The role of terrestrial routing processes and shallow groundwater in land-atmosphere coupling

D. Gochis and W. Yu

Research Applications Laboratory,
National Center for Atmospheric Research,
Boulder, CO 80304 USA

1. Introduction:

Underlying the development of land surface parameterizations is the need for improved representation of the exchanges of heat, moisture and momentum between the land and atmosphere. However, many land surface properties influencing such exchanges are highly scale-dependent meaning that, in the context of modeling, they may or may not be explicitly resolvable at a selected model resolution. This complexity is particularly evident in the representation of terrain physiography in coupled land surface-atmosphere models. Depending on the atmospheric conditions or regime (e.g. stability and synoptic forcing) the influence of terrain features may or may not be an important control on surface fluxes. In this short paper, a few basic land surface processes that are impacted by terrain features are discussed which, in turn, seek to partly address the following three questions:

- How do routing processes influence atmospheric circulations?
- Is there a detectable difference from a Numerical Weather Prediction/Quantitative Precipitation Forecasting perspective?
- What are the potential reasons for such differences?

In section 2, a model experiment is described which seeks to understand the impact of representing the high-resolution (~100m) land surface model process of terrain routing of surface and sub-surface runoff, on the evolution of a severe convective event in the U.S. Colorado Front Range region on a flash flood event. Section 3 describes the results from this experiment focusing on the complex feedbacks found in the coupled model simulation. This short report concludes in Section 4 with a brief discussion on some of the outstanding issues raised by high resolution coupled modeling. Suggestions for future investigations are also put forward.

2. Experimental Setup:

The influence of terrain routing processes on atmospheric circulations and precipitation is explored in the context of a case study. The National Center for Atmospheric Research currently conducts operational flash flood forecasting activities over the Colorado Front Range region of the central Rocky Mountains. The forecasting approach utilizes both NWP and short term radar nowcasting as forcing datasets for distributed hydrological modeling. In this paper we will examine a retrospective extreme rainfall event that occurred on July 28, 1997 over Fort Collins, Colorado. The event is somewhat emblematic of an extreme, warm season convective rainfall event occurring along the Colorado Front Range. During this event nearly 206 mm of precipitation fell in during two concentrated episodes over a 5 hour period on the evening of July 28. Runoff from this event resulted in 5 fatalities and several million dollars in property damages. Warm season convection is common in this region during the summer time in the lee of the Rocky Mountains. During the mid to late summer months, mid and upper level wind speeds diminish and incursions of low and mid level moisture occur from the south. Moisture advection is typically the limiting factor in producing heavy rains and the terrain of the Rocky Mountains provides an elevated heat source for driving valley circulations and mountain-plain circulations.

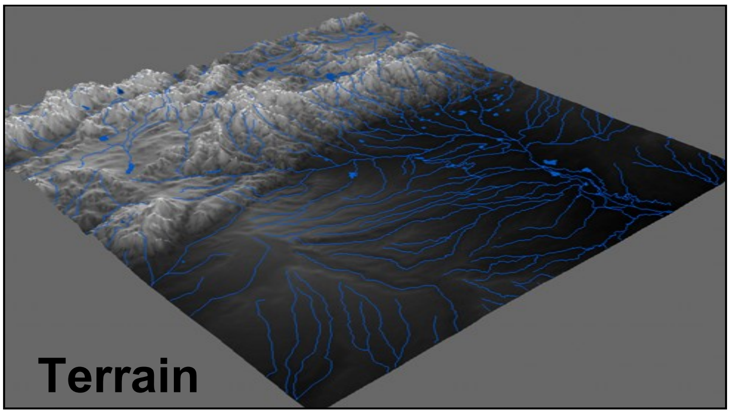
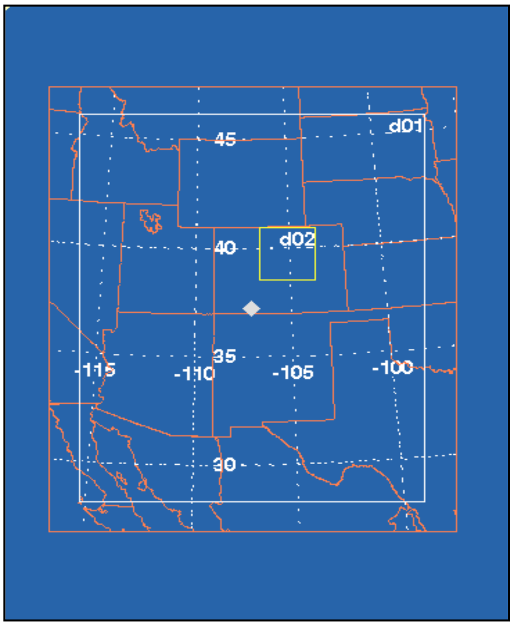


