaluation and real-time calibration of microwave-based satellite precipitation products.

With each new generation of satellite, additional techniques are developed to make use of the improvements in accuracy and resolution which become available, and some current research priorities include (e.g. Turk et al. 2008; Sorooshian et al. 2011):

- Quantification of the uncertainty in individual sensors and precipitation products
- Optimization of algorithms for different climate regions, storm regimes, surface conditions, seasons, and altitudes
- Further development of performance metrics

To help to provide a focus for this development work, the International Precipitation Working Group was established in 2001 (Turk et al. 2008). Since 2003, one activity has included routine reporting of comparisons with raingauge and weather radar observations for locations in several regions, including parts of Australia, Europe, South America, Japan and the USA. For example, one finding based on comparisons of nine satellite precipitation products and the outputs from four Numerical Weather Prediction (NWP) models (Ebert et al. 2007) was that, for daily values over land at ~25 km spatial scales:

> Satellite estimates of rainfall occurrence and amount are most accurate during summer and at lower latitudes, while the NWP models show greatest skill during winter and at higher latitudes. Generally speaking, the more the precipitation regime tends toward deep convection, the more (less) accurate the satellite (model) estimates are.

2.5 Multi-sensor Precipitation Estimates

When precipitation measurements are available from several observation systems then a logical next step is to combine the best features from each approach into a single estimate. In weather radar research, products of this type are often called Multi-sensor Precipitation Estimates (MPE) whilst the term High Resolution Precipitation Product (HRPP) is also used in satellite-based applications. The terms multi-parameter, multi-sensor fusion, blending, multisource or data fusion are also used.

The generation of this type of product has been a topic for research for many years with many operational applications appearing in the past one to two decades. The impetus for development has arisen from several directions with many aspects in common, including the following examples:

- Nowcasting – the blending of weather radar, raingauge, satellite, lightning detection and other real-time observations to provide an initial precipitation, cloud and visibility analysis for use in short-range weather forecasting, sometimes guided by the outputs from Numerical Weather Prediction models; see Sect. 4.3 (e.g. Golding 1998; Wilson 2004)
- Satellite Precipitation Estimates – the use of both geostationary and polar-orbiting satellite observations, sometimes including real-time raingauge and weather radar observations where these are available, and making use of the outputs from Numerical Weather Prediction models; see Sect. 2.4 (e.g. Xie and Arkin 1996; Scofield and Kuligowski 2003; Turk et al. 2008)
- Weather radar – the long-established use of real-time raingauge observations to adjust radar rainfall observations, more recently making use of satellite and other types of observations and Numerical Weather Prediction model outputs for the quality control of outputs and infilling of areas with poor coverage; see Sect. 2.3 (e.g. Wilson and Brandes 1979; Zhang et al. 2011)

More generally, the use of multiple sources of observations in the data assimilation process has been routine since the outset for Numerical Weather Prediction models. However, as discussed in Chaps. 4 and 12, in recent years the increasing use of higher resolution convective-scale and mesoscale models has led to the need to consider a wider range of observation systems (e.g. Dabberdt et al. 2005).

Table 2.4 provides some examples of the types of observations which could potentially be included in a multi-sensor precipitation product. In a multi-sensor approach, the aim is typically to use sensors which either provide direct estimates of precipitation, or clues to the presence of precipitation or rain-bearing storms. For example, visible and infrared observations from satellites can show whether a given pixel contains cloud of a type likely to generate rainfall, whilst lightning observations often indicate the presence of convective activity, such as thunderstorms. Numerical Weather Prediction model outputs also provide useful information on atmospheric conditions at different elevations and the extent of cloud and precipitation. Many of the examples shown in the table are candidates for use in a multi-sensor approach and Box 2.3 describes one system which combines several of these types of inputs: the National Mosaic and Multi-sensor QPE (NMQ) System in the USA.

Table 2.4 Some examples of the types of observations which could be used in multi-sensor precipitation estimates, in addition to raingauge, weather radar and satellite observations

