A New Hydrological Model Extension Package for the Weather Research and Forecasting System

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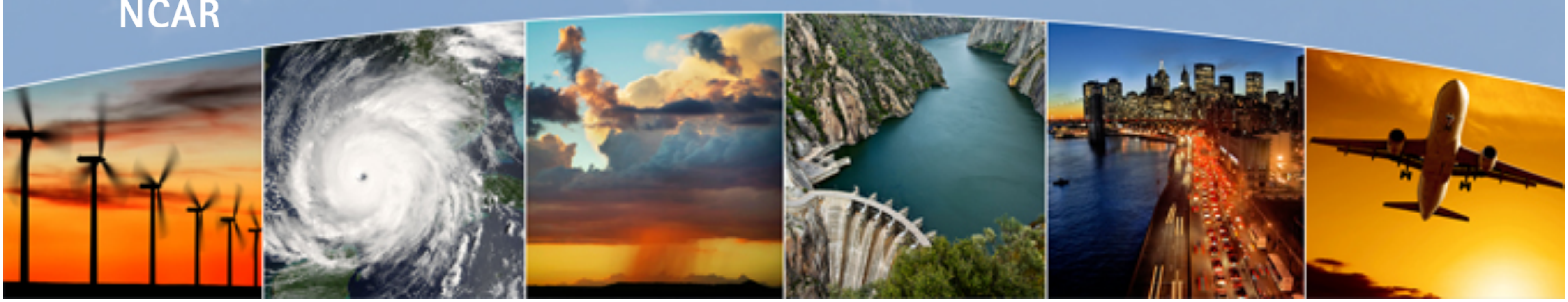

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- Israeli Water Authority
- Intra-Americas Development Bank
- National Science Foundation – EarthCube, AGS, Hydrology Programs
- Many other contributors and supporters…

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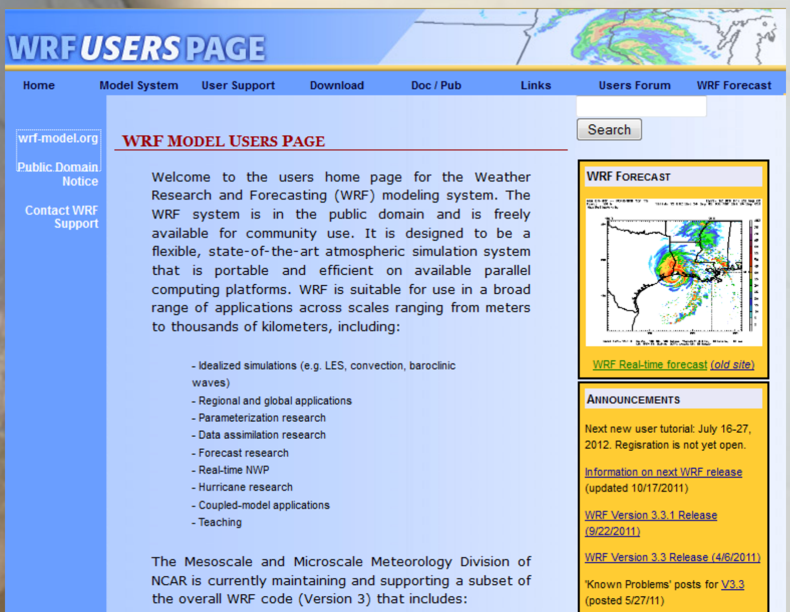
Practical motivation:

- NCAR was being requested to support an increasing number of single or team investigator projects supporting the coupling of hydrologic models to WRF and CCSM via the ‘community land models’ Noah and CLM for coupled hydrometeorological prediction
- Increasing demand from the NWP and regional climate modeling community to include ‘hillslope-scale’ flow processes in land surface models for regional climate impacts assessment
- Needed to develop an modular, HPC-oriented architecture that facilitated ‘community’ modeling goals

Relevant community modeling systems:

Weather Research & Forecasting Model – WRF (Regional)



http://www.mmm.ucar.edu/wrf/users/

Community Earth System Model – CESM (Global Climate)

http://www.cesm.ucar.edu/

- nearly 20,000 users
- basis for many National operational centers

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Gochis et al., 2012 WRF Workshop

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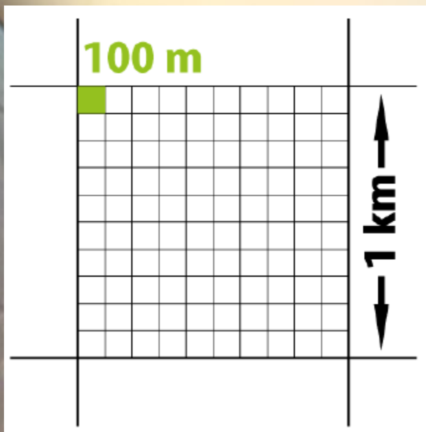
Community Model Attributes/Requirements:

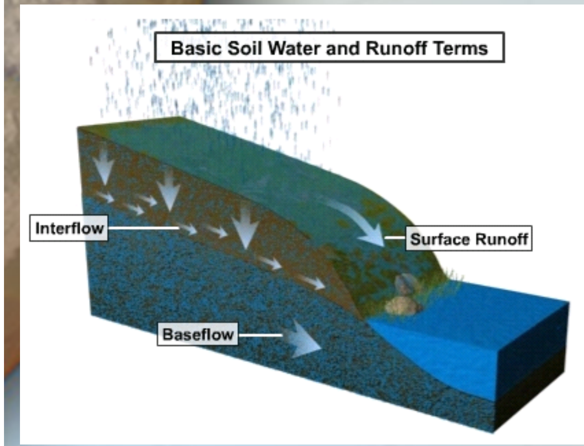
- Community Requirements:
  - Freely available
  - Supported (documentation, training…)
  - Extensible by knowledgeable users
  - Open/participatory development framework
    - Leverage the existing WRF community

Community Model Attributes/Requirements:

