Heuristic Probabilistic Forecasting Workshop
Munich, Germany, 30-31 August 2014

Loris Foresti, Alan Seed and Isztar Zawadzki

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Organizers

Loris Foresti <loris.foresti@meteo.be>
Royal Meteorological Institute of Belgium, Brussels, Belgium

Alan Seed <a.seed@bom.gov.au>
Bureau of Meteorology, Melbourne, Australia

Isztar Zawadzki <isztar.zawadzki@mcgill.ca>
McGill University, Montreal, Canada

Local organizing committee:
Christian Keil, Tobias Necker and George Craig
Meteorologisches Institut, Ludwig Maximilians Universität München, Germany

Scientific program

Day one, Saturday 30 August

09:00-09:15	Introduction by Alan Seed
09:15-10:30	**1. Keynote talks on precipitation predictability and nowcasting** Isztar Zawadzki - *Empirical studies of precipitation predictability* Daniel Schertzer - *Multifractal predictability and nowcasting*
10:45-12:15	**2. Cell tracking and field advection techniques** Gyuwon Lee - *Fuzzy-logic cell tracking, storm statistics, and lightning* Mike Dixon - *TITAN - identifying and tracking convective storms as objects* Alan Seed - *Optical flow for advection of precipitation fields*
13:15-14:30	**3. Nowcasting rainfall initiation, growth and decay** Jim Wilson - *Recent advances in thunderstorm initiation nowcasting* Rita Roberts - *Use of satellite data for nowcasting convective initiation*
14:45-16:00	**4. Nowcasting with high-resolution radar networks and in complex orography** V. Chandrasekar - *Very-high resolution nowcasting within the CASA radar network* Urs Germann - *Nowcasting in complex orography - the United Skills of CombiPrecip, MAPLE, NORA and REAL*
16:00-17:00	**Free discussion**

Day two, Sunday 31 August

09:00-10:15	**5. Ensemble and probabilistic nowcasting** Alan Seed - *Review of probabilistic nowcasting of precipitation* Geoff Pegram - *Space-time stochastic simulations with the "String of Beads" model*
10:30-11:45	**6. NWP post-processing, blending and space-time heterogeneity of precipitation statistics** Clive Pierce - *Generation of a seamless, 5 day ensemble precipitation forecasts for flood forecasting* Loris Foresti - *Flow-dependence and spatial heterogeneity of the precipitation predictability*
13:00-14:30	**7. Hydrological applications, operational and end-user needs** Aurora Bell - *The role of the forecaster in a deterministic nowcasting service* Marc Berenguer - *Continental scale nowcasting for hydrology* Miguel Rico-Ramirez - *Urban scale nowcasting for hydrology*
14:30-15:00	**Planning of future joint efforts**

Workshop website: http://cawcr.gov.au/meetings/HeuristicNowcasting/index.php

List of participants

Aurora Bell	Bureau of Meteorology, Melbourne, Australia
Alan Seed	Bureau of Meteorology, Melbourne, Australia
Vera Meyer	Zentralanstalt für Meterologie und Geophysik, Vienna, Austria
Loris Foresti	Royal Meteorological Institute, Brussels, Belgium
Lipen Wang	University of Leuven, Belgium
Aitor Atencia	McGill University, Montreal, Canada
Isztar Zawadzki	McGill University, Montreal, Canada
David Getreuer Jensen	Aalborg University, Denmark
Pekka Rossi	Finnish Meteorological Institute, Helsinki, Finland
Daniel Schertzer	École des Ponts ParisTech, France
Ioulia Tchiguirinskaia	École des Ponts ParisTech, France
Dirk Heizenreder	Deutscher Wetterdienst, Offenbach, Germany
George Craig	Ludwig Maximilians Universität München, Germany
Luca Panziera	University of Trento, Italy
Kohin Hirano	National Research Institute for Earth Science and Disaster Prevention Center, Tsukuba, Japan
P.C. Shakti	National Research Institute for Earth Science and Disaster Prevention Center, Tsukuba, Japan
Geoff Pegram	University of KwaZulu-Natal, South Africa
Gyuwon Lee	Kyungpook National University, Daegu, South Korea
Shinju Park	Kyungpook National University, Daegu, South Korea
Joan Bech	University of Barcelona, Spain
Marc Berenguer	Centre de Recerca Aplicada en Hidrometeorologia, Barcelona, Spain
Urs Germann	MeteoSwiss, Locarno-Monti, Switzerland
Alessandro Hering	MeteoSwiss, Locarno-Monti, Switzerland
Clive Pierce	MetOffice, Exeter, UK
Miguel Rico-Ramirez	University of Bristol, UK
Michael J. Dixon	National Center for Atmospheric Research, Boulder, Colorado, USA
Rita Roberts	National Center for Atmospheric Research, Boulder, Colorado, USA
Jim Wilson	National Center for Atmospheric Research, Boulder, Colorado, USA
V. Chandrasekar	Colorado State University, Fort Collins, USA
Evan Ruzanski	Vaisala Inc, Louisville, Colorado, USA