Technique	Description
Aircraft- and ship-borne instruments	Automated equipment for monitoring key atmospheric parameters, for transmission by radio or satellite telemetry. For example, aircraft typically report on wind speed and direction, air temperature, altitude, a measure of turbulence and the aircraft position. In some countries (e.g. the USA) this approach has been extended to include turboprop aircraft which typically operate at lower altitudes than jet aircraft. Several thousand aircraft and ships are included in these long-established voluntary programmes (World Meteorological Organisation 2007)
Ground-based GPS	The use of ground-based Global Positioning System receivers in conjunction with surface air pressure observations to estimate the atmospheric precipitable water or integrated water vapour. The estimates are based on the time delay of the signal between satellite and ground, expressed in terms of ionospheric or hydrostatic and 'wet' or water vapour related components. This technique is useful both to assist with thunderstorm forecasting and data assimilation in atmospheric models and has been increasingly used by meteorological services since the 1990s (e.g. Fig. 12.1)
Lightning detection systems	Ground-based networks for detecting the locations of cloud-to-ground lightning flashes, typically inferred from the differences in time of travel to each sensor of electromagnetic waves in the lower atmosphere. These low-frequency emissions sometimes propagate for hundreds of kilometers. These observations are increasingly used as part of the data assimilation process in atmospheric models and in thunderstorm forecasting (see Chap. 4)
Radiosondes	Expendable air pressure, air temperature and humidity sensors for providing vertical profiles within the atmosphere, launched on helium-filled weather balloons and typically using a radio transmitter to relay data. Approximately 1,000 are launched twice each day internationally as part of a coordinated effort within the WMO World Weather Watch Programme and heights of up to 20–35 km are reached. Rawinsondes also provide information on wind speed and direction
Weather Stations	Automatic or manually operated sites typically combining air temperature, air pressure, wind speed, wind direction, humidity, solar radiation, rainfall and (sometimes) other sensors, such as for soil temperature and snow cover. Synoptic stations usually record other parameters such as visibility, cloud cover, present weather and cloud-base. Instruments are mainly operated from land-based locations (including airports and meteorological stations), ocean buoys and oil and gas platforms. Smaller instruments incorporating mainly solid-state sensors are widely used in road weather information systems
Wind profilers	Ground-based vertically-pointing UHF and other radar-based instruments for continuously measuring the vertical wind profile in the lower atmosphere, and sometimes equipped with radio-acoustic sounding systems for estimating air temperature profiles. For example, in one widely used approach, wind speeds at different levels are deduced from the frequency shifts and time of travel for several beams transmitted vertically and at an angle to the vertical resulting from backscattering due to variations in refractivity. Profilers provide the advantage of continuous monitoring of wind speed and, in some cases, air temperature profiles, and have been widely used since the 1990s (e.g. Fig. 12.1)

As for weather radar and satellite observations, it is important to understand the uncertainty in outputs, both for the final multi-sensor product and the individual inputs which are used. The general approaches which are under development are similar to those described in Box 2.2 for weather radar observations with the results presented as quality indices, ensemble outputs, and error covariance matrices. Again, to assess the performance for extreme events, it is often desirable to perform a reanalysis exercise using the present operational configuration of sensors and algorithms (e.g. Nelson et al. 2010). However, it is worth noting that if Numerical Weather Prediction model outputs are used in the product generation process then – as discussed in Chap. 4 – this can be a considerable undertaking.

Box 2.3 NMQ Multi-sensor Precipitation Estimates, USA

Weather radar, satellite and raingauge observations provide estimates for precipitation at different temporal and spatial scales and to varying degrees of accuracy. To help to overcome these limitations, multi-sensor products aim to build on the strengths of each measurement system and to infill any gaps in coverage. The outputs from Numerical Weather Prediction models can also assist with the interpretation of observations and spatial interpolation of data.

For more than a decade, the various NOAA agencies involved in developing multi-sensor precipitation estimates have been combining their efforts to develop a suite of operational products. These include Quantitative Precipitation Estimation (QPE) products for applications such as flash flood warning and water resources management and 3-D radar mosaic tools to assist in severe weather detection, aviation applications and data assimilation for atmospheric models. Contributors include the National Severe Storms Laboratory (NSSL), the Office of Hydrologic Development (NWS/OHD), and the Office of Climate, Water, and Weather Services, together with the Federal Aviation Administration (FAA) and the Central Weather Bureau of Taiwan.

The overall programme is called the National Mosaic and Multi-sensor QPE (NMQ) System (Zhang et al. 2011). Some necessary capabilities which have been identified include (Vasiloff et al. 2007):

- real-time processing of radar, rain/snow gauge, satellite, lightning, and NWP output data
- quality control tools for input datasets
- variable resolution and formatting of input data and output products
- long-term retrospective analysis, that is, reanalysis
- robust verification and assessment tools
- integration of externally derived precipitation products
- high-bandwidth servers for product generation and dissemination

(continued)

Box 2.3 (continued)

