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Preface

Weather radar and hydrology

1. Introduction

The growing concerns about environmental and climate change issues, as well as the emergence of the concept of sustainable development enshrined in the European Water Framework Directive (WFD) legislation, has modified the requirements for future hydrological observation and modelling initiatives and techniques. Originally, the focus at larger catchment scales was on the water stream flow at a limited number of locations, essentially for operational purposes such as flood prediction, dam regulation and hydropower production as well as hydrological process understanding. Water is now considered under its multiple functions such as water supply, hydrological risk, hydropower, irrigation, tourism, ecological value, to name a few. The demand for better hydrological understanding and techniques has thus moved to a more integrated prediction of the water balance components (rainfall, runoff, water storage, transpiration, evaporation, groundwater levels, etc.) at every point within a region [21]. In addition, consideration of land-use and human-induced landscape modifications is now a major concern for water management problems (i.e. for flood forecasting) and impact studies of land use change on stream flow, pollutants and/or sediments transport. For most of these questions, knowledge of the general characteristics of water balance components is not sufficient, more detailed process understanding (i.e. storm responses) throughout the landscape are required. The development of distributed and/or semi-distributed hydrological models, where there is a greater representation of the land-surface heterogeneities and the characterization of distributed inputs, are thus increasingly necessary. The usefulness of distributed hydrological models has been questioned, mainly due to overparameterization problems, parameter estimation and validation limitations [9,43,8]. Such difficulties cannot be ignored but the continuous development of hydrological observation and landscape characterization techniques are likely to offer renewed possibilities in this field. We must recognise there is an inevitable compromise between the complexity of the model proposed, and the spatial data that is available to drive the model (inputs) and robustly evaluate its predictions.

We suggest weather radar technology offers a unique means for characterizing the rainfall variability over the range of scales and with the space-time resolutions required for a large variety of hydrological problems. This is especially true for risk management in urban and mountain watersheds characterized by fast dynamics and for which rainfall monitoring and nowcasting are critical [21,37]. For the largest scales, continental rainfields derived from radar networks may also provide valuable information in terms of water budget in complement with climatologic networks and satellite imagery.

This article is a preface to a special issue journal that has been initiated in parallel to the International Symposium Weather Radar and Hydrology, held in Grenoble and Autrans, France, in March 2008. This event continues a series of symposia originally called Hydrological Applications of Weather Radar that started in 1989 at the University of Salford, UK. This first symposium was followed by the Hannover (1992), Sao Paulo (1995), San Diego (1998), Kyoto (2001) and Melbourne (2004) meetings. The main objective of the 2008 symposium was to promote the use of quantitative precipitation estimates (QPE) derived from weather radar technology in hydrological sciences and their applications. The symposium was composed of two events:

(i) A 3-day conference held on 10–12 March 2008 in Grenoble. The programme was composed of 5 keynote speeches, 52 oral and 80 poster presentations covering the multiple aspects of radar physics, radar QPE and distributed hydrological modelling. This scientific material (abstracts, extended abstracts, oral presentations) can still be accessed on the symposium web site at the following address: http://www.wrah-2008.com.
(ii) A 2-day workshop held on 13–14 March 2008 in Autrans (Vercors). The workshop was dedicated to thematic discussions aimed at summarizing the symposium results and investigating future research directions.

In the following, a presentation of the most promising techniques for radar rainfall QPE is proposed in Section 2 prior to a discussion about some of the challenges of distributed hydrological modelling (Section 3). A set of recommendations is made in Section 4 to foster the use of weather radar in hydrologic sciences. Section 5 briefly introduces the articles of the special issue.

2. The most promising techniques for radar rainfall estimation

Real-time rainfall detection and estimation as well as rainfall nowcasting have been the main motivations for the deployment of operational weather radar networks over the past six decades. Although the qualitative value of radar networks is unquestioned, the complex technology of weather radar systems combined with the variety of uncertainty sources and the strong variability of precipitation at all scales [30] has limited the quality of radar precipitation estimates [37] and therefore the use of radar QPE in operational hydrology.

Measurement artefacts (e.g., clear air echoes, ground and sea clutter, anthropogenic targets such as wind mills, airplanes, etc.) are a first very important limitation for quantitative use. In spite of automated identification techniques now being routinely

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implemented for conventional radars (i.e. single-polarization non-coherent Doppler radar in the following), residual artefacts may significantly alter rain reflectivity values and the subsequent radar data processing steps. An agreement exists now about the main radar error sources related to both instrumental and sampling properties [75,45,37]: calibration, attenuation due to wet radome, ground clutter and beam blockages, attenuation due to gas and rain, vertical heterogeneity of the hydrometeors (referred to as the vertical profile of reflectivity –VPR- in the following), reflectivity-rain rate conversion (Z–R relationship), rainfall advection. Volume-scanning protocols and physically-based data processing are now generally implemented operationally to cope with such error sources. Although some noticeable progress has thus been obtained [39,68,69,26] some inherent limitations will continue to exist due for instance to the difficulty in performing an absolute calibration, to the sampling problems (radar resolution varies as a function of range, non-uniform beam filling, non-observation of the low-level altitudes above ground level beyond 60–80 km), to entangled errors (e.g., combination of calibration, attenuation and VPR errors at C-band) and to the high intra-field variability of the Z–R relationship [72].