Acronyms

CAPE	Convective Available Potential Energy
CASA	Collaborative Adaptive Sensing of the Atmosphere
CIN	Convective Inhibition
COSMO	COnsortium for Small-scale Modelling
CSO	Combined Sewer Overflow
CTT	Cloud Top Temperature
EUMETSAT	EUropean organization for the exploitation of METeorological SATellites
GOES	Geostationary Operational Environmental Satellite
HIRLAM	HIgh Resolution Limited Area Model
IMF	Image Mean Flux
LST	Local Sidereal Time
MAPLE	McGill Algorithm for Precipitation Nowcasting by Lagrangian Extrapolation
MCS	Mesoscale Convective System
NCAR	National Center for Atmospheric Research
NEXRAD	NEXt-generation RADar
NWP	Numerical Weather Prediction
OPERA	Operational Programme for the Exchange of RAdar Information
QPE	Quantitative Precipitation Estimation (radar-based)
QPF	Quantitative precipitation Forecasting (radar- or NWP-based depending on context)
REAL	Ensemble radar precipitation for hydrology in a mountainous region
RR	Radar Rainfall
STEPS	Short-Term Ensemble Prediction System
TITAN	Thunderstorm Identification, Tracking Analysis and Nowcasting
VDRAS	Variational Doppler Radar Analysis System
WAR	Wet Area Ratio

Summary of sessions

<u>Introduction by Alan Seed</u>

- Workshop motivation
  - Quantitative rainfall nowcasts have significant errors at the scales that are important to end-users – determinism is dead, long live ensembles
  - The probability distribution of rainfall nowcast errors is situation dependent
  - We want to improve the sharpness in the ensemble by accounting for this dependence
- What does Heuristic mean?
  - Heuristic (/hjʉˈrɪstɨk/; Greek: "Εὑρίσκω", "find" or "discover") refers to experience-based techniques for problem solving, learning, and discovery that give a solution which is not guaranteed to be optimal
  - Where the exhaustive search is impractical, heuristic methods are used to speed up the process of finding a satisfactory solution via mental shortcuts to ease the cognitive load of making a decision
  - Examples of this method include using a rule of thumb, an educated guess, an intuitive judgment, stereotyping, or common sense
- Workshop goals and outcome
  - To improve probabilistic rainfall nowcasting techniques through the use of heuristic techniques
  - Better understanding of the fundamental issues in probabilistic rainfall nowcasting
  - Indications on the directions of research that are likely to have an impact
  - More collaborative research on the topic based on better understanding of the common goals and issues

<u>Session 1: *Keynote talks on precipitation predictability and nowcasting*</u>
Isztar Zawadzki - *Empirical studies of precipitation predictability*
Daniel Schertzer - *Multifractal predictability and nowcasting*

Empirical studies on precipitation predictability (Isztar Zawadzki):

- The first slide starts with the following questions:
  - In ensemble NWP the member with the best skill remains the best for a very short time. WHY?
  - The knowledge of the basic equations and the understanding of convective mechanisms is only helpful for very short lead-time of prediction. WHY?
  - Precipitation nowcasts by NWP do not have complementary information to nowcasts by Lagrangian persistence. WHY?
  - Adding tendencies to nowcast by Lagrangian persistence does not improve the nowcast. WHY?
  - Radar data assimilation has a long lasting effect on NWP but the improvement in forecast skill is very short. WHY?
- The loss of predictability at small scales is unavoidable given the highly non-linear and chaotic behaviour of the atmosphere, the non-Gaussian behaviour of turbulence and the human activities, which can introduce perturbations at the convective scale.
- Even with a very simple microphysics the growth of the errors can be large. The growth of the errors is larger in the convective regions, where there is more exchange of latent heat.
- The growth of the errors is driven by a stochastic process, i.e. the microphysics (drop size distribution), and even with a perfect NWP the predictability of the small scale features is likely to remain small.
- This rather pessimistic view on the small scale predictability of precipitation justifies the continuous development of heuristic approaches for precipitation nowcasting.
- Radar data assimilation forecast ensembles look good by eye, but the scale decomposition tells a different story. Beyond 10 hours lead time there is total loss of predictability of features of the order of 100 km. Features of 20-30 km are only predictable up to 5 hours lead time. There is no difference in decorrelation scale if cases are classified into more and less predictable according to the ensemble spread.
- The assimilation of radar reflectivity seems to have a positive impact on predictability only up to 5 hours lead time since there is no upscale propagation.
- There is a range of scales with some predictability of the model state but no predictability of the atmospheric state. The main errors in forecasting moist convection are not due to errors at convective

scales, but to errors at larger scales and in the model formulation (biases).

- The theory of analogues could be exploited to predict the forecast uncertainty since the growth of the errors is different depending on the starting location on the Lorenz attractor. The initial error growth does not follow an exponential behaviour if perturbations are added to the initial conditions but rather exhibit a power law behaviour as it is the case for longer lead times.
- A strange attractor of precipitation can be constructed from observations using the radar image 1st and 2nd order statistics evaluated at the mesoscale: area, eccentricity, marginal mean, variance, correlation, etc. The growth of the errors is similar to the one of the Lorenz system with strong dependence on the location in the attractor. The stratification of the attractor into different seasons reveals different behaviours.
- The increasing size of radar data archives (e.g. 17 years for the US radar composite) motivates further research on the spatial and temporal variability of precipitation predictability.