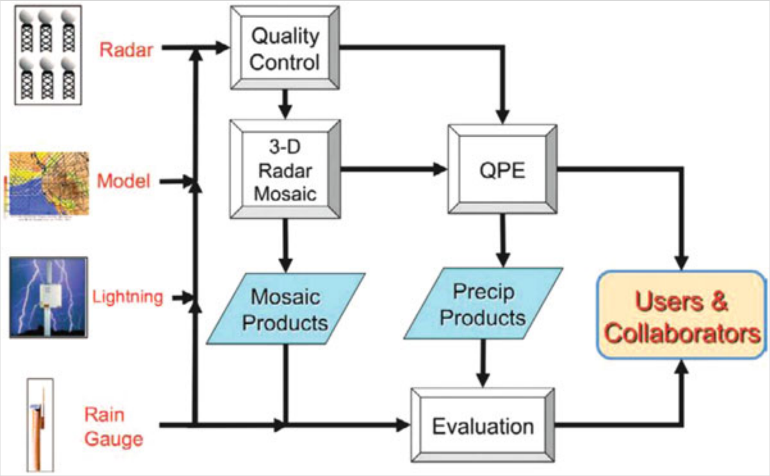

Fig. 2.8 An overview flowchart of the NMQ system illustrating some of the key inputs (Zhang et al. 2011)

Since 2006, experimental products have been generated with a 1 km horizontal resolution and 2.5 min (formerly 5 min) update cycle. These are distributed via a publicly available website (http://nmq.ou.edu/) and directly to key users, and a rolling 3-year archive is also available on-line. The outputs cover the continental regions of the USA, excluding Alaska and off-shore territories.

Since 2007, the NMQ precipitation outputs have also been provided to National Weather Service River Forecasting Centers (RFCs) in parallel with products from the existing Multi-sensor Precipitation Estimator (MPE). From an operational perspective, in addition to including new data sources and algorithms, more use is also made of automation for the initial data quality control, gap-filling and blending of sources. As part of the development programme, extensive comparisons have also been performed both with other precipitation estimators and with the outputs when used with distributed rainfall-runoff models (e.g. Kitzmiller et al. 2011).

The types of real-time observations which feed into the system change as technological developments occur but the main inputs include (Fig. 2.8):

- A quality-controlled three dimensional (3-D) reflectivity mosaic at a grid scale of approximately 1 km for 31 vertical levels derived from more than 140 of the S-Band NEXRAD WSR-88D weather radars operated in the USA and from the Environment Canada network of 31 C-band radars

(continued)

Box 2.3 (continued)

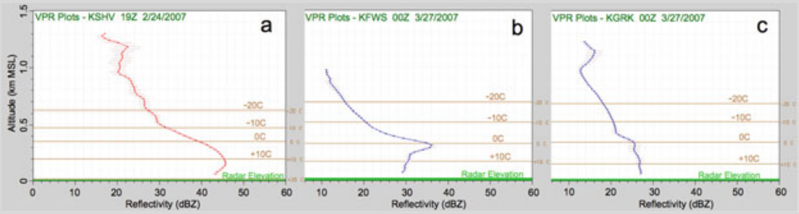

Fig. 2.9 Examples of Vertical Profiles of Reflectivity (VPRs) for (**a**) convective, (**b**) stratiform and (**c**) tropical precipitation. The *horizontal lines* indicate, from *top to bottom*, −20, −10, 0, and 10 °C temperature heights at the radar sites. Some features suggested in the profiles include (**a**) a region with coalescent growth of large rain droplets and possibly hail stones immediately above cloud base at ~1,500 m (**b**) a bright-band feature near the freezing level and (**c**) continued growth towards the ground of a large amount of medium sized raindrops in a very moist environment (Zhang et al. 2011)

- Ground-based observations from several thousand raingauges transmitted via Data Collection Platforms to the GOES East and GOES West geostationary satellites for initial processing by the Hydrometeorological Automated Data System HADS (http://www.weather.gov/oh/hads/WhatIsHADS.html)
- Short-range forecasts from the NOAA/NCEP Rapid Update Cycle/Rapid Refresh atmospheric model which has a 13 km grid scale at 50 vertical levels and is updated every hour from 1 to 18 h ahead (Benjamin et al. 2004, http://rapidrefresh.noaa.gov/)

Several other types of observation are also ingested, including lightning observations and data from selected Terminal Doppler Weather Radars and television station radars.

The multi-sensor products are derived by automatically comparing and combining outputs from these individual systems. For example, estimates for the probability of severe hail and the maximum hail size are derived primarily from the 3-D radar reflectivity and model-derived air temperature analyses.

For flash flood forecasting, one key component of the overall system is the next-generation QPE (Q2) suite of tools, which derive best estimates for the types and intensity of precipitation. This includes an automated precipitation classification scheme which is based on information from the 3-D reflectivity mosaic, the model outputs, and lightning, surface air temperature and moisture observations. The algorithm distinguishes at a pixel scale between stratiform, convective and warm rain, hail and snow and then applies an adaptive reflectivity relationship appropriate to the type of precipitation. Vertical profile of reflectivity corrections are also applied (e.g. Fig. 2.9).