- Other Development Requirements
  - Preserve integrity of existing land model structure/conceptualizations
  - Enable multi-scale functionality
  - Utilizes existing data (netcdf) and modeling frameworks (e.g. ESMF…)
  - Scalable across High Performance Computing architectures
  - Ported or easily portable to many platforms and readily available compilers

Current/Developing Hydro-Model Features:





Courtesy the COMET Program

- Multi-grid functionality between land and routing grids with spatial aggregation/ disagregation
- Physics:
  - Column LSMs:
    - Noah, Noah-MP, P-X (via WRF)
    - CLM (via CESM)
  - Overland Flow: Diffusive wave
  - Saturated Vadose Zone: Bottom-up saturation, Boussinesq
  - Channel Flow: Diffusive wave w/ variable time-stepping, gridded or linked, Musking.
  - Reservoir flow: Level-pool reservoir model
  - ‘Deep’ groundwater/baseflow: Simple, empirical baseflow model
- Currently coupled with the following systems: WRF, CESM, NASA-LIS

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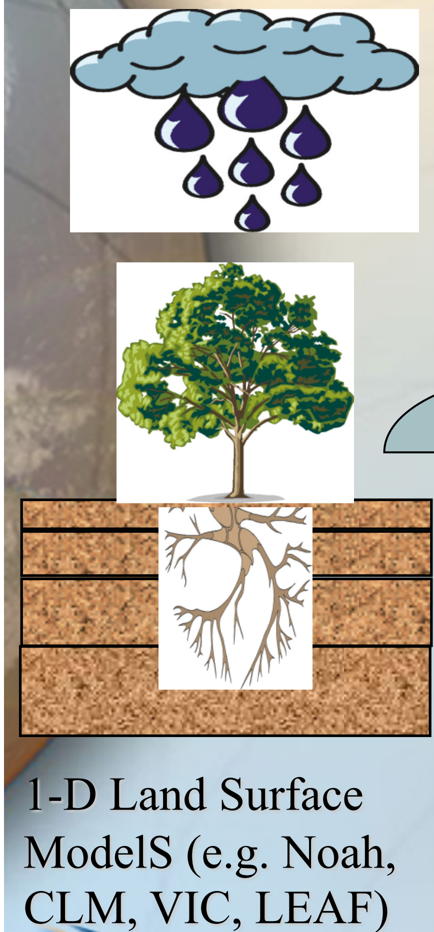
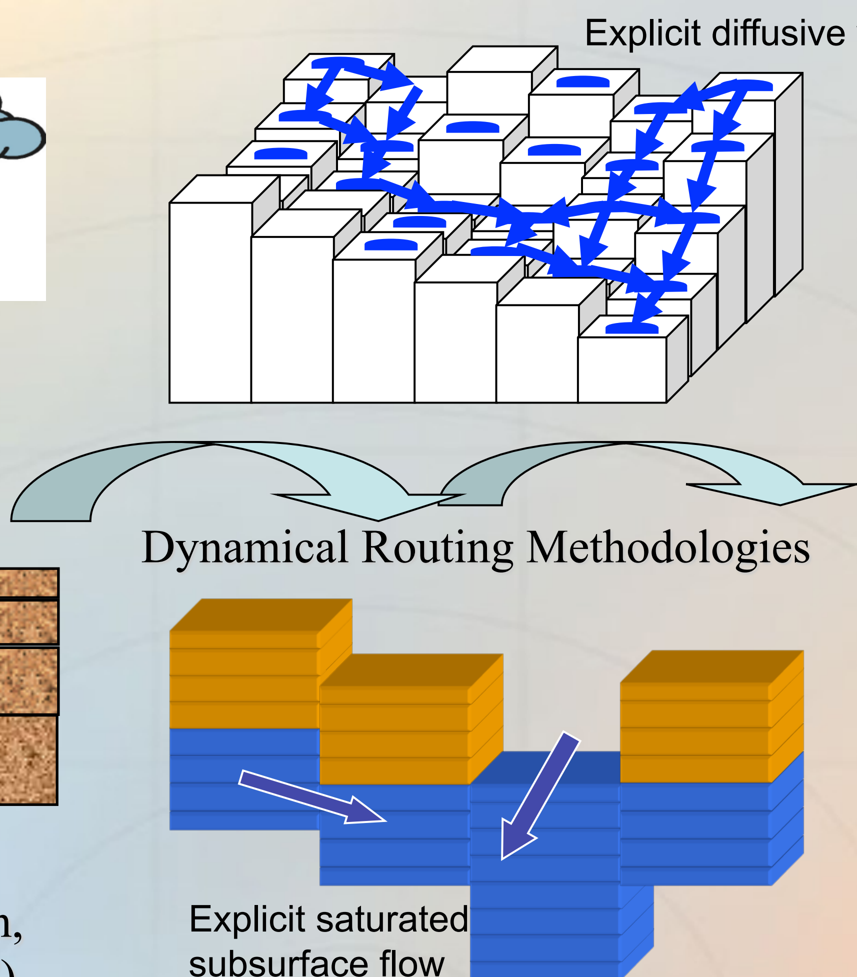
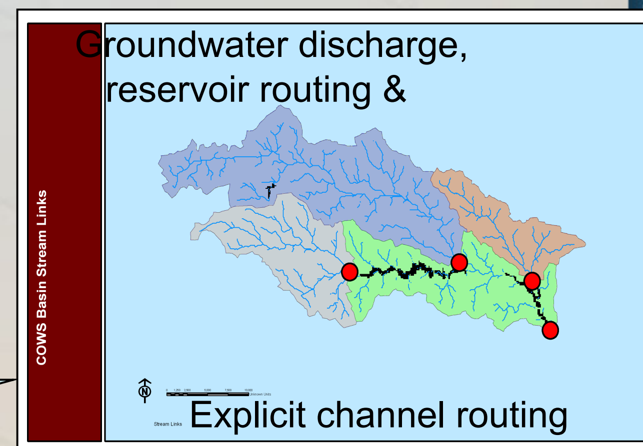
Hydrologically-enhanced Land Surface Models