Figure 1: An oblique view of the terrain elevation of the Colorado Front Range at 1km spatial resolution.

The basic principles of terrain circulations and their climatological relationship to summertime rainfall patterns are relatively well documented. What is not well understood is the role soil moisture heterogeneity, as controlled by terrain routing processes, plays in modulating the background terrain circulation. The role of soil moisture initialization on the simulated storm event is explored. The Weather Research.and Forecasting (WRF) model (v2.7) coupled with the community Noah land surface model (LSM) is setup with a 1 km spatial resolution over the Front Range region (Fig. 2). The model parameterizations used in the simulation are as follows:



- No convection parameterization
- Purdue/Lin 6-class microphysics
- RRTM longwave radiation, Dudhia shortwave
- Yonsei planetary boundary layer and Monin-Obukov surface layer
- Noah land surface model w/ and w/out coupled Noah-distributed terrain routing

Figure 2: Nested WRF modeling domains (4 km and 1 km)

Description of the routing physics implemented in the Noah land surface model are described in Gochis and Chen (2003) and are shown conceptually in Figure 3. Briefly, surface infiltration excess, estimated by the standard Noah LSM is allowed to pond and move downslope under gravitational influence using a 1-dimensional diffusive wave approximation of the fully-dynamic St. Venant equations. Saturated sub-surface lateral flow is also represented in the model. In the current model setup, the vertical 1-dimensional land surface model physics in Noah are calculated on a 1km grid, as is the 1km WRF grid, while the overland and subsurface routing physics are calculated on a 100m terrain subgrid.

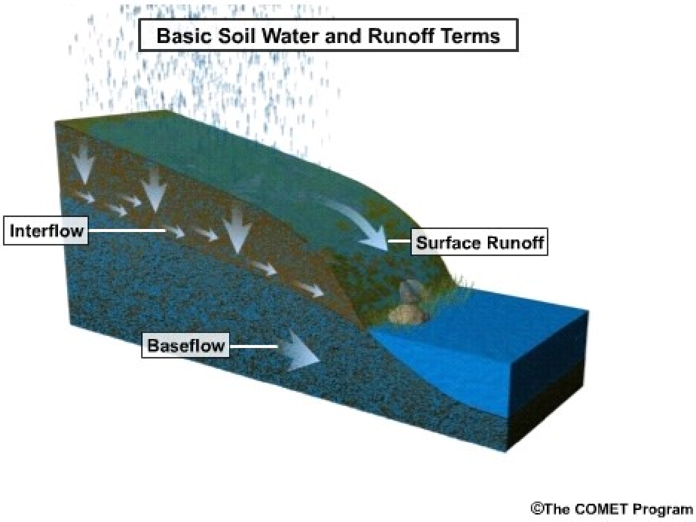


Figure 3: Conceptual representation of runoff processes treated in the 'Noah-distributed' hydrological model. In the model, only surface runoff and shallow (down to 2 meters) saturated subsurface flow is represented.

To explore the impacts of soil moisture on model performance, we designed three model runs as follows:

- Experiment 1: 36-hour WRF simulation with spun-up land surface hydrology conditions that do NOT include terrestrial routing and there is no routing during the coupled WRF model simulation
- Experiment 2: As in Exp. 1 but the spun up land surface conditions do include the impacts of terrestrial routing, but there is no routing during the coupled WRF model simulation
- Experiment 3: As in Exp. 2 but terrestrial routing processes during the coupled WRF simulation are active.