Multifractal predictability and nowcasting (Daniel Schertzer):

- Multifractals can clarify the predictability of complex space-time systems and provide concrete methods to forecast within the predictability limits by exploiting the past memory and controlling the admissible futures.
- The Lorenz system is complex only in time (ordinary differential equations), while precipitation is complex in both space and time (partial differential equations). Therefore, studying the predictability of the Lorenz system only gives a limited picture of what could be the space-time evolution of a precipitation field.
- There are several tools to measure and simulate the multifractal behaviour of precipitation:
    - Simple scaling analysis (Fourier power spectrum), trace and double trace-moment techniques (used to check the multifractality of the field).
    - Precipitation fields can be simulated stochastically using the β-cascade model, the α-model and the universal multifractals. The β-model is only able to simulate dead and alive structures (binary process). The α-model is a relaxation of the β-model to allow the structures to be more or less alive. Finally the universal multifractals provide advanced tools to simulate realistic precipitation fields, which have correct scaling properties, intermittency and power law behaviour of the extremes.
- The turnover time of turbulence is proportional to the lifetime of features. By assuming scale invariance, the small scales diverge and propagate the errors up to the larger scales following a power law.
- The temporal evolution of two stochastic multiplicative cascades also exhibits a power law divergence: the scale at which the two cascades are dependent (correlated) decays as a power law with lead time.
- The characterization of the intermittency of precipitation, a very non-gaussian process, remains a challenging research topic.
- The anisotropy between space and time and between the vertical and horizontal components of the atmosphere should receive more attention in the research community.
- Discrete multiplicative cascades have good potential for stochastic downscaling of NWP and radar data to assess the small scale sub-grid rainfall variability. They can also be applied to study the spatial and temporal sampling errors that affect the comparison of radar and rain gauges. The radar pixel (1x1 km^2) can be downscaled to the resolution of the rain gauge measurement (20x20 cm^2) to separate the small scale rainfall variability from the other errors.
- The complexity of wind fields appearing on the “Art piece Windswept” can be modeled by a multifractal fractionally integrated flux model to account for the non-conservativeness of the field. These ideas could be exploited to generate an ensemble of realistic velocity fields to represent the uncertainty in their future evolution within a nowcasting model.
- The Short Term Ensemble Prediction System (STEPS) is based on the concept of lognormal multiplicative cascades and is a simplification of multifractals, but it is for the moment the only operational nowcasting approach available. The generation of noise within STEPS is done by applying a power law filter to Gaussian noise to reproduce the spatial scaling properties and correlations of the rainfall field. Gaussian noise is a particular case of the Lévy noise that is used within the universal multifractals. A full space-time multifractal model for forecasting rainfields was already developed (Marsan et al., 1996), but there are still technical issues concerning the estimation of the sub-generator of the data, which still limits its potential operational use. More research would be needed to extend STEPS based on multifractal principles, in particular for a better treatment of intermittency and to treat the cases where the lognormal assumption (Gaussian noise) is not justified.

Both Zawadzki and Schertzer led to the conclusion that there is a characteristic scale above which precipitation fields are strongly correlated and predictable and below which they are not. The unpredictable scales can be efficiently simulated by stochastic models that emulate the space-time behaviour of precipitation.

Session 2: Cell tracking and field advection techniques
Gyuwon Lee - *Fuzzy-logic cell tracking, storm statistics, and lightning*
Mike Dixon - *TITAN - identifying and tracking convective storms as objects*
Alan Seed - *Optical flow for advection of precipitation fields*

Cell tracking techniques and spatio-temporal characteristics of convective cells (Gyuwon Lee):

- Importance of using 3D volumetric data for convective cell identification.
- Use of probability density functions and fuzzy logic to integrate several parameters for the identification and tracking of convective cells over subsequent images.
- The fuzzy logic cell tracking is less sensitive to the speed threshold and number of convective cells.
- Need for studying the spatial and temporal distribution of convective cells in complex orography due to diurnal cycles, monthly variation, windward and leeward effects, etc.
- There is significant convective activity during the morning (04~09 LST).
- How to account for beam broadening and signal convolution in the detection of convective cells from volumetric data?
- Need for developing lightning activity nowcasting.
- What are the statistical characteristics of lightning and non-lightning convective cells?
- Development of lightning nowcasting systems using fuzzy logic driven by statistical characteristics of convective cells.

TITAN enhancements (Mike Dixon):

- Cell trackers are designed for nowcasting severe weather, for storm and climatological studies, but are less useful for quantitative precipitation nowcasts.
- How can we detect convective storms embedded into large areas of stratiform rain in the presence of bright band? TITAN tends to merge the stratiform and convective regions into a single storm identification. The Steiner method does not appear to work well enough to solve this problem.
- The latest version of TITAN separates convective and stratiform areas using the texture of the reflectivity field as a discriminator.
- For nowcasts of 30-60 minutes the scales measured by the radar and detected by the enhanced TITAN seem to be appropriate.
- For longer lead times (say 2 hours) we should identify and track only larger scale features, which have different motion and predictability than the shorter duration storms. Fast Fourier scale filtering helps in isolating and identifying these larger scale features.
- Optical flow can be used to improve the tracking and matching of convective cells, in particular when radar scans are not frequently updated (e.g. a scan interval of 10-15 minutes). The combinatorial problem of matching the cells and detecting mergers and splits is thus simplified.
- TITAN can nowcast storm growth and decay using a weighted linear trending approach with previous storm features (intensity, volume, area, etc). Although rainfall region growth and decay have low predictability, this feature could nevertheless be exploited to forecast worst or best case scenarios.
- The advantage of the object-based approach is that additional attributes can be attached to the storm object, e.g. dual polarization information, presence of hail and lightning, etc.
- Cell trackers help operational forecasters to focus the attention on the potentially damaging convective storms and can give added value to field advection techniques.
- How to use the multifractality of the rainfall field to improve the detection of objects (convective storms)?

