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The challenge of predicting flash floods from thunderstorm rainfall

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A major characteristic of the hydrometeorology of semi-arid regions is the occurrence of intense thunderstorms that develop very rapidly and cause severe flooding. In summer, monsoon air mass is often of subtropical origin and is characterized by convective instability. The existing observational network has major deficiencies for those regions in providing information that is important to run-off generation. Further, because of the complex interactions between the land surface and the atmosphere, mesoscale atmospheric models are currently able to reproduce only general features of the initiation and development of convective systems. In our research, several interrelated components including the use of satellite data to monitor precipitation, data assimilation of a mesoscale regional atmospheric model, modification of the land component of the mesoscale model to better represent the semi-arid region surface processes that control run-off generation, and the use of ensemble forecasting techniques to improve forecasts of precipitation and run-off potential are investigated. This presentation discusses our ongoing research in this area; preliminary results including an investigation related to the unprecedented flash floods that occurred across the Las Vegas valley (Nevada, USA) in July of 1999 are discussed.

Keywords: monsoon season; flash flood; quantitative precipitation forecasting; mesoscale atmospheric model; four-dimensional data assimilation; land-surface model

1. Monsoon season rainfall and flash-flood forecasting

The hydrometeorology of the semi-arid southwestern US consists of two distinct seasons. Winter is characterized by middle-latitude cyclones and frontal systems typical of the continental US. However, the summer monsoon air mass is often of subtropical origin and is prone to convective instability. Solar heating destabilizes the boundary layer, and convection preferentially develops over the high terrain. Movement of the convective cells off the high terrain, and development of further convection, results in short-lived air-mass-type thunderstorms, with a diurnal maximum and minimum in convection occurring at roughly 6 p.m. and 6 a.m. local times,

One contribution of 18 to a Discussion Meeting 'Flood risk in a changing climate'.

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respectively. If the upper-level wind profile is favourable, there can be organization of the convection into tropical squall lines, and occasionally into mesoscale convective systems, that can persist for several hours. The resulting precipitation is highly localized, heterogeneous (in space and time), and strongly influenced by topography.

The task of monitoring the strongly heterogeneous precipitation in semi-arid regions poses special challenges. The existing observational network is grossly inadequate and gaps in information exist that are important to run-off generation. The rain-gauge network sparsely samples locations that are relatively accessible and at low altitudes, while mountains cause considerable blockage of the Next Generation Radar (NEXRAD). Further, the standard Z–R (reflectivity–rainfall rate) relationship works poorly in semi-arid regions, in particular for various types of storms. It also does not correct for atmospheric evaporation of falling raindrops. As a result, the rapidly changing patterns of precipitation over the mountains, which contribute to most of the water supply in semi-arid regions, are poorly monitored.

The complex nature of the interactions between the land surface and the atmosphere also makes the hydrometeorology of the semi-arid Southwest, especially the thunderstorms of the monsoon season, difficult to model. Real-time forecasts for Arizona generated by a mesoscale atmospheric model and initialized using the Eta model analysis provided by the National Centers for Environmental Prediction (NCEP) (Black 1994) are able to reproduce general features of the diurnal cycle of convection and evolution of temperature in the boundary during the summer season. However, the NCEP/Eta analysis that is used for the initial and boundary conditions includes no information about the regions of active convection. This is believed to be a primary source of inaccuracy in the precipitation forecasts and placement of convective cells. Also, there is poor representation of the land-surface processes that influence evolution of the boundary layer, since the model uses climatological values of quantities such as soil moisture, vegetation, etc. Consequently, the mesoscale atmospheric model has limited accuracy in predicting the initiation and subsequent development of convective systems.

In addition to precipitation, knowledge of the regional distribution of land-surface wetness and run-off potential is very important. In this area, small variations in precipitation can result in huge fractional changes in run-off and recharge. Such changes in the amounts of available surface water can have significant impacts on the life cycles of plant and animal life. Similarly, they can lead to severe flash flooding. However, current land-surface model (LSM) components are not specifically adapted to semi-arid conditions.

The problems mentioned above (i.e. poor spatiotemporal sampling of precipitation and unresolved problems with the model) make it difficult to obtain sufficient lead-time and accuracy on hydro-meteorological forecasts, particularly for thunderstorm flood events. Deterministic forecasts of precipitation perform poorly. Enhanced skill in model-based quantitative precipitation forecasting (QPF) for semi-arid regions requires that the convection be generated in the correct location and with the proper intensity. Meanwhile, a better representation of the uncertainties associated with the model requires probabilistic forecasts using ensemble techniques.