(continued)

Box 2.3 (continued)

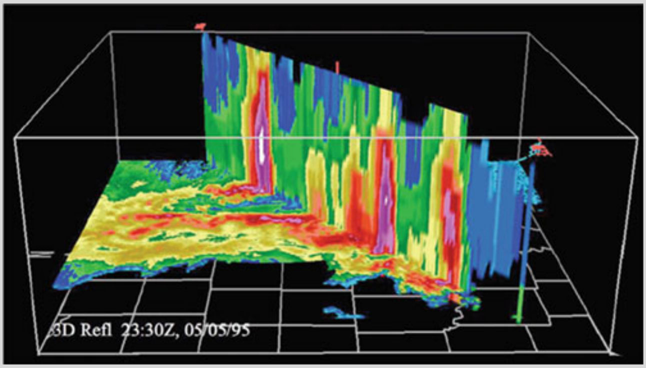

Fig. 2.10 Horizontal and vertical cross-sections from the 3-D reflectivity mosaic of a hail storm in Dallas on 5 May 1995 (Zhang et al. 2011)

For example, the procedure used to distinguish between convective and stratiform rain makes use of threshold values of reflectivity, the detection of one or more cloud-to-ground lightning flashes in the vicinity of the pixel within the last 5 min, and vertical profiles of air temperature from the atmospheric model (Zhang et al. 2011).

Some other Q2 products include raingauge-adjusted radar rainfall outputs, produced using an inverse-distance weighting scheme and – for the western USA – the 'Mountain Mapper' raingauge product which is derived using a high-resolution reference precipitation climatology (Daly et al. 1994; Schaake et al. 2004). Where raingauge values are used, these are first checked using a suite of validation tools which search for anomalous values and reject those that seem implausible.

In total, approximately 20 products are available. Some other examples include real-time assessments of weather radar coverage and quality and cross sections of 3-D reflectivity for any user defined cross section across the USA and southern Canada (e.g. Fig. 2.10).

The NMQ system and website also includes a suite of real-time verification outputs, based on comparisons with telemetry observations from local and regional raingauge networks and manually recorded values provided by the extensive national voluntary observer network (e.g. Fig. 2.11; see also http://www.cocorahs.org/). Outputs from other systems are also available for comparison, such as the satellite-based Hydro-Estimator product (Scofield and Kuligowski 2003).

The statistics which are reported include the bias, correlation coefficient and root mean squared error, with outputs provided on a map, tabulated and graphical basis. One particular focus for validation is the western USA

(continued)

Box 2.3 (continued)

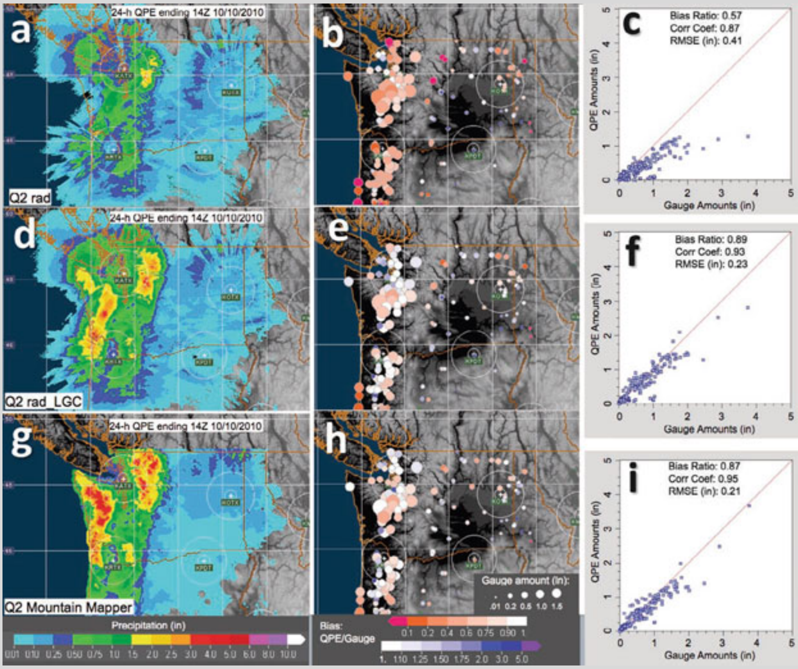

Fig. 2.11 24-h accumulations of precipitation estimates in the Pacific-Northwest region for the period ending at 1400 UTC on 10 October 2011 (**a**) Q2 radar (**d**) Q2 radar with local raingauge correction and (**c**) Q2 raingauge-only Mountain Mapper. The bubble charts (**b**, **e**, and **h**) show the bias ratios between the three different Q2 products and manually-recorded (CoCoRaHS) raingauge observations, where the circle size represents gauge-observed amount and the intensity of shading represents the Q2/gauge bias. The scatter plots (**c**, **f**, and **i**) show the correlation between the Q2 estimated and raingauge-observed amounts. Similar plots for other types of rainfall (e.g. convective) and/or in other parts of the USA (e.g. the southwestern USA) often show better performance for the Q2 radar-raingauge product (Zhang et al. 2011)

where, due to the mountainous terrain, there are significant gaps in radar coverage (e.g. Fig. 2.6 – see main text).