Optical flow techniques (Alan Seed):

- Issues when applying optical flow to real rainfall fields
    - Rainfall fields evolve in time in a scaling manner.
    - The translation is generally greater than one pixel per frame. The translation is spatially dense.
    - The frame rate is slow relative to the evolution rate of the field at small scales (< 10 km).
    - The radar contains artefacts that compromise the optical flow estimation (in particular permanent echoes).

- Tracking methods should be fast, optimized for prediction, robust (stable) and defined at each pixel over the forecast domain.
- Main steps of optical flow:
  - Smooth image to enhance signal to noise ratio.
  - Calculate the spatio-temporal derivatives or the local correlation.
  - Estimate the vectors where there is rain.
  - Interpolate to produce a vector field.
- Optical flow options:
  - Gradient techniques (first order local differentiation): reliable results.
  - Region-based matching techniques: good for high velocities and small domains.
  - Polynomial expansion techniques (e.g. Farneback, 2003): fast and able to provide a dense vector field.
- Open questions:
  - How to track a multifractal field?
  - What is the space-time structure of advection?
  - What is the space-time structure of advection errors? How to model it stochastically to generate ensembles?
  - The temporal evolution of the advection field is slow relative to the radar time step, so should we be developing a Kalman filtering approach to update the fields?
  - How to estimate advection on multi-radar mosaics? Is it better to merge radar data and evaluate the tracking on the composite or to compute the tracking on single radars and merge the tracks?
  - How to deal with radars scanning at different times?
  - How to perform multiscale tracking of precipitation features using Fourier- or Wavelet-based approaches?
  - How to perform multiscale advection and obtain spatially coherent precipitation fields after the re-composition?

Session 3. Nowcasting rainfall initiation, growth and decay

Jim Wilson - *Recent advances in thunderstorm initiation nowcasting*
Rita Roberts - *Use of satellite data for nowcasting convective initiation*

Convective initiation nowcasting (Jim Wilson):

- In many flash flood situations, location specific warnings are not possible until after the rain begins. It is then critical to closely monitor radar and gauge accumulations and monitor the radar for slow moving, back building and training storms in order to issue heavy precipitation warnings after the rain has begun (case study from Beijing June 2014).
- Nowcast ensembles, e.g. as given by STEPS, are not a solution if the initiation and development of convection does not follow the general direction of storm motion.
- The primary clue which can aid a forecaster in nowcasting storm initiation is the observation and tracking of boundary layer convergence lines. However, the observation of the convergence lines does not necessarily imply the initiation of convection or the development of a severe storm; other parameters such as stability and cumulus cloud development must be monitored.
- Recent experiments with a variety of NWP models and radar data assimilation schemes have not shown significant improvement in forecasting the specific location of heavy rain producing thunderstorms, with the possible exception of strongly forced synoptic situations. There is still work to do to improve the respective weighting of observations and model background weather variables in the data assimilation process.
- Improved nowcasting will require accurate high resolution 3D analysis of the wind, temperature and moisture fields. The VDRAS (Variational Doppler Radar Analysis System) is being tested as a promising method to obtain these high resolution analyses.

Nowcasting convective initiation and use of satellites (Rita Roberts):

- High resolution moisture information is a necessary ingredient in accurate nowcasting of convection initiation. Making use of the existing Meteosat Second Generation water vapour channels and the three high resolution water vapour channels that will come online with GOES-R satellite series will be important for improving convection initiation nowcasts.