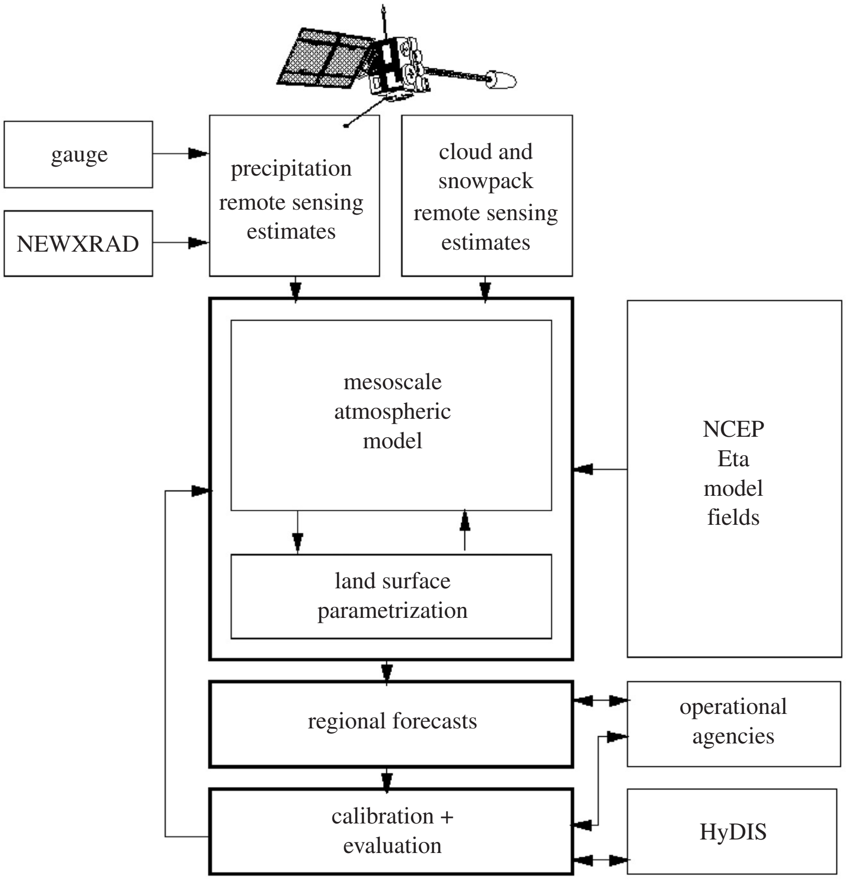

Figure 1. Conceptual outline of relationship between research components.

2. Integrated modelling approach

This study consists of several interrelated components (figure 1).

(a) Use of EOS (Earth observation system) data to monitor precipitation and cloud cover at high spatial and temporal resolutions.

(b) Assimilation of EOS and other data products into the regional atmospheric model.

(c) Modification of the land parametrization to better represent the semi-arid region surface processes that control run-off generation and convection.

(d) Use of ensemble forecasting techniques to develop improved forecasts of precipitation and flash flood and measures of associated forecast uncertainty.

(e) Calibration and validation of the regional model.

This research is aimed at the improvement of precipitation, flash-flood and other relevant forecast products in collaboration with local and regional weather service offices and water-resources management agencies.

(*a*) *Monitoring precipitation*

The precipitation estimation system is a neural-network algorithm, entitled PERSIANN (precipitation estimation from remote sensing information using artificial neural networks) (Hsu *et al*. 1997, 1999). The PERSIANN system uses multi-channel imagery from the Geostationary Operational Environmental Satellite (GOES), EOS/TRMM (Tropical Rainfall Measurement Mission) and DMSP (Defense Meteorological Satellite Program) polar-orbiting satellite rainfall estimates, NEXRAD radar images and rain-gauge network measurements. This methodology provides an effective and efficient synthesis of the continuous monitoring capability provided by geostationary satellites and the high-quality, but infrequent and incomplete, coverage information provided by the polar orbiting satellites and ground-based radar and gauge measurements.

(*b*) *Precipitation forecasting*

The regional precipitation forecasting system is a mesoscale atmospheric model, specially adapted for semi-arid regions. Initialization and boundary conditions for the regional forecasts are taken from the Eta model analysis provided by the NCEP. As mentioned earlier, the NCEP/Eta analysis includes no information about the regional development of active convection, while the representation of the land-surface processes (soil moisture, vegetation, etc.) that influence evolution of the boundary layer is not accurate. As a result, the placement of convective cells and precipitation intensities within the region is poorly estimated. To deal with these problems, our approach is to augment the atmospheric model fields with remotely sensed data, thereby constraining the physical parametrizations to evolve in a realistic fashion. This involves

(a) assimilation of satellite-based estimates of clouds and radiation,

(b) assimilation of estimated soil moisture and surface temperature,

(c) initialization of model latent-heat release based on satellite-based estimates of precipitation, and

(d) implementation of a four-dimensional data assimilation (4DDA) scheme.