(Gochis and Chen, 2003, Gochis et al., 2012 NCAR Tech Notes)

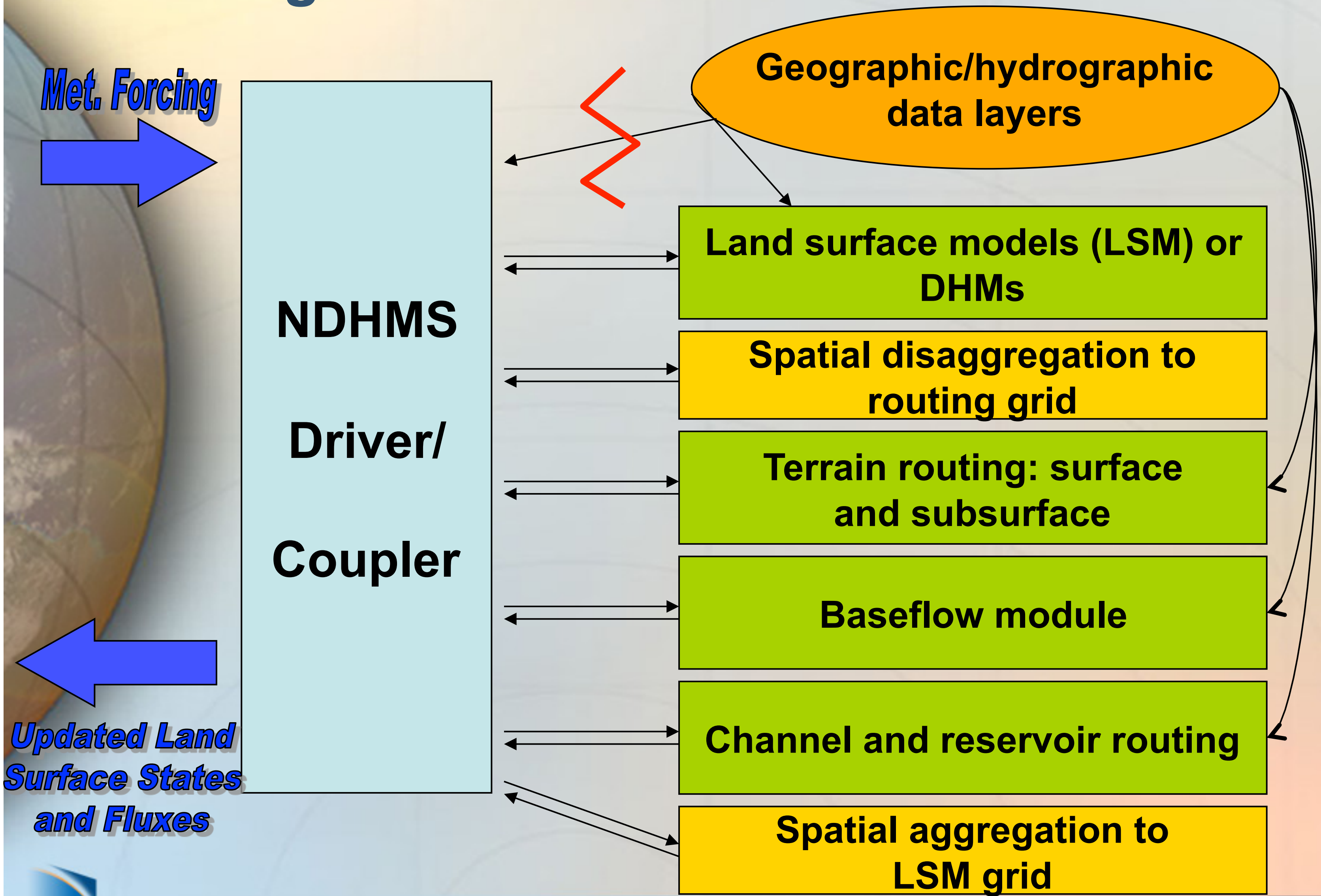






- **fully distributed flow/head**
- **reservoir levels**
- **distributed soil moisture**
- **distributed land/atmo fluxes**
- **distributed snow depth/SWE**

Distributed Hydrological Modeling System modeling architecture:



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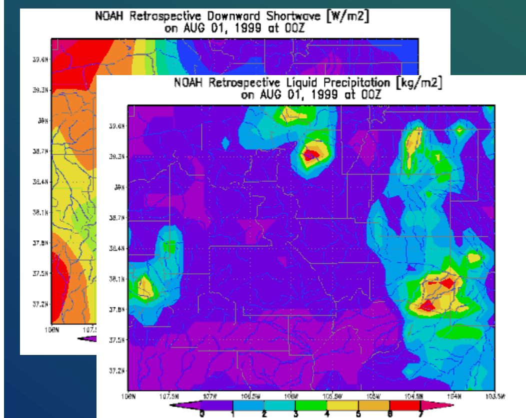
NDHMS coupling with WRF: ‘WRF-Hydro’

Standard WRF:
1-D land surface models (LSMs)

Coupled:
NDHMS/WRF-Hydro
(w/ WRF LSMs or others…)