- The benefit in nowcasting convection initiation is the additional lead time it provides in nowcasting of thunderstorms. More relevant and of great interest to end-users, is being able to nowcast those storms that will produce the heavy rain and flash flooding.
- In those regions of the world where there is no radar data and satellite data is the only operationally available dataset, it is important to track the location of gust fronts using the available visible and infrared imagery, and where available, the EUMETSAT RGB products. Gust fronts are often well observed in the RGB Dust Product imagery. In West Africa, gust fronts have been observed to play a key role in Mesoscale Convective System (MCS) evolution (intensification/dissipation) over a period of days. As mentioned in Wilson's talk, detection of gust fronts (cumulus cloud lines) is also critical for nowcasting convection initiation on storm scale, and local and regional scales.
- Roberts and Rutledge (2003) showed that the rate of change of Cloud Top Temperature (CTT) observed in satellite Infrared imagery is a good predictor of convective storm growth, as it often precedes radar detection of precipitation formation in convective storms. Thus, satellite data can provide extra lead time in nowcasting thunderstorms as long as there are no high level anvil cloud or cirrostratus obscuring the observation of the lower level cumulus clouds. The temporal evolution of CTT derived from Meteosat Second Generation is one of a few algorithms that has been developed for tracking and predicting thunderstorm growth.
- Extrapolation and other types of tracking algorithms have been applied to satellite data to monitor and track the movement of convective clouds. However, because of the two-dimensionality of the satellite imagery, multiple layers of clouds observed in the imagery frequently move in different directions based on their steering level winds. This complicates the tracking of storms on satellite data using existing extrapolation techniques.
- The presence of the anvil cloud is one of the major limiting factors for using satellite data in nowcasting.
- Atmospheric stability indices, such as Lifted Index, K-Index, CAPE, CIN, that are derived from satellite sounder data are only available in cloud free regions. Their combination with NWP and terrain data should provide better convective analysis fields.
- How can gust fronts and convergence lines be detected over complex orography?
- The GOES-R series that will be launched in 2016 will provide 1 and 5 min updates of satellite imagery. Is 1-minute better than 15-minutes update of satellite products for nowcasting? This is not yet known.
- It is important to monitor the storm features in order to anticipate which storm is more likely to produce flash floods. These features could be: stationarity (storms not moving with the general flow speed of the image), storm trains affecting the same location, merging storms, etc.
- There is a need for nowcasting nocturnal elevated convection. Elevated convection is associated with a stable nocturnal boundary layer underneath an unstable layer. Much is still unknown on when and where elevated convection will occur.

Open questions (both talks):

- Is elevated convection important in your country and worth considering?
- Do we spend too much effort in modeling and verifying non-heavy rainfall events?
- Need for improving extrapolation techniques on satellite data due to the presence of several cloud layers. Are efforts being undertaken to improve the situation?
- Will higher resolution satellite data lead to an improvement in thunderstorm nowcasting?
- How accurate in space, time and intensity should a QPE system be to nowcast flash floods?
- Are ensemble and probabilistic nowcasts sufficient for people to take life saving actions?
- When might we expect to obtain analysis of wind convergence, vertical air motion, moisture fields, CAPE and CIN that will provide sufficient detail to significantly improve nowcasting thunderstorms?
- Nowcasting rainfall growth and decay remains a difficult task for both field and cell tracking approaches. Will higher resolution satellite data with higher update rates be helpful in improving the prediction of growth and decay of storms? The directions for improvements rely on exploiting the orographic forcing as a source of predictability, monitoring the location of convergence lines and gust fronts and using satellite data.
- What new methods might be explored that use multiple observation systems and analysis methods to significantly improve automated techniques for detection and tracking of boundary layer convergence lines?

Session 4. Nowcasting with high-resolution radar networks and in complex orography
V. Chandrasekar - *Very-high resolution nowcasting within the CASA radar network*
Urs Germann - *Nowcasting in complex orography - the United Skills of CombiPrecip, MAPLE, NORA and REAL*

Very-high resolution nowcasting (V. Chandrasekar):

- Very-resolution is of the order of 250x250 m^2 in space and 60 seconds in time.
- NWP is not going to solve the problem of nowcasting in the near future, in particular when needing timeliness (30 seconds update) and very high resolution, which motivates the continuous development of heuristic techniques.
- In the CASA nowcasting system the radars can scan adaptively and collaboratively. A very short-term nowcast is issued to anticipate where the radar should scan for precipitation (adaptive). The radars scan different places over the same region and avoid revisiting the same region (collaborative).
- What is the optimal balance between exploitation of the nowcast to direct the scanning and exploration of the space to detect newly developed convection?
- Tipping bucket rain gauges are not always accurate, especially at low rainfall rates. In such situations the radar can become a reference for the rain gauges.
- Verification of forecasts should focus on the end-user impact, not simply using traditional skill scores.
- 20 minute lead time nowcasts are already useful for emergency decision making and warnings.
- What is the scale-dependence of the predictability at very small spatial and temporal scales?

Nowcasting in complex orography (Urs Germann):

- A dream nowcasting system should:
  - provide seamless QPE/QPF,
  - work properly in complex orography,
  - incorporate knowledge about uncertainties,
  - take advantage of all possible sources of predictability (orography, mesoscale flow, air stability, diurnal cycle, etc),
  - place special emphasis on intensive convective cells.
- The lifetime of precipitation by Lagrangian persistence of radar images is 5 hours in the US and 3.5 hours over the Swiss Alps (using MAPLE). The cross-over time of MAPLE with the COSMO-2km NWP model over the Swiss Alps is 2.6 hours.
- The orography influences the precipitation patterns only at given spatial scales. Is the presence of orography a trouble or an opportunity in terms of predictability?
- The vertical distribution of radar reflectivity over the Maggia river catchment is a good predictor for the intensity of the flood. How to integrate this information into a forecasting system?
- Convective cells have a more isotropic shape at 13 UTC than later on in the afternoon when they become anisotropic. How to account for this diurnal cycle within a nowcasting system?
- How to extend Lagrangian persistence nowcasting to account for all these sources of predictability in complex orography?
- Analogue-based methods showed great potential for ensemble nowcasting of orographic rainfall on the southern side of the Alps. How to extend analogue-based methods to work over other regions?
- The increasing size of radar data archives should be exploited more to improve QPE and QPF by heuristic techniques. We need to be prepared in terms of algorithms and techniques to take advantage of this treasure of data.
- One idea is to construct probability density functions (p.d.f.) at each grid point by looking backwards in Lagrangian coordinates over the whole radar rainfall archive. This approach should help in detecting regions of systematic rainfall growth and decay, e.g. due to orographic forcing. These p.d.f.s can then be used to sample an ensemble of nowcasts using a stochastic ensemble generator that combines the pdfs, the space-time covariance of precipitation and is conditioned to the observed radar field. Craig states that it is also important to estimate the joint p.d.f. to keep the spatial dependence between the locations.
- Schertzer gives the idea to do some hierarchical data mining from the large down to the small scales to retrieve analogue situations.
- Global NWP archives and satellite data are available everywhere and should be exploited to build more portable analogue-based nowcasting approaches.