(*c*) *Land-surface modelling*

The land-surface component of the regional model is being adapted to semi-arid conditions using a modified version of the NOAH LSM. The strategy is to partition the study region into the three primary hydrographic types (mountains, plains and riparian zones), which differ in terms of their dominant hydrological processes. We are investigating the use of the Smith–Goodrich (Smith & Goodrich 2000) model of the infiltration excess process, which provides a realistic representation of subgrid-scale partial area generation of run-off (and hence recharge) that occurs at low-to-medium rainfall intensities, and is therefore appropriate for the large grid size scales used in regional modelling. Also, we are modifying the subsurface hydrological representation to permit rapid drying of the surface layer. Parameter values for the model are being derived using GIS methods to define homogeneous areas based on hydrographic, vegetative and soil characteristics, and multi-criteria calibration methods for parameter estimation (Gupta *et al*. 1998, 1999; Bastidas *et al*. 1999, 2001). We are investigating the use of remotely sensed thermal and soil-moisture fields and aggregation techniques (Shuttleworth *et al*. 1999) to constrain the model and identify parameter values at large scales.

3. Case studies

A major characteristic of the hydrometeorology of semi-arid regions is the occurrence of intense thunderstorms that develop very rapidly and cause severe flooding. On 8 July 1999, unprecedented flash floods occurred across the Las Vegas Valley, NV, USA. A large part of the valley experienced 40–70% (40–75 mm) of its annual rainfall (110 mm) within *ca.* 3 h (10.00 a.m.–1.00 p.m. local time). This caused severe flooding that resulted in the death of two persons, $20 million in damage to property and roads, and severe erosion of the rivers. This case study illustrates the usefulness of satellite remote sensing and modelling techniques for severe storm prediction.

Figure 2 shows a sequence of five consecutive hourly images, from 17.00 UTC to 21.00 UTC, 8 July 1999, derived from various sources including cloud infrared image from GOES-8 satellite, NEXRAD radar, satellite-based PERSIANN hourly rain estimates (figure 2*a*–*c*), regional atmospheric model system (RAMS) predicted rain estimates, cross-sections of column cloud ice, and liquid water contents (figure 2*d*, *e*). The GOES satellites provide infrared cloud images at 4 km and 15 min resolution. Four of these images (at 1 h spacing) are presented in figure 2*a*, showing that this event includes a sequence of several convection events with the strongest one occurring over the city of Las Vegas. The life cycle of formation, maturity and decline for each event can be clearly seen.

The ground-based radar observations of the same thunderstorm events are depicted in figure 2*b*. These radar data are at 4 km and hourly resolution, and are obtained by the US National Weather Service using the NEXRAD radar. These images indicate that the coverage and intensity of rainfall at the ground first expanded (17.00 UTC) and intensified (18.00–19.00 UTC), and then quickly shrank and diminished as the cloud system matured (20.00 UTC). The rainfall estimates computed by the PERSIANN system (using GOES infrared satellite images) are presented in figure 2*c* for the same time periods. These estimates are computed at 0.25° × 0.25° and hourly resolution. Note that the timing and location of the estimated rainfall fields generally match the ground-based observations (figure 2*b*) quite well. However, the spatial and temporal variability of the rainfall fields estimated by the PERSIANN system is considerably smoother than indicated by the ground observations. Further, the PERSIANN system tends to underestimate the rainfall intensity during the onset of the event, while overestimating both the intensity and coverage during the mature phase of the event. This suggests that information about the life cycle of the storm event must be merged with the information provided by cloud top brightness temperatures to obtain a better model of the relationship between cloud imagery and surface rainfall.