Some current areas for research include how best to use space-borne radar observations of precipitation from the TRMM satellite and its successor (GPM), improvements to hydrometeor identification and radar data quality control using dual polarisation outputs, the use of gap-filling X-band and mobile C-band radars, and the development of techniques to quantify the uncertainty associated with each product. More generally, the community-wide approach which is being adopted easily allows researchers access to data and provides a ready-made validation framework for the evaluation of new techniques as these become available.

2.6 Summary

- Raingauges provide direct measurements of rainfall at a single location. Tipping bucket gauges are perhaps the most widely used recording type, although weighing gauges and solid state instruments are increasingly used. When a network of gauges is available, catchment-wide and other spatial estimates are typically derived using weighting or surface-fitting approaches, with the accuracy of the estimates dependent on the density of the gauge network, topography, typical storm types and scales, and a range of other factors
- Weather radar networks are used in many countries although – due to the expense – the coverage is limited in some parts of the world. The accuracy of outputs continues to improve with Doppler techniques introduced in the 1990s and dual polarisation methods recently adopted in several countries. The spatial view of precipitation makes radar a useful complement to raingauge observations although with some assumptions needed to estimate values at the ground surface and to compensate for other sources of error. C- and S-band devices are generally used in national networks although shorter range X-band radars are increasingly used for gap-filling and in flash flood and other applications
- The complementary nature of raingauge and weather radar observations has led to the widespread use of raingauge adjustment schemes for radar outputs. In recent years, this approach has been extended to make use of other sources of real-time information, such as the outputs from Numerical Weather Prediction models and satellite and lightning observations. The resulting outputs increasingly include quality indices or ensemble estimates for the uncertainty
- Satellite precipitation algorithms provide a spatial estimate of rainfall but usually at a coarser spatial resolution and less frequent intervals than for weather radar. A number of products are available using a wide range of techniques and sources of real-time information. Increasingly these combine the visible and infrared observations from geostationary satellites with the microwave observations from polar orbiting satellites, in some cases guided by the outputs from Numerical Weather Prediction models
- In recent years, multi-sensor precipitation products have started to become available operationally and have great potential for flash flood (and other) applications. These are not tied specifically to any one observation system and aim to provide a best estimate of current precipitation from a wide range of sources together with an estimate for the uncertainty in the outputs
- For individual measurement systems, there are many guidelines and standards available. International intercomparison studies have also been performed for raingauges, weather radar products, and satellite precipitation estimates. These allow users to compare the performance of equipment and algorithms for different storm types and climatic regions, and in some cases – such as for satellite precipitation estimates – to view regular near real-time updates to results on a project website
- Some current research themes which are likely to benefit flash flood applications include the provision of real-time uncertainty estimates for all types of approach,

the increasing use (and understanding) of dual polarisation weather radar outputs, and improvements to the resolution and accuracy of satellite-based precipitation estimates. For the future, the outputs from the international Global Precipitation Mission (GPM) are likely to be of particular interest for flash flood applications.

References

Benjamin SG, Dévényi D, Weygandt SS, Brundage KJ, Brown JM, Grell GA, Kim D, Schwartz BE, Smirnova TG, Smith TL (2004) An hourly assimilation–forecast cycle: the RUC. Mon Wea Rev 132:495–518

Bringi VN, Chandrasekar V (2001) Polarimetric Doppler weather radar: principles and applications. Cambridge University Press, Cambridge

Ciach GJ, Krajewski WF, Villarini G (2007) Product-error-driven uncertainty model for probabilistic Quantitative Precipitation Estimation with NEXRAD data. J Hydrometeorol 8:1325–1347

Collier CG (1996) Applications of weather radar systems: a guide to uses of radar data in meteorology and hydrology, 2nd edn. Wiley, Chichester

Creutin JD, Obled C (1982) Objective analyses and mapping techniques for rainfall fields: an objective comparison. Water Resour Res 18(2):413–431

Dabberdt W, Schlatter T, Carr F, Friday E, Jorgensen D, Koch S, Pirone M, Ralph F, Sun J, Welsh P, Wilson J, Zou X (2005) Multifunctional mesoscale observing networks. Bull Am Meteorol Soc 86(7):961–982

Daly C (2006) Guidelines for assessing the suitability of spatial climate data sets. Int J Climat 26:707–721

Daly C, Neilson RP, Phillips DL (1994) A statistical-topographic model for mapping climatological precipitation over mountainous terrain. J Appl Meteor 33:140–158