Session 5. Ensemble and probabilistic nowcasting

Alan Seed - *Review of probabilistic nowcasting of precipitation*
Geoff Pegram - *Space-time stochastic simulations with the "String of Beads" model*

Review of probabilistic nowcasting (Alan Seed):

- Motivation to use ensembles:
  - The skill of quantitative precipitation nowcasts improved between the Sydney 2000 and Beijing 2008 Olympics, but not dramatically. The Critical Success Index of nowcasting rain > 1 mm/hr was around 0.1-0.2 at Sydney and 0.2-0.4 at Beijing.
  - The motivation to use an ensemble comes from the acknowledgement that we cannot in fact forecast convective scale rainfall at 60 minute lead time with the accuracy that is required by quantitative applications.
- User requirements:
  - The forecasts must look like rain in space and time, in particular for hydrological applications. The spatial and temporal correlation of the QPE and QPF errors affect the response of the catchment.
  - The ensemble spread must represent the forecast error at the time when the forecast was generated and at the location of a point or area of interest.
  - Deterministic forecasts must be unbiased and probabilistic forecasts must be reliable.
  - 30 (100) ensemble members.
  - 2 (1) km, 10 (6) min resolution.
  - 0-6 (12) hour lead time.
  - 10 (6) min ensemble update.
- Sources of forecast errors:
  - Radar rainfall estimation uncertainty.
  - Tracking and evolution of the velocity field.
  - Evolution of rainfall in Lagrangian coordinates (initiation, growth and decay).
- Radar rainfall estimation uncertainty:
  - Up to half of the nowcasting errors during the first hour is simply caused by the uncertainty of radar rainfall measurements.
  - There are major gains in improving the QPE system and to complement nowcasting systems with stochastic models describing the measurement error.
  - The residual errors between the radar and rain gauges are correlated over scales that are significant for hydrology, i.e. 30-50 km in space and 90-150 minutes in time. These correlations lengths also depend on the weather situation and type of rain.
- Tracking errors:
  - TITAN tracking errors are of the order of 15 km at 60 minute lead time. This tracking error may reduce a lot the forecast skill since convective features have only a correlation scale of 5-10 km.
  - Tracking errors can be significant after 30 minutes lead time for convective weather.
- Rainfall evolution:
  - We need rule-based (heuristic) algorithms to determine the probability of growth and decay of the rain area or intensity. The rules tend to be developed for a particular region and therefore the algorithms are not very portable.
  - We need to work on rules to modify the stochastic noise components of the ensemble nowcasting system to create areas of preferential development or decay.
  - The presence of orography can be used to increase the predictability of precipitation by inferring systematic precipitation growth and decay processes.
  - The identification and tracking of convergence lines can also be exploited to improve the skill above the simple Lagrangian extrapolation. The NCAR Auto-Nowcaster provides a forecast of the likelihood of thunderstorm initiation using a fuzzy logic scheme to combine the different predictors, including the convergence lines. However, convergence lines are often too erratic and it is not clear how to use them for quantitative precipitation nowcasting.
- We need to understand the probability distribution of forecast errors conditioned on situation, location and intensity.
- Long term gains can be made in developing good stochastic models of forecast uncertainty and using them to generate probabilistic products.
- Is our current nowcasting capability being used fully?

    - Need to work with the end users to provide them with forecasts that they can use in their business.
    - Need to generate the products in a way that makes them easy to use.
    - Need to engage with the end users to help them to develop the vision for how to use the new products to generate new services, especially based on ensembles.
- Zawadzki argues that basic users still deal better with ambiguous erroneous information (deterministic forecasts) than precise uncertain information (probabilistic forecasts) in the decision making process. Other people assert that the general public is more and more educated and will hopefully understand how to use probabilistic information in the decision process.

Nowcasting with the "String of Beads" and rain gauge data merging (Geoff Pegram):