The detailed results from experiments 1 and 2 are discussed in the following section. Results from Experiment 3 did not differ substantially from Exp. 2 suggesting that the influence of the terrestrial routing processes on storm evolution during the 36-hour simulation were not substantial in this case. Results from Exp. 3 will not be discussed further.

3. Results

The Ft. Collins rainfall event was extreme in the sense that it dropped over 200 mm of rainfall in less than 5 hours over a very small area. A radar mosaic compiled from operational NEXRAD radar data is shown in Figure 4 and the Ft. Collins storm event is circled in red. While this event was not the most intense event occurring that day in terms of instantaneous radar reflectivity its stationarity in time was one of the main factors influencing the catastrophic flood response.

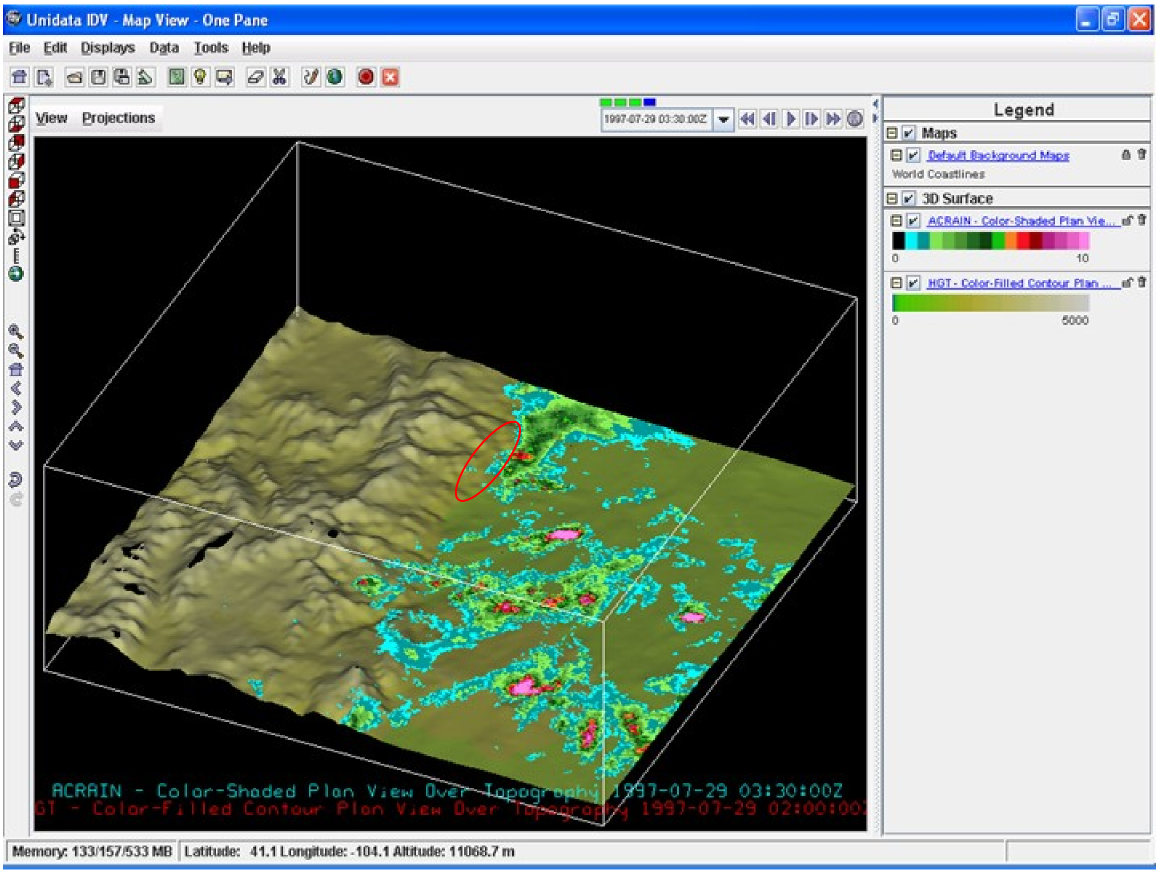


Figure 4: NEXRAD mosaic of accumulated rainfall for the July 28, 1997 Fort Collins storm event (circled in red).