Delrieu G, Braud I, Borga M, Boudevillain B, Fabry F, Freer J, Gaume E, Nakakita E, Seed A, Tabary P, Uijlenhoet R (2009) Weather radar and hydrology. Adv Water Resour 32:969–974

Ebert EE, Janowiak JE, Kidd C (2007) Comparison of near-real-time precipitation estimates from satellite observations and numerical models. Bull Am Meteorol Soc 88(1):47–64

Einfalt T, Szturc J, Ośródka K (2010) The quality index for radar precipitation data: a tower of Babel? Atmos Sci Lett 11(2):139–144

Gebremichael M, Hossain F (eds) (2009) Satellite rainfall applications for surface hydrology. Springer, Dordrecht

Germann U, Berenguer M, Sempere-Torres D, Zappa M (2009) REAL – ensemble radar precipitation estimation for hydrology in a mountainous region. Q J R Meteorol Soc 135:445–456

Gjertsen U, Šálek M, Michelson DB (2004) Gauge adjustment of radar-based precipitation estimates in Europe. In: ERAD 2004 3rd European conference on radar in meteorology and hydrology, Visby, 6–10 September 2004

Golding BW (1998) Nimrod: a system for generating automated very short range forecasts. Meteorol Appl 5:1–16

Goovaerts P (2000) Geostatistical approaches for incorporating elevation into the spatial interpolation of rainfall. J Hydrol 228:113–129

Heinemann T, Lattanzio A, Roveda F (2002) The EUMETSAT Multi-sensor Precipitation Estimate (MPE). In: Proceedings of the first International Precipitation Working Group (IPWG) meeting, Madrid, 23–27 September 2002. http://www.isac.cnr.it/

Holleman I, Michelson D, Galli G, Germann U, Peura M (2006) Quality information for radars and radar data. Deliverable: OPERA 2005 19, OPERA work package 1.2. http://www.knmi.nl/opera/

Hou AY, Skofronick-Jackson G, Kummerow CD, Shepherd JM (2008) Global Precipitation Measurement. In: Michaelides S (ed) Precipitation: advances in measurement, estimation and prediction. Springer, Dordrecht

Huffman G, Adler R, Bolvin D, Gu G, Nelkin E, Bowman K, Hong Y, Stocker E, Wolff D (2007) The TRMM Multisatellite Precipitation Analysis (TMPA): quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. J Hydrometeorol 8:38–55

Joyce RJ, Janowiak JE, Arkin PA, Xie P (2004) A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. J Hydrometeorol 5(3):487–503

Kidd C, Heinemann T, Levizzani V, Kniveton DR (2008) International Precipitation Working Group (IPWG): inter-comparison of regional precipitation products. 2008 EUMETSAT meteorological satellite conference, Darmstadt, Germany, 8–12 September 2008. http://www.eumetsat.int/

Kitzmiller D, Van Cooten S, Ding F, Howard K, Langston C, Zhang J, Moser H, Zhang Y, Gourley JJ, Kim D, Riley D (2011) Evolving multisensor precipitation estimation methods: their impacts on flow prediction using a distributed hydrologic model. J Hydrometeorol 12:1414–1431

Krajewski WF, Ciach GJ (2003) An analysis of small-scale rainfall variability in different climatic regimes. Hydrol Sci 48(2):151–162

Krajewski WF, Georgakakos KP (1985) Synthesis of radar rainfall data. Water Resour Res, 21(5):764–768

Krajewski WF, Smith JA (2002) Radar hydrology: rainfall estimation. Adv Water Resour 25: 1387–1394

Krajewski WF, Villarini G, Smith JA (2010) Radar-rainfall uncertainties: where are we after thirty years of effort? Bull Am Meteorol Soc 91(1):87–94

Leone DA, Endlich RM, Petričeks J, Collis RTH, Porter JR (1989) Meteorological considerations used in planning the NEXRAD network. Bull Am Meteorol Soc 70(1):4–13

Maki M, Maesaka T, Kato A, Shimizu S, Kim D-S, Iwanami K, Tsuchiya S, Kato T, Kikumori T, Kieda K (2010) X-band polarimetric radar networks in urban areas. ERAD 2010 – 6th European conference on radar in meteorology and hydrology, Sibiu, 6–10 September 2010. http://www.erad2010.org/

Mandapaka PV, Germann U (2010) Radar-rainfall error models and ensemble generators. In: Testik FY, Gebremichael M (eds) Rainfall: state of the science, vol 191. American Geophysical Union, Geophysical Monograph Series, Washington, DC

Marshall J, Palmer W (1948) The distribution of raindrops with size. J Meteorol 5(4):165–166