'WRF-Hydro' Hydrometeorological Prediction System



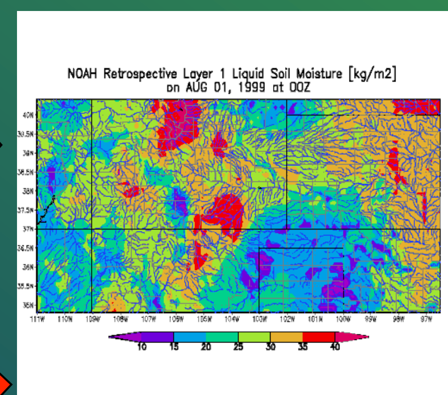
Observed
Met. Forcing

Precip.
Temp.
Humidity
Radiation
Wind
Pressure

'Offline' Land Surface Parameterization

NDHMS

Initial conditions for forecast run

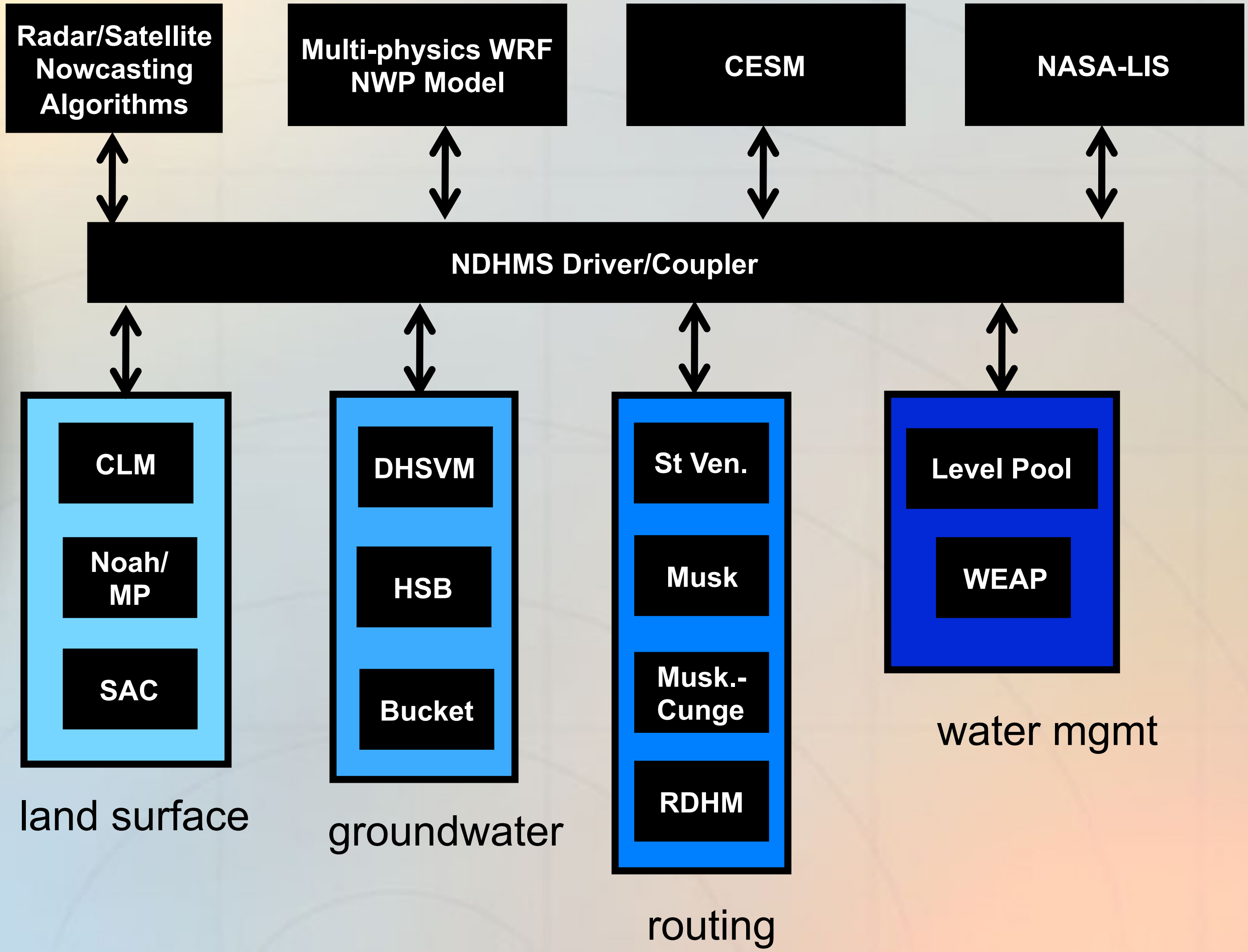


WRF / Nowcasting +Hydro

Decision Support Systems

(Images Courtesy: http://ldas.gsfc.nasa.gov/)

'Beyond-WRF' modeling architecture:



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Looking Forward:

0. Now have prototypes built around WRF and CCSM with Noah, CLM, in addition to other LSMs in WRF and in LIS

1. Standardize data models, I/O and coupling protocols for the next generation ESM's via NSF EarthCube and EU 'DRIHM' efforts

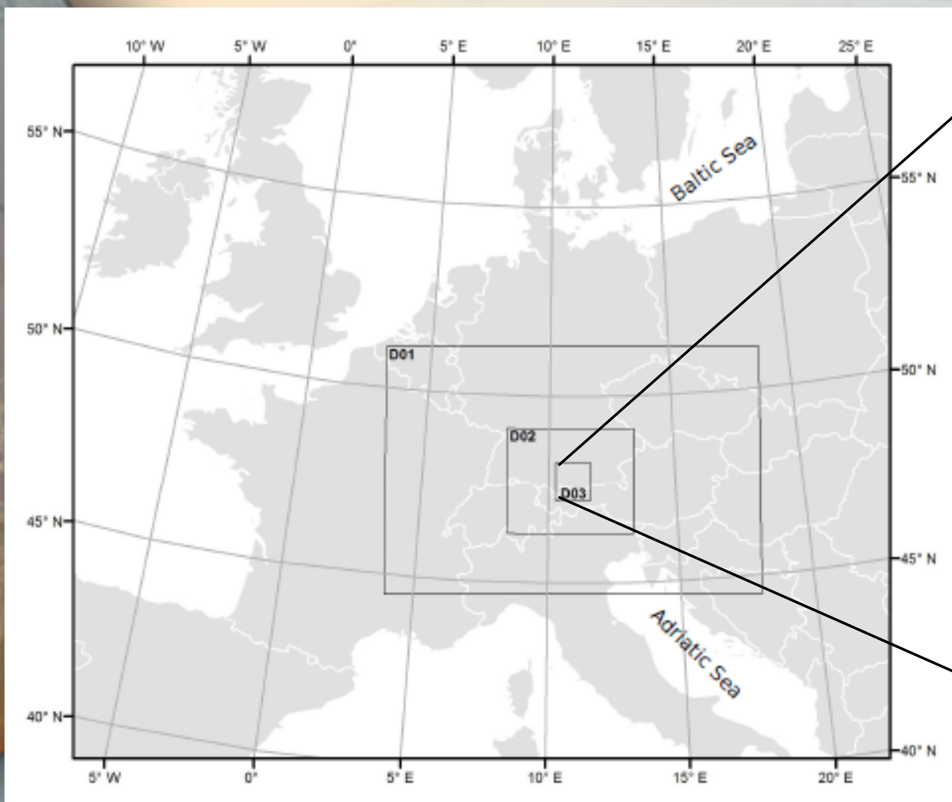
2. On schedule to release 'WRF-Hydo' extension in 2013 release…this will significantly increase our user support demands