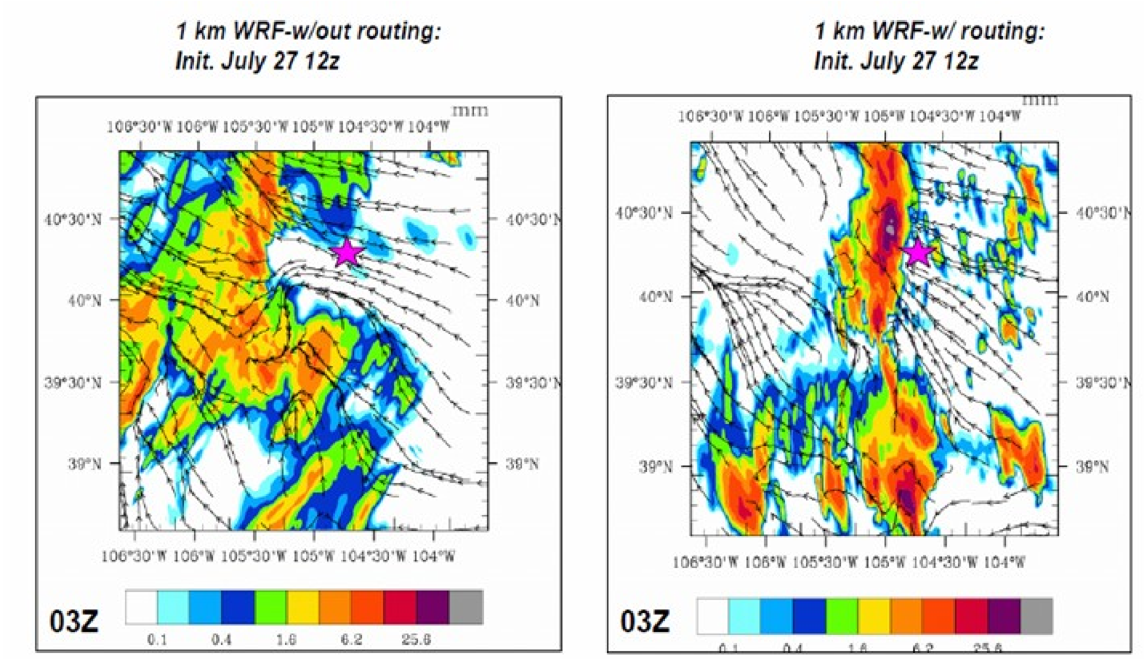


Figure 5: Hourly rain rate from the no-routing and routing spin-up WRF simulations. Pink stars indicates the location of the Ft. Collins flood event.

Figure 5 shows the hourly precipitation rate from the WRF model simulations at 03 UTC from Exp. 1 (without routing spin-up) and Exp. 2 (with routing spinup), respectively. The pink stars in Fig. 5 indicate the true location of the Ft. Collins flood event. There is a clear difference in the location, spatial extent and maximum hourly rain rate between the two simulations. Although the Exp. 2 simulation does not place intense rainfall directly over the observed flood location, it does simulate a storm structure that is most similar to what was observed by the NEXRAD radar mosaic in terms of highly concentrated rainfall over a small area. The time-evolution of this storm event as shown in cross-sections shown in Fig. 6 also highlights some subtle differences. While both Exp. 1 and Exp. 2 simulations show a heavy precipitation event developing over the Front Range and moving eastward away from the mountain front, the Exp. 2 storm event (with the routed spin-up conditions) exhibits an event that shows evidence of slower propagation and evidence of storm-cell splitting. While the present analysis is not conclusive of storm-splitting, it is clear from the observed 5 min time-sequences of radar reflectivity that storm splitting and storm 're-training' over the flood area did occur.