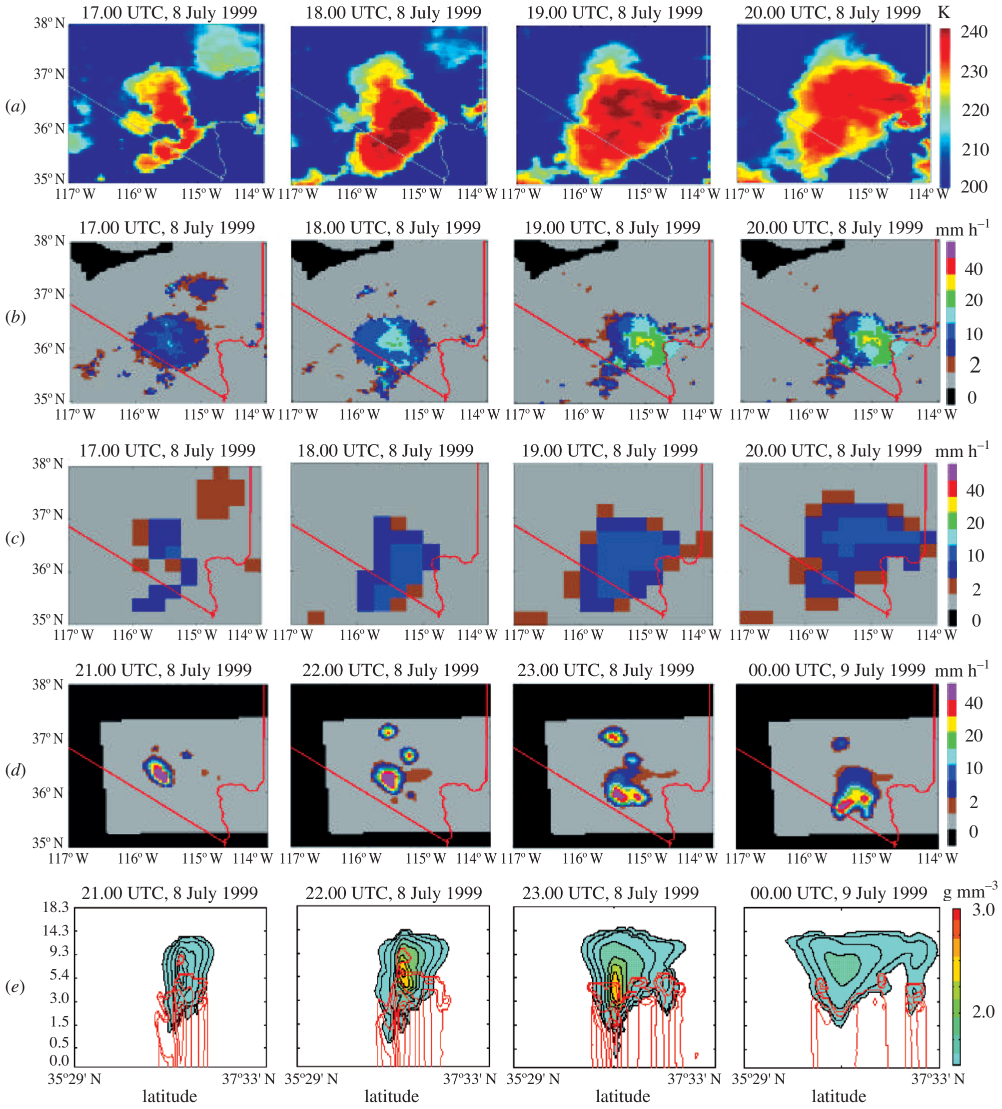

Figure 2. Comparison of 4 h period (*a*) GOES satellite IR images, (*b*) NEXRAD rainfall rate images, (*c*) estimated rainfall rate from PERSIANN, (*d*) estimated rainfall from RAMS, and (*e*) cross-sections of column cloud ice and liquid water (red) content from RAMS.

Figure 2*d* shows the hourly rainfall accumulations (for the same time periods) simulated by the RAMS regional atmospheric model, nested inside the Eta model at 2 km resolution. The predictions are made 24 h ahead using 12 h updates of the Eta model boundary forcing. These predictions seem to provide a good representation of the rate of onset, maturation and rapid decline (after the peak) that are characteristic of strong convective thunderstorms. They also seem to provide a reasonably good representation of the strong spatial gradients, although the simulated gradients appear to be somewhat stronger than are indicated by the observations, leading to