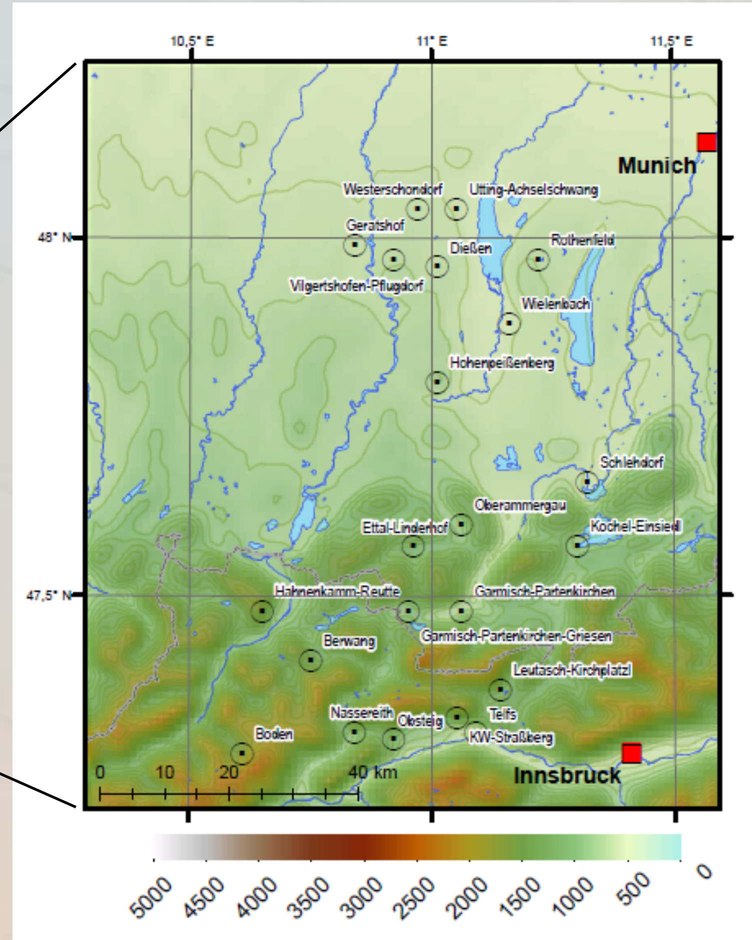
3. Develop community repositories of data, code *and* pre/post process scripts - Done

4. Develop a community support structure (version control, documentation, training) for hydrological model extension capabilities
   - Have now given 4 int'l training/tutorials with more planned…

Recent Application

Regional Climate Downscaling for Bavaria, Germany





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Regional Climate Downscaling for Bavaria, Germany: Column Soil Moisture