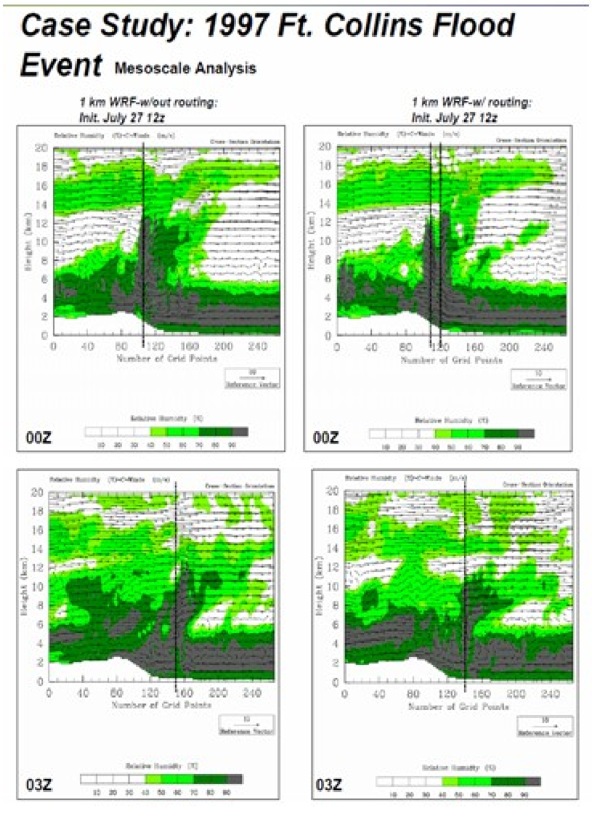


Figure 6: Cross-sections of the storm event at 00 and 03 UTC from the no-routing (left column) and routing (right column) spin-up conditions in the WRF simulations.

The differences in spatially-averaged accumulated rainfall over the actual flood area are shown in Fig. 7. The observations in this figure are averages of surface gauge locations and the model values are averages from model gridcells overlying the gauge locations. While spatial inconsistencies and uncertainties between gauges and gridcells exist there is evidence that more rainfall occurred in Exp. 2 that was simulated in Exp. 1.

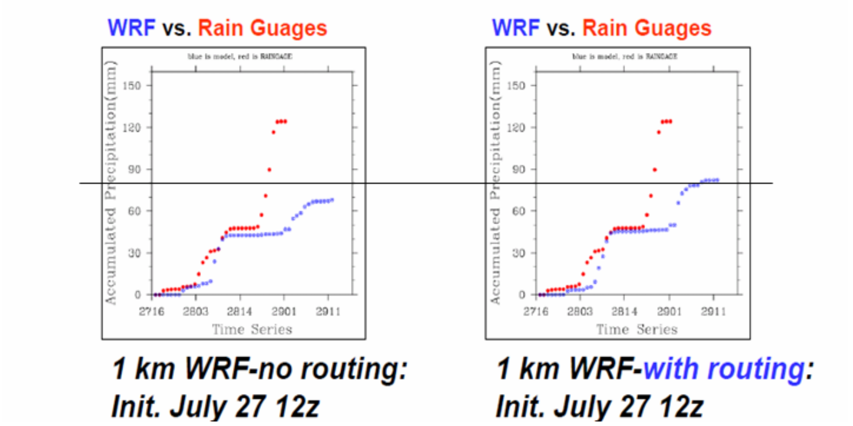


Figure 7: Spatially-averaged accumulated rainfall from local rain gauges (red) and WRF model gridcell values (blue). Solid black line provided as a reference between plots.