A major advent in the recent years is the implementation of dual polarization and Doppler techniques in a pre-operational mode for several weather radar networks [76,62,42]. In addition to the reflectivity Z, the differential reflectivity Z_{DR}, the cross correlation ρ_{hv} and the differential phase shift ϕ_{DP} between the horizontal and vertical polarizations can be measured for each radar resolution volume. It is worth noting that the potential for dual-polarisation techniques to eliminate non-meteorological echoes [42] has actually been the main reason why several countries have decided to deploy a network of polarimetric radars. Classification algorithms are used to distinguish several classes of liquid and frozen hydrometeors [67] prior to the application of specific rainrate estimators using various combinations of the radar measurables [62]. Polarimetry also offers some interesting possibilities such as self-calibration of reflectivity, attenuation correction [70,41] and DSD retrieval [16,57]. Of lesser direct value for radar QPE, the Doppler capability allows for a better description of the rain system dynamics [15]. Refractivity measurements from the phase variation of ground targets [31] also offer potential for the characterization of low-level humidity fields.

There is an agreement about the critical importance of calibration and maintenance operations for quantitative applications. The parameters of the radar systems need to be monitored continuously and alarms have to be triggered when predefined thresholds are exceeded. Data from the monitoring system are critical metadata and need to be archived along with the radar observations and products. Polarization means more measured variables and thus more information, but also increased technical complexity and workload in terms of system maintenance.

Despite the promises of polarimetry, there is evidence that the density of existing operational radar networks is insufficient for a proper hydrological coverage at the national/continental scale if one considers the 100-km range as a maximum practical limit. Two complementary solutions are currently being investigated:

- The X-band frequency offers attractive design characteristics compared to the S-band and C-band frequencies (reduced transmitted power and antenna size; reduced sensitivity to ground clutter) that are counterbalanced by a dramatic sensitivity to rain attenuation. In the recent years, a breakthrough has been achieved in radar QPE at X-band through the use of polarimetry and range-profiling algorithms [70,2,40,51,53]. Several industrial (e.g. (http://www.casa.umass.edu/) and research projects have been initiated to further develop this concept which has certainly a great future for radar QPE in rugged topography and/or in urban areas.
- Although much less established, microwave links rainfall measurement also offers interesting potential with the deployment of wireless communication networks all over the world [56,49]. A major advantage is related to the fact that such measurements are made close to the ground. First studies indicate that effects of rainfall variability are limited if the link length and frequency are chosen correctly [6,50]. For such settings, the main error sources are related to the wetting of antenna covers and to the resolution of power measurements.

3. Distributed hydrological modelling

Recent and ongoing research initiatives such as DMIP (Distributed Model Intercomparison Project; [66]) and PUB (Prediction in ungauged basins; [34]) are focused on distributed hydrological modelling. For PUB the concept is to reduce the uncertainties in the modelling process by improving our understanding and representation in models. We briefly review hereafter some of the related challenges.

One of the difficulties in hydrological modelling is that the spatial and temporal scales of hydrological processes span several orders of magnitude: from a few m^2 and minutes for soil infiltration to thousands of km^2 and several years for groundwater [13]. Furthermore, depending on the climate and the characteristics of the catchment (topography, land use, pedology, etc.), only one or several of these processes may be dominant. For instance, it is usually recognized that runoff (both surface and sub-surface runoff) is dominant in the case of flash-floods, but that evapotranspiration must be accounted for in long-term simulations. According to the scale of interest, the dominant processes might also change. For example while soil hydraulic characteristics are influential for runoff generation through infiltration excess and ponding at the plot scale, the presence of macropores and preferential flow might be the dominant factor when studying the runoff generated at the hillslope scale. Finally, there are several thresholds in hydrology (e.g., appearance of ponding, snow melting, saturated areas, flooding, etc.) which make the modelling more complex due to the associated high level of non-linearities in hydrological responses [65].

A second type of difficulty arises from the combined heterogeneities of the land surface and the sub-soil. The large spatial heterogeneity of the land surface is driven by topography, land use, geology and pedology and increasingly by human actions. To simplify the problem, hydrologists try to define so-called homogeneous zones, i.e. areas where the hydrological behaviour can be considered as homogeneous. This has led to the definition of Hydrological Representative Units (HRU) [33,10], Representative Elementary Areas (REA) [74], Representative Elementary Watersheds [61]. In terms of modelling, this range of concepts has led to various landscape discretizations. Models are mostly based on regular meshes that are usually derived from Digital Terrain Models (e.g. [1,11,60,18]. However, the continental surface heterogeneity is not well described by regular grids and other discretizations have been proposed such as triangular irregular networks [44], hillslopes [71] and hydrolandscapes [24].

For process representations, two approaches can be distinguished [64]. The first one is an upward approach where processes are modelled using equations established at very small scales (such as the Richards equation for water transfer within the saturated/unsaturated zone, the St-Venant equation for water flow within a river channel, or the Boussinesq equation for water transfer within an aquifer) and extended to larger scales. Effective parameters, relevant to the scale of discretization must therefore be specified if not calibrated [13]. This approach is difficult to verify due to limitations with current hydrological observation techniques (e.g., for subsurface flow processes). Given the non-linearity in hydrological