McLaughlin D, Pepyne D, Chandrasekar V, Philips B, Kurose J, Zink M, Droegemeier K, Cruz-Pol S, Junyent F, Brotzge J, Westbrook D, Bharadwaj N, Wang Y, Lyons E, Hondl K, Liu Y, Knapp E, Xue M, Hopf A, Kloesel K, DeFonzo A, Kollias P, Brewster K, Contreras R, Dolan B, Djaferis T, Insanic E, Frasier S, Carr F (2009) Short-wavelength technology and the potential for distributed networks of small radar systems. Bull Am Meteorol Soc 90(12):1797–1817

Meischner P (2004) Weather radar: principles and advanced applications, Series: Physics of Earth and Space Environments. Springer, New York

Met Office (2009) National Meteorological Library and Archive fact sheet 15 – weather radar (Version 01), Met Office, Exeter. http://www.metoffice.gov.uk/

Michaelides S (ed) (2008) Precipitation: advances in measurement, estimation and prediction. Springer, Dordrecht

Moore RJ (1999) Real-time flood forecasting systems: perspectives and prospects. In: Casale R, Margottini C (eds) Floods and landslides: integrated risk assessment. Springer, Berlin/Heidelberg

Moulin L, Tabary P, Parent du Châtelet J, Gueguen C, Laurantin O, Soubeyroux J-M, Dupuy P, L'Hénaff G, Andréassian V, Loumagne C, Andrieu H, Delrieu G (2009) The French Community Quantitative Precipitation Estimation (QPE) Re-analysis project: Establishment of a reference multi-year, multi-source, nation-wide, hourly QPE data base for hydrology and climate change studies. American Meteorological Society 34th conference on radar meteorology, Williamsburg, 5–9 October 2009. http://ams.confex.com/ams/

Nelson BR, Seo D-J, Kim D (2010) Multisensor precipitation reanalysis. J Hydrometeorol 11:666–682

Nitu R, Wong K (2010) CIMO Survey on national summaries of methods and instruments for solid precipitation measurement at automatic weather stations. Instruments and observing methods Report No. 102, WMO/TD No.1544, Geneva

NOAA (2010) An historical look at NEXRAD. NEXRAD Now, 20: 31–35. http://www.roc.noaa.gov/WSR88D/NNOW/NNOW.aspx

Norman K, Gaussiat N, Harrison D, Scovell R, Boscacci M (2010) A quality index scheme to support the exchange of volume radar reflectivity in Europe. ERAD 2010 – the sixth European conference on radar in meteorology and hydrology, Sibiu, 6–10 September 2010. http://www.erad2010.org/

Pedersen L, Jensen NE, Madsen H (2007) Network architecture for small X-band weather radars – test bed for automatic intercalibration and nowcasting. Paper 12B.2, 33rd conference on radar meteorology, 6–10 August 2005, Cairns, Australia

Rasmussen RM, Hallett J, Purcell R, Landolt SD, Cole J (2011) The hotplate precipitation gauge. J Atmos Oceanic Technol 28:148–164

Ryzhkov AV, Schuur TJ, Burgess DW, Heinselman PL, Giangrande SE, Zrnic DS (2005) The Joint Polarization Experiment. Polarimetric Rainfall Measurements and Hydrometeor Classification. Bull Am Meteorol Soc 86(6):809–824

Schaake J, Henkel A, Cong S (2004) Application of PRISM climatologies for hydrologic modeling and forecasting in the western U.S. Paper 5.3, American Meteorological Society 18th conference on hydrology, Seattle, 10–15 January 2004. http://ams.confex.com/

Scharfenberg KA, Miller DJ, Schuur TJ, Schlatter PT, Giangrande SE, Melnikov VM, Burgess DW, Andra DL, Foster MP, Krause JM (2005) The Joint Polarization Experiment: polarimetric radar in forecasting and warning decision making. Weather Forecast 20:775–788

Schlatter P (2010) The dual polarization radar technology update. Eastern Region Flash Flood Conference, Wilkes-Barre, 2–4 June 2010. http://www.erh.noaa.gov/bgm/research/ERFFW/

Scofield RA, Kuligowski RJ (2003) Status and outlook of operational satellite precipitation algorithms for extreme precipitation events. Weather Forecast 18:1037–1051

Seo D-J (1998) Real-time estimation of rainfall fields using rain gage data under fractional coverage conditions. J Hydrol 208(1–2):25–36

Seo D-J, Breidenbach JP (2002) Real-time correction of spatially nonuniform bias in radar rainfall data using rain gauge measurements. J Hydrometeorol 3:93–111

Sevruk B, Ondrás M, Chvílac B (2009) The WMO precipitation measurement intercomparison. Atmos Res, 92(3):376–380

Sireci O, Joe P, Eminoglu S, Akyildiz K (2010) A comprehensive worldwide web-based weather radar database. TECO 2010 WMO technical conference on meteorological and environmental instruments and methods of observation, Helsinki, 30 August – 1 September 2010. http://www.wmo.int/