- String of Beads:
    - The "String of Beads" approach has good potential to model the temporal evolution of the Image Mean Flux (IMF) and Wet Area Ratio (WAR) as a joint auto-regressive process. "String" refers to the dry period while "Beads" to the wet period.
    - The other parameters needed by the model are the mean and standard deviation of the logarithm of rainfall rates of the image and the spectral slope β of the radially averaged spatial power spectrum, which is used to generate spatially correlated noise fields by power law filtering (such as in STEPS).
    - SBMcast is the nowcasting implementation of the String of Beads model.
    - In contrast to STEPS, the temporal correlations are imposed before applying the Fourier power law filter to obtain spatially correlated perturbed rainfall fields. This is done because the power spectrum is likely to evolve in time as a consequence of the temporal evolution of the joint IMF-WAR process.
    - SBMcast seems to have higher ensemble spread than STEPS due to the larger variability of the IMF-WAR process.
    - How to account for the dynamic scaling of rainfall in SBMcast, i.e. that empirical observation that the lifetime of precipitation features is a power law of their spatial scale?
- Rain gauge data merging:
    - Instant radar rainfall fields have approximate isotropic behaviour. The anisotropy is more accentuated when rainfall is accumulated due to the flow drift.
    - Conditional merging can be used to generate stochastic radar rainfall fields that are conditioned to the rain gauge measurements. Stochastic rainfall fields are generated by power law filtering a white noise field using the spatial power spectrum of the radar. The obtained rainfall fields honour the rain gauge measurements and preserve the spatial variability given by the radar.
    - The availability of rain gauges still remains important, in particular for conditional merging with radar data.
    - Germann states that the stochastic conditional merging should include spatial and temporal non-stationarity.

<u>Session 6. NWP post-processing, blending and space-time heterogeneity of precipitation statistics</u>

Clive Pierce - *Generation of a seamless, 5 day ensemble precipitation forecast for flood forecasting*
Loris Foresti - *Flow-dependence and spatial heterogeneity of precipitation predictability*

NWP blending and seamless forecasting (Clive Pierce):

- Seamless forecasting consists of optimally downscaling NWP forecasts and blending with radar extrapolation to obtain a single continuous forecast up to several days ahead.
- The general idea is to stochastically perturb a dynamically perturbed NWP ensemble in order to improve the reliability of probabilistic forecasts.
- The perturbations add variability at the scales that are not resolved by the NWP model and which are consistent with the spatial and temporal correlations of the forecast errors.
- The noise perturbations can be generated using parametric and non-parametric filters. A parametric filter is for example represented by the slope of the climatological radially-averaged power spectrum of the rainfall field. A non-parametric filter is intended as the empirical power spectrum of the observed radar field, which can adapt in real-time. Non-parametric filters are mostly used to generate noise for ensemble nowcasting, while parametric filters for downscaling of NWP (it is not possible to know in advance about the small scale statistical structure of the precipitation field).
- The characteristics of the noise perturbations gradually evolve from the radar field to the NWP field.

- More research is needed to allow the noise perturbations to be spatially heterogeneous, in particular when two rainfall systems coexist over the forecast domain. Promising results are obtained by spatially varying means and standard deviations.
- When blending radar and NWP forecasts, the velocity field should gradually move from the one diagnosed on the sequence of radar images to the apparent motion of NWP precipitation fields.
- An interesting idea is to stochastically model the differences between the ensemble members and the ensemble mean of a NWP model to save computational time. The ensemble spread could be calibrated to improve the reliability of the probabilistic forecasts.
- Neighbourhood verification approaches can be used to construct reliability diagrams, in particular to account for the double penalty error occurring at the convective scale.

Spatial heterogeneity of nowcasting errors and precipitation predictability (Loris Foresti):

- The presence of orography causes systematic forecast biases in the Lagrangian extrapolation of precipitation.
- The systematic upwind and downwind under- and over-estimations can be exploited to infer systematic precipitation growth and decay processes respectively.
- The bias locally contributes up to 30-40% of the forecast error.
- The predictability of precipitation is scale-dependent, flow-dependent and spatially heterogeneous.
- The precipitation lifetime can be a factor two longer on the upwind side compared with the downwind side of orographic features.
- Both the forecast biases and different lifetimes could be used to locally adapt the stochastic simulations performed by STEPS.
- The online computation of statistics opens the way to design self learning nowcasting systems that improve with experience as more and more data and forecast are collected and analyzed.

Session 7. Hydrological applications, operational and end-user needs

Aurora Bell - *The role of the forecaster in a deterministic nowcasting service*
Marc Berenguer - *Continental scale nowcasting for hydrology*
Miguel Rico-Ramirez - *Urban scale nowcasting for hydrology*

Forecast services (Aurora Bell):

- In which situations are the forecasters useful and can give added value to an automatic forecasting/nowcasting system?
- One of the answers is based on this statement: the human brain works with pattern recognition. The forecasters are still better than computers in recognizing patterns and subtle clues both in observations and NWP outputs. Using pattern recognition, forecasters can apply conceptual models that have been developed by researchers.
- Forecasters can increase the understanding of the NWP and improve the forecast process by adapting a pre-existing conceptual model to a subtle variation in a particular day. This process can be facilitated by developing the culture of a “learning” organization, where new understandings and conclusions from the operational facts are fed back into the procedures.
- Forecasters can use high spatial resolution outputs to identify small scale meteorological features when these features are not obvious in the observations (e.g. a flow convergence line). They can also identify the situations when a model does not pick up a small scale feature that is present in the observations and decide whether the NWP guidance is good or needs adjustment.
- Are 10 minute resolution forecasts harder to ingest by forecasters? Do they have value? Forecasters can use high temporal resolution outputs of convective permissive NWP, like the 10 minutes rainfall accumulations and compare these fields with the radar reflectivity data; they can also identify the initiation, timing and mode of convection by analysing the structure of the 10 minute rainfall fields. This gives them a feeling of the severity of the convection that will initiate with an anticipation that can go up to 8 hours.
- How to deal with the overconfidence of forecasters on the models? Forecasters tend to feel helpless in front of the development of NWP and abundance of data to be analyzed. They also start to feel a time pressure during the operational forecasts and often give up to analysis or discussions in the forecasting room. In time, this develops the so called “meteorological cancer” when forecasters lose confidence in their own understanding of the atmosphere and rely on model. This process can be stopped by running

demonstration projects or test beds, where developers and forecasters work together to evaluate new models or applications. During these interactions forecasters can understand the strengths and the limitations of the models and the developers can understand how to better present the data to the forecasters.