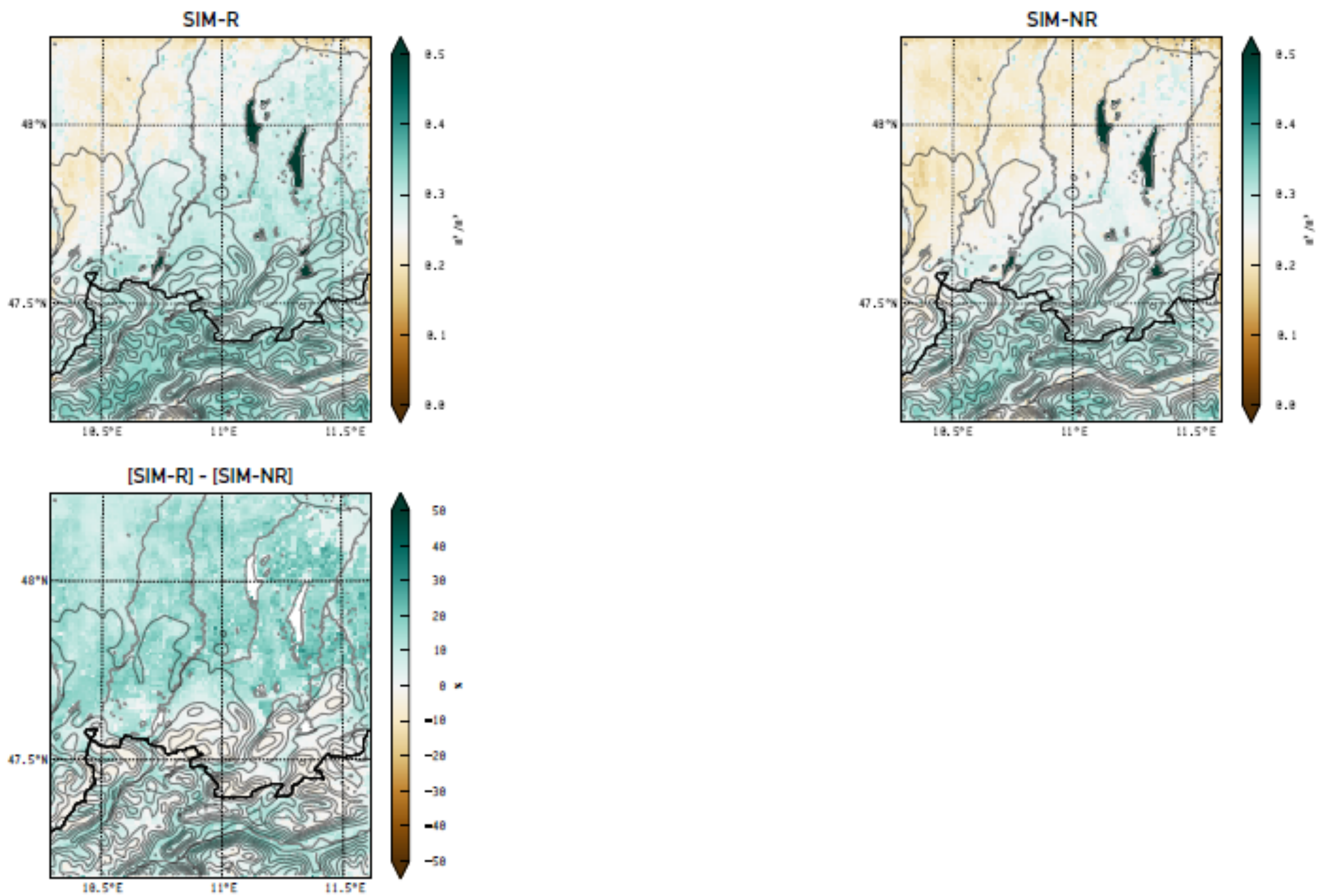

FIG. 15. Total column of soil moisture for SIM-R and SIM-NR and the relative difference between both at the end of the simulation period.

Regional Climate Downscaling for Bavaria, Germany: Latent Heat Flux

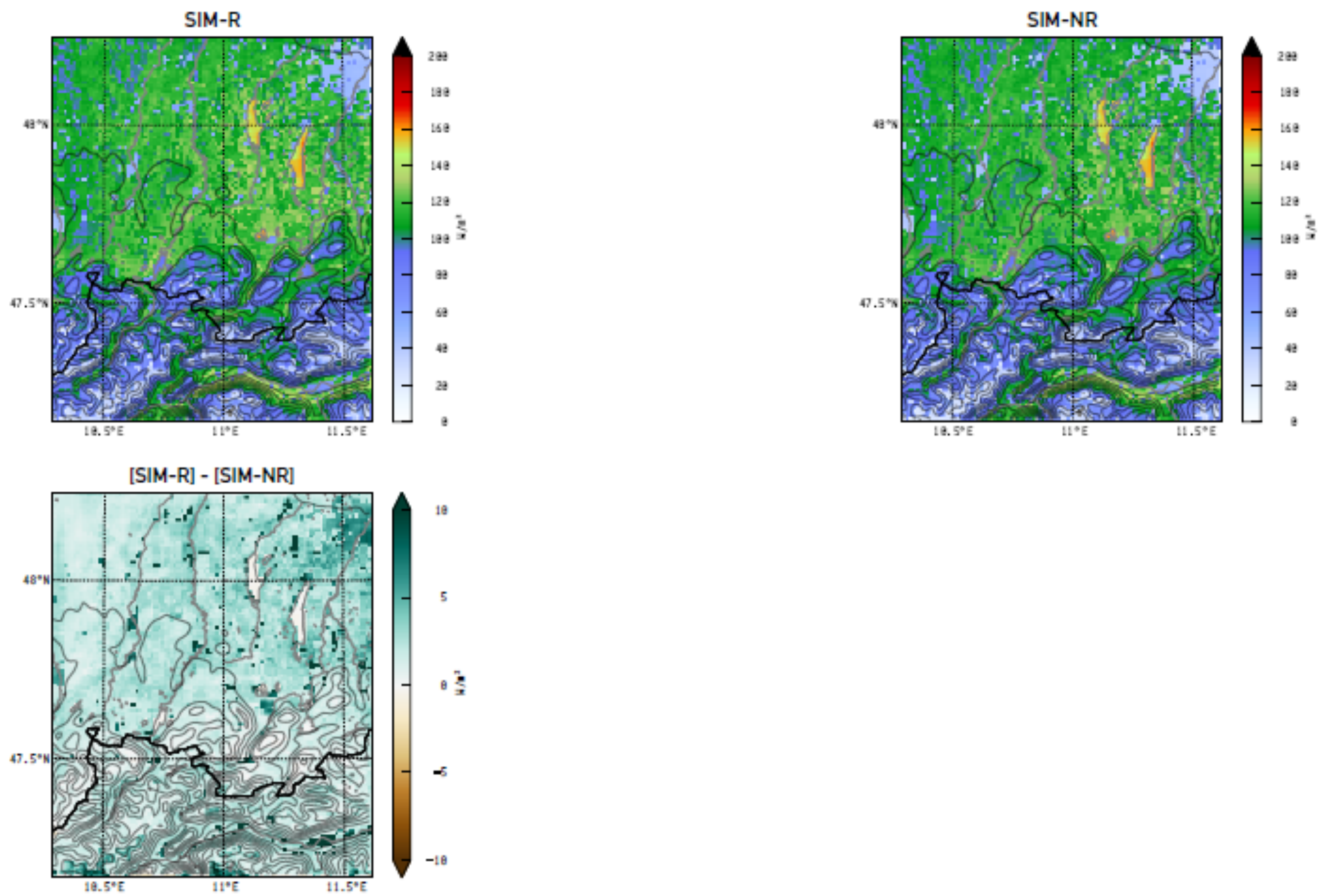

FIG. 12. Average latent heat flux for SIM-R and SIM-NR and the difference between both.

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Regional Climate Downscaling for Bavaria, Germany: Simulated Precipitation

TABLE 3. Observed and simulated daily precipitation sums (mm) during the study period (JJA). Frequency and Intensity are relative to the daily observed values.

Station	**Precipitation sums (mm)**			**Bias (%)**		**Frequency (%)**		**Intensity (%)**	
Station	OBS	SIM-R	SIM-NR	SIM-R	SIM-NR	SIM-R	SIM-NR	SIM-R	SIM-NR
Berwang	632.5	785.4	784.5	24.2	24.0	-14.3	-14.3	44.8	44.7
Boden	560.2	636.6	669.7	13.6	19.6	-8.8	-10.5	24.6	33.6
Diessen/Ammersee-Dettenschwang	395.2	354.3	373.5	-10.4	-5.5	-10.2	-8.2	-0.2	2.8
Ettal-Linderhof	672.3	699.8	718.0	4.1	6.8	-14.3	-15.9	21.4	26.9
Garmisch-Partenkirchen	563.4	758.5	736.3	34.6	30.7	-13.1	-14.8	54.9	53.2
Garmisch-Partenkirchen-Griesen	460.9	623.8	639.2	35.3	38.7	-12.5	-12.5	54.7	58.5
Geratshof	432.4	301.5	273.6	-30.3	-36.7	-12.8	-17.0	-20.1	-23.9
Hahnenkamm-Reutte	783.2	783.1	807.2	-0.0	3.1	3.6	0.0	-3.5	3.0
Hohenpeissenberg	505.7	583.7	561.3	15.4	11.0	-5.6	-5.6	22.2	17.5
KW-Strassberg	526.5	394.2	378.4	-25.1	-28.1	-21.7	-21.7	-4.5	-8.3
Kochel-Einsiedl (Kraftwerk)	872.8	763.0	721.9	-12.6	-17.3	-12.3	-10.8	-0.3	-7.3
Leutasch-Kirchplatzl	693.4	726.5	729.2	4.8	5.2	-15.3	-18.6	23.6	29.2
Nassereith	485.4	555.8	593.2	14.5	22.2	-3.6	-5.4	18.7	29.1
Oberammergau	564.7	867.9	882.9	53.7	56.4	-11.3	-9.7	73.2	73.1
Obsteig	396.6	361.8	372.1	-8.8	-6.2	-9.3	-13.0	0.5	7.7
Rothenfeld	536.2	476.2	466.7	-11.2	-13.0	-9.6	-7.7	-1.8	-5.7
Schlehdorf	643.3	618.9	552.8	-3.8	-14.1	-8.2	-14.8	4.8	0.7
Telfs	366.2	446.1	443.0	21.8	21.0	-8.3	-14.6	32.8	41.5
Utting-Achselschwang	369.9	349.3	370.4	-5.6	0.1	-14.0	-18.0	9.7	22.0
Vilgertshofen-Pflugdorf	402.4	403.3	396.7	0.2	-1.4	-14.0	-14.0	16.5	14.6
Westerschondorf	351.0	353.6	369.4	0.7	5.3	-20.0	-21.8	25.8	34.5
Wielenbach (Demollstr.)	446.0	464.6	502.2	4.2	12.6	-7.7	-1.9	12.8	14.8
Average	530.0	559.4	561.0	5.4	6.1	-11.1	-12.3	18.7	21.0

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Regional Climate Downscaling for Bavaria, Germany: Simulated Streamflow

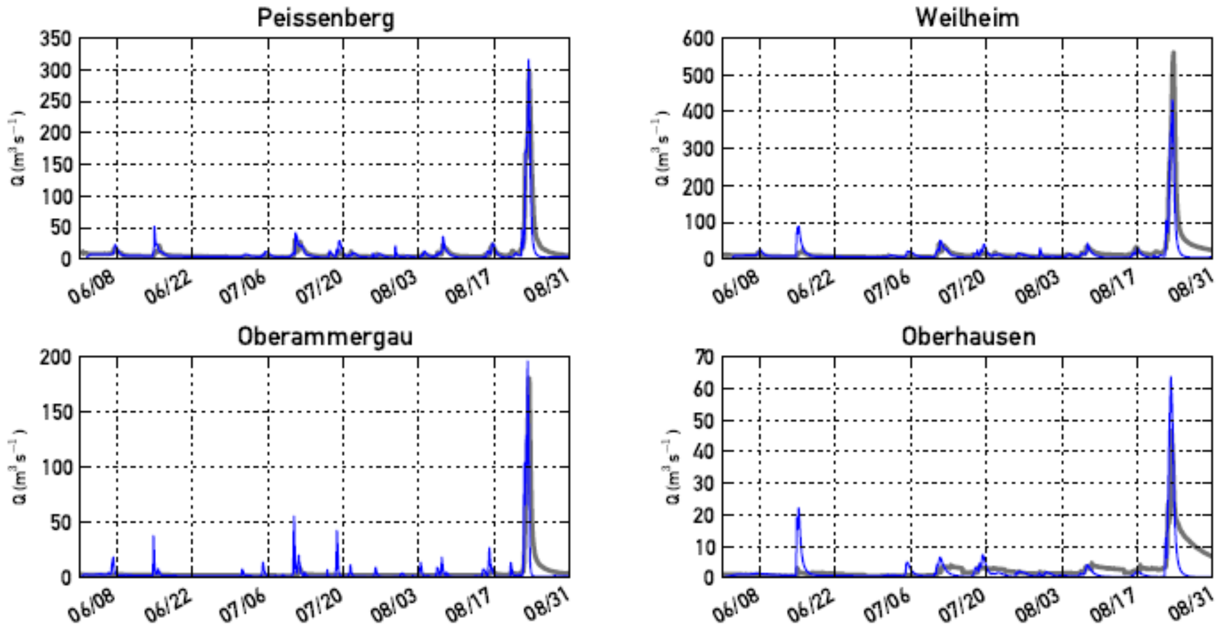

FIG. 7. Simulated (blue) and observed (grey) streamflow at four gauging stations in the Ammer catchment.

TABLE 2. Nash-Sutcliffe efficiency and coefficients of determination for simualted streamflow at 5 gauging station in the Ammer catchment.