Sorooshian S, AghaKouchak A, Arkin P, Eylander J, Foufoula-Georgiou E, Harmon R, Hendrickx JMH, Imam B, Kuligowski R, Skahill B, Skofronick-Jackson G (2011) Advancing the remote sensing of precipitation. Bull Am Meteorol Soc 92(10):1271–1272

Strangeways I (2007) Precipitation: theory, measurement and distribution. Cambridge University Press, Cambridge

Tabios GQ, Salas JD (eds) (1985) A comparative analysis of techniques for spatial interpolation of precipitation. J Am Water Resour Ass 21(3):365–380

Testik FY, Gebremichael M (2010) Rainfall: state of the science, vol 191. American Geophysical Union, Geophysical Monograph Series, Washington, DC

Tian Y, Peters-Lidard CD, Eylander JB (2010) Real-time bias reduction for satellite-based precipitation estimates. J Hydrometeorol 11:1275–1285

Todini E (2001) A Bayesian technique for conditioning radar precipitation estimates to rain-gauge measurements. Hydrol Earth Syst Sci 5(2):187–199

Turk FJ, Arkin P, Ebert EE, Sapiano MRP (2008) Evaluating High-Resolution Precipitation Products. Bull Am Meteorol Soc 89(12):1911–1916

Vasiloff SV, Seo D-J, Howard KW, Zhang J, Kitzmiller DH, Mullusky MG, Krajewski WF, Brandes EA, Rabin RM, Berkowitz DS, Brooks HE, McGinley JA, Kuligowski RJ, Brown BG (2007) Improving QPE and very short term QPF: an initiative for a community-wide integrated approach. Bull Am Meteorol Soc 88(12):1899–1911

Villarini G, Krajewski WF (2010) Review of the different sources of uncertainty in single polarization radar-based estimates of rainfall. Surv Geophys 31(1):107–129

Villarini G, Mandapaka PV, Krajewski WF, Moore RJ (2008) Rainfall and sampling uncertainties: a rain gauge perspective. J Geophys Res 113:D11102

Volkmann THM, Lyon SW, Gupta HV, Troch PA (2010) Multicriteria design of rain gauge networks for flash flood prediction in semiarid catchments with complex terrain. Water Resour Res 46:W11554

Vuerich E, Monesi C, Lanza LG, Stagi G, Lanzinger E (2009) WMO field intercomparison of rainfall intensity gauges (Vigna di Valle, Italy) October 2007 – April 2009. Instruments and Observing Methods Report No. 99, WMO TD-1504, Geneva

Weckwerth TM, Pettet CR, Fabry F, Park S, LeMone MA, Wilson JW (2005) Radar refractivity retrieval: validation and application to short-term forecasting. J Appl Meteorol 44:285–300

Wilson JW (2004) Precipitation nowcasting: past, present and future. Sixth international symposium on hydrological applications of weather radar, Melbourne, 2–4 February 2004

Wilson JW, Brandes EA (1979) Radar measurement of rainfall – a summary. Bull Am Meteorol Soc 60(9):1048–1058

Wood SJ, Jones DA, Moore RJ (2000) Static and dynamic calibration of radar data for hydrological use. Hydrol Earth Syst Sci 4(4):545–554

World Meteorological Organisation (2000) Precipitation estimation and forecasting. Operational Hydrology Report No. 46, WMO-No. 887, Geneva

World Meteorological Organisation (2006) Preventing and mitigating natural disasters: Working together for a safer world. WMO-No. 993, Geneva

World Meteorological Organisation (2007) Guide to the Global Observing System. WMO-No. 488, Geneva

World Meteorological Organisation (2008) Guide to meteorological instruments and methods of observation. WMO-No. 8, Geneva

World Meteorological Organisation (2009) Guide to hydrological practices, 6th edn. WMO-No. 168, Geneva

World Meteorological Organisation (2011) Guide to climatological practices, 3rd edn. WMO-No. 100, Geneva

Xie P, Arkin PA (1996) Analyses of global monthly precipitation using gauge observations, satellite estimates, and numerical model predictions. J Climate 9:840–858

Zhang J, Howard K, Langston C, Vasiloff S, Kaney B, Arthur A, Van Cooten S, Kelleher K, Kitzmiller D, Ding F, Seo D-J, Wells E, Dempsey C (2011) National Mosaic and Multi-sensor QPE (NMQ) System – description, results and future plans. Bull Am Meteorol Soc 92(10): 1321–1338

Zrnic DS, Ryzhkov AV (1999) Polarimetry for weather surveillance radars. Bull Am Meteorol Soc 80(3):389–406

Springer
http://www.springer.com/978-94-007-5163-7

Flash Floods
Forecasting and Warning
Sene, K.
2013, XIV, 386 p., Hardcover
ISBN: 978-94-007-5163-7