While there are clear differences between the Exp. 1 and Exp. 2 simulations, the reasons for these differences remain quite unclear. The processes leading to the initiation and evolution of convective rainfall in complex terrain regions are highly non-linear and exhibit threshold-like behavior making it very difficult to isolate the mechanistic pathways responsible for the differences from model 'noise'. An example of this is provided in Figure 8 which shows the differences (no routing minus routing spinup conditions) in 2m potential temperature and surface latent heat flux. While numerous difference patterns exist there are some large area, counter-intuitive features to the figures. For example, much of the eastern/south-eastern portion of the model domain show negative difference values in potential temperature (great in the routing case) while simultaneously showing negative difference values in latent heat flux over the same region. Typically, all else being equal, there is a

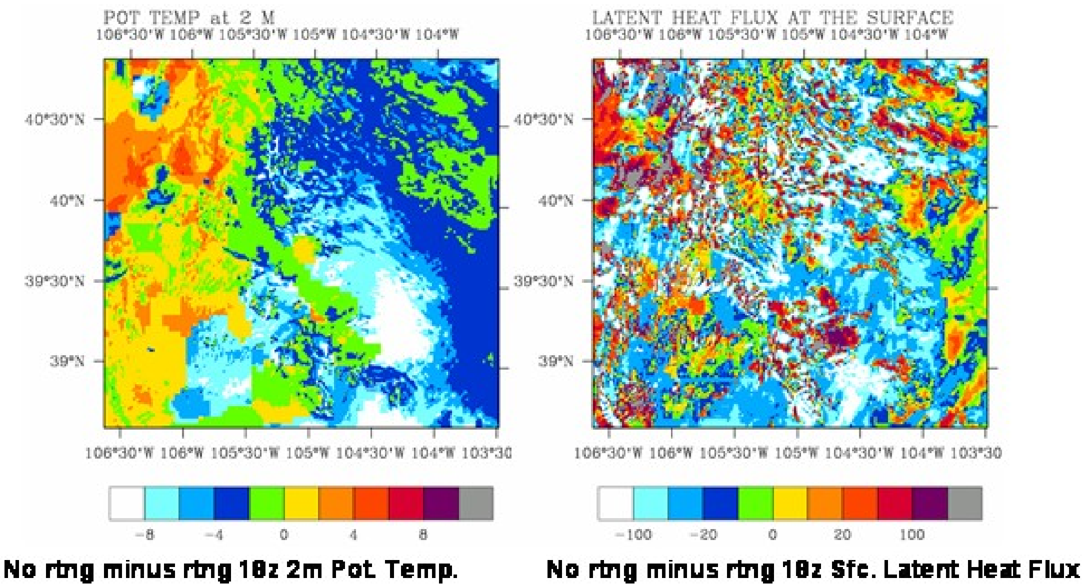


Figure 8. Difference (no routing minus routing) in 2 meter potential temperature and surface latent heat flux at 18 UTC prior to storm initiation from WRF model simulations.

tradeoff between sensible and latent heat fluxes at the land surface in that as latent heat flux increases sensible heat flux decreases and along with the sensible heat flux, so decreases the near surface air temperatures. Departures from this simple trade-off behavior typically imply other changes are occurring such as changes in radiative forcing or advective conditions. Here we suspect that there are significant differences in the simulated cloud fields which influence surface energy partitioning in non-linear and non-intuitive ways. Nevertheless, we suspect that the differences can be attributed, at least in part, to both the different absolute soil moisture content (from a domain integrated perspective), as well as the spatial distribution of soil moisture in the routed spin up case.

4. Conclusions and Future Work:

Much work remains to further the evaluation and interpretation of the influence of soil moisture and complexity in land surface processes on coupled model simulations of convective precipitation in complex terrain. It is well known that models can be quite sensitive to subtle and small changes in initial conditions of the land surface and/or atmosphere. However, it is much less clear as to how realistic such sensitivity is in the real world. In effect, is the real atmosphere very sensitive small changes in the spatial distribution land surface hydrological conditions super-imposed upon regional orography? A more conclusive answer to this question awaits a more comprehensive observational effort but the present model results suggest that the impacts can be quite significant under certain conditions.

To understand the nature and limitations of the influences and feedbacks of complex land surface representation in models, much more work needs to be done from a climatological perspective. While detailed case studies can be very informative from a process perspective, a better understanding of the climatological sensitivity of convective precipitation to land surface forcing requires a more time-integrated approach. Such work is currently underway and will hopefully address this issue more thoroughly.