Gauging station	Oberammergau	Peissenberg	Weilheim	Obernach	Oberhausen
Nash-Sutcliffe efficiency	0.49	0.86	0.77	0.51	0.15
R^2	0.50	0.83	0.78	0.46	0.42

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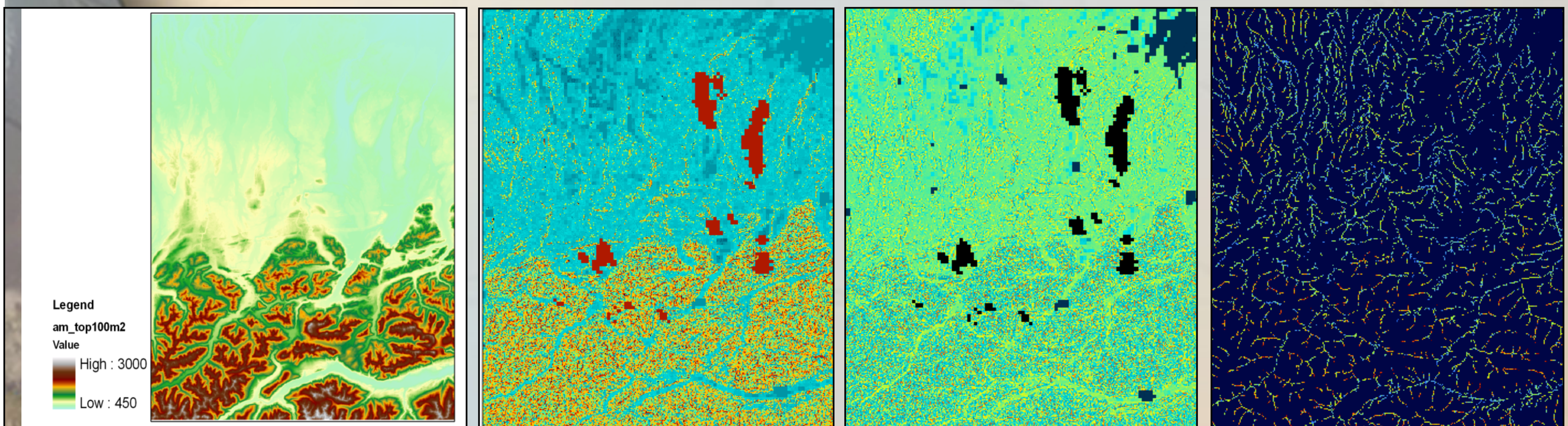
High Resolution Spatially—Distributed Fields

DEM: 100 m

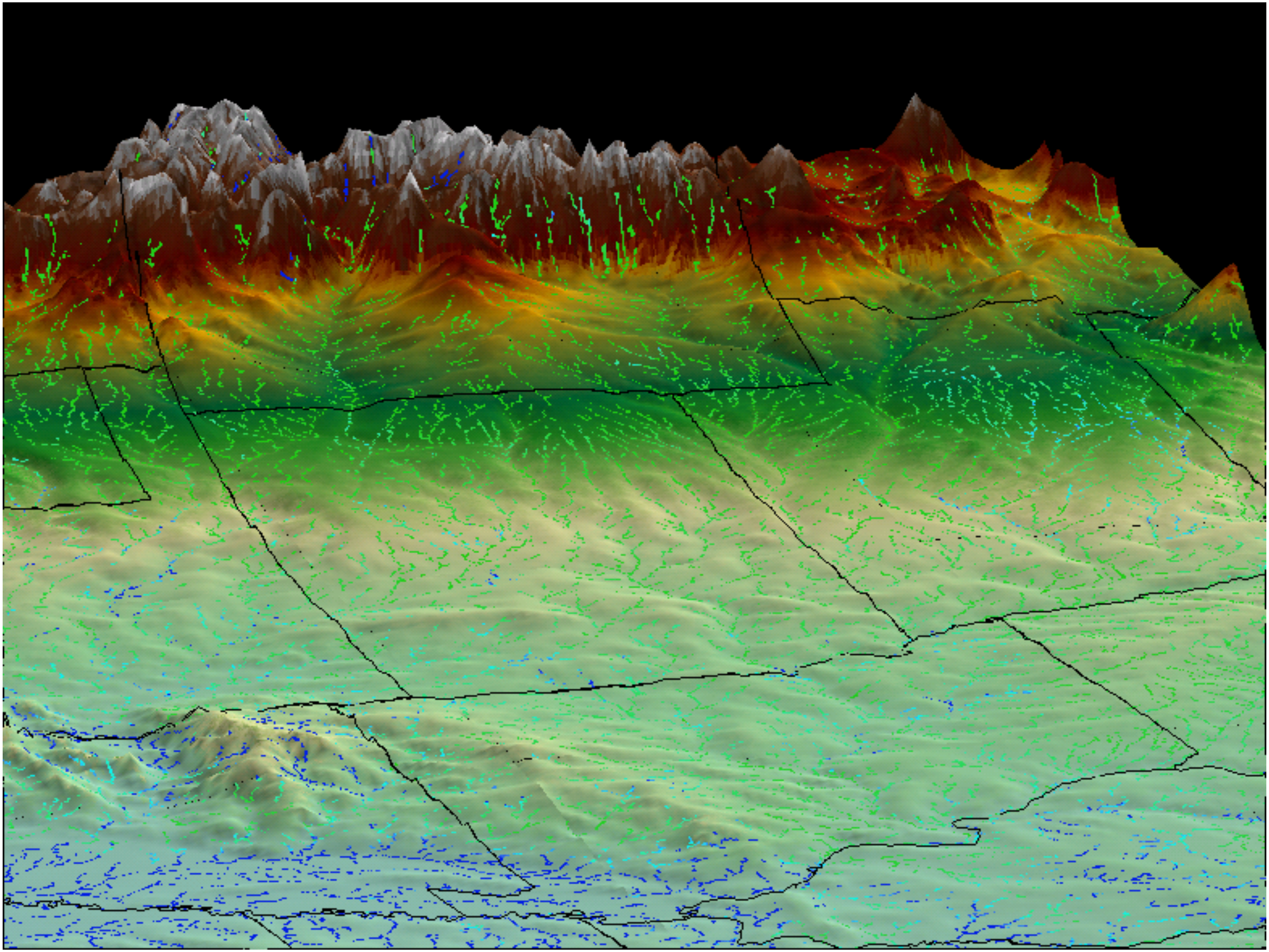
Water table depth (m)

Soil moisture

Stream channel inflows