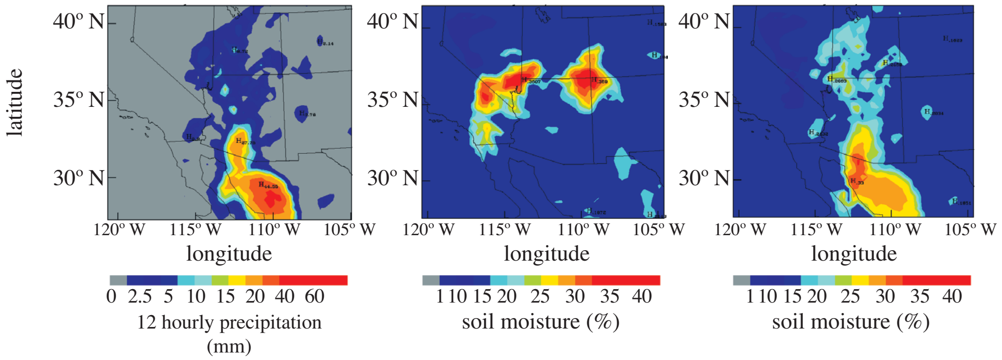

Figure 3. Adjustment of soil moisture from the assimilation of PERSIANN rain estimates to the RAMS model: (*a*) 12 h PERSIANN accumulated rainfall (6 July 1999, 00.00–12.00 UTC); (*b*) soil moisture contents before assimilation of PERSIANN rainfall (8 July 1999, 12.00 UTC); and (*c*) adjusted RAMS soil moisture contents after assimilation of PERSIANN rainfall (8 July 1999, 00.00–12.00 UTC).

excessive localization of the peak intensities. However, the predictions show a 4 h lag (delay) relative to the observed event and are somewhat displaced in space.

To understand the reasons for the behaviour displayed by the model, it is instructive to look at the computed vertical profile of the atmosphere. Figure 2*e* shows vertical cross-sections of the convective storm system with the distribution of cloud ice particles indicated in blue and the liquid water indicated in red. Notice that at the initiation of the event, the horizontal (spatial) distribution of cloud ice particles corresponds closely with the distribution of surface rainfall. However, once the event has matured, the spatial distribution of rainfall declines rapidly, while the broader distribution of cloud ice particles persists for some time.

As described in the above example (figure 2), the RAMS rainfall estimates are delayed by *ca.* 4 h, although the amount and location of the rainfall are forecast well. The results of numerous simulations have indicated that, in general, the timing and location of storm development tends to be inaccurately simulated by the model. In the southwestern US the source of monsoon-season atmospheric moisture is the Gulf of Mexico. Severe thunderstorms and flash floods develop rapidly in the presence of convectively unstable environments, with strong vertical wind sheer. The soil moisture is augmented by the continuous supply of heavy rainfall. However, the RAMS model is unable to properly simulate the evolution of soil moisture and land-surface temperature, resulting in a poor ability to represent the timing and location of moist convection. The resulting rainfall predictions are significantly in error with respect to location, timing and intensity.

Figure 3 illustrates one approach to correction of the modelled soil moisture fields by assimilation of satellite-based rainfall estimates provided by the PERSIANN system (Sorooshian *et al.* 2000). Figure 3*a* shows the PERSIANN rainfall estimates, indicating a high-intensity rainfall event centred on southern Arizona and northeastern Mexico. Figure 3*b* shows, however, that the RAMS model simulation is inconsistent with the rainfall observations, indicating high levels of soil moisture in northeastern Arizona and southern Nevada. The inability of the model to properly predict rainfall and soil moisture is partly attributable to incorrect initial and boundary forcing. Figure 3*c* shows that when rainfall estimates are assimilated into the land-surface model component, the simulated soil moisture pattern is more realistic.

4. Discussion

This paper describes a flood forecasting system for the southwestern US that is under development. The system will integrate a number of components including satellite remote sensing of precipitation, data assimilation, land-surface parametrization and run-off generation. The preliminary case study demonstrates that precipitation forecasting could be significantly improved by a proper synthesis of remotely sensed information with regional atmospheric modelling. Model experiments have indicated that the atmospheric model is fairly good in its ability to reproduce and forecast the characteristic life cycle of precipitation events, but is weak at correctly initiating the event and localizing it in space. There are many possible reasons for this, including inadequate specification of atmospheric boundary conditions, oversimplified representation of the land surface, incorrect model physics and poor scientific understanding of the processes that govern storm initiation. Remotely sensed data sources are strong at indicating spatial and temporal location but do not provide the necessary lead time required for operational use. The goal, as shown in the case study, is to merge remote sensing and models in a manner that enhances the strengths of each. Our ongoing research is focused on two approaches to model improvement.

(1) The understanding of the land-surface properties and initial soil moisture to the convective process of cloud and thunderstorm rainfall generation in the atmospheric model.

(2) Assimilation of the satellite precipitation data into the land-surface model to provide better localization and initiation of the atmospheric model, thereby improving the prediction of the timing and spatial location of storm events.

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