- Can blended forecasts be interpreted correctly? This can be facilitated by allowing access to unblended products too, so the forecasters can understand the nature of the constriction. The forecasters can understand when the blending helps or when it is not appropriate, e.g. when the two forecast fields are shifted with respect to each other.
- Forecasters should have more time to work in close cooperation with scientists to develop tools for automatic detection of boundaries and other features prone to convection development.

Nowcasting and warning at European scale (Marc Berenguer):

- Continental scale nowcasts using the European radar composite OPERA benefit from the availability of radar data upstream and a better estimation of the large scale apparent motion of precipitation.
- Implementing ensemble nowcasting systems at continental scales is a computational challenge which requires some simplifications.
- The data quality of OPERA is a major factor that limits the quality of the nowcasts and the analysis of the spatial and temporal variability of its predictability. However, some seasonal differences and spatial inhomogeneities could be still discovered. For example, winter precipitation was observed to be more predictable than summer convection. The regions of extended predictability also seem to be in part connected to the ones affected by the highest rainfall accumulations.
- The temporal variability of the precipitation lifetime is comprised between 2 and 6 hours with peaks exceeding 10 hours, which is very similar to the one estimated using the NEXRAD composite over US.
- The cross-over time with the NWP model HIRLAM is 4 hours on average.
- The spatial inhomogeneity of precipitation statistics is a major problem over continental scales where different precipitation systems can coexist.
- Precipitation exceedance thresholds are different among European countries. Is there a way to define them objectively based on the local precipitation climatology and hydrological properties (soil types, etc)?
- The initiative for using European radar mosaics for nowcasting and warnings came from a university. According to Zawadzki, nowcasting at European scale would be better if not constrained by institutional issues (data access, copyright, etc).

Nowcasting at urban scale (Miguel Rico-Ramirez):

- The forecasting lead time needed for the real-time control of urban drainage systems is in many cases very short (e.g. less than 1-2 hours).
- Radar rainfall-based forecasts can provide the lead time required to control urban sewer systems that might help to predict (or reduce) CSO (Combined Sewer Overflow) spills into natural streams/rivers.
- There are differences in sewer flow simulations when using radar or rain gauge data. In some cases, flow simulations with radar rainfall produces better results than using gauges, but in other cases they are worse. Keeping both measurements can give a different picture of the situation.
- The different sources of uncertainty in the flow simulations come from the input measurements (rainfall), the hydraulic model used to simulate sewer flows and uncertainties in rainfall forecasts (for short-term predictions 1-2 hour ahead).
- Radar rainfall (RR) uncertainties can be modeled using statistical methods by comparing radar observations with ground truth measurements from rain gauges in order to generate RR ensembles (e.g. REAL). However, the RR QPE error structure can change if a new radar is introduced (or removed) from the RR mosaic. This can also affect the hydraulic flow predictions when using ensembles generated based on the original radar QPE error structure.
- RR ensembles can be used to produce ensemble precipitation forecasts that are able to account for the uncertainty in the input radar rainfall observations.
- It is hard to separate the uncertainty of the hydraulic model from the uncertainty in the input precipitation. However, in more than half of the simulated events, the uncertainties in the RR measurements are able to explain the uncertainties in the simulated flow volumes.
- There are cases where neither the rain gauges nor the RR ensembles were able to capture the measured flow volumes. Additional uncertainties may come from the hydraulic model. The calibration of

the hydraulic model can be an issue for extreme events.

- Some of the ensemble forecasts are able to capture the peaks of the hydrographs, but more work is needed to further validate the probabilistic nowcasts for applications in urban catchments.
- It is important to have a hydrological catchment model running on the background of the urban hydraulic model to avoid underestimating the peak discharge.
- There is more work to do to model additional uncertainties in nowcasting models by incorporating more meteorological knowledge (e.g. to model growth/decay processes and uncertainties in the temporal evolution of the velocity field) and to propagate the uncertainties into hydrological/hydraulic models.

General outcomes of the workshop

- Better exploitation of the huge archives of multisource data (radar, satellite, NWP, ground stations, etc).
- Development of self learning nowcasting systems that improve with experience.
- Better integration of cell trackers and optical flow techniques.
- Significant advances in nowcasting heavy rainfall require improved use of available high resolution observations as well as new observation and analysis techniques to obtain high resolution wind and thermodynamic fields.
- Nowcasting rainfall growth and decay remains a difficult task for both field and cell tracking approaches and the improvements are expected to be local in space and time depending on the weather situation.
- Improved blending of radar-based nowcasts with the output of high-resolution NWP models, in particular to account for the spatial and temporal variability of the rainfall structure and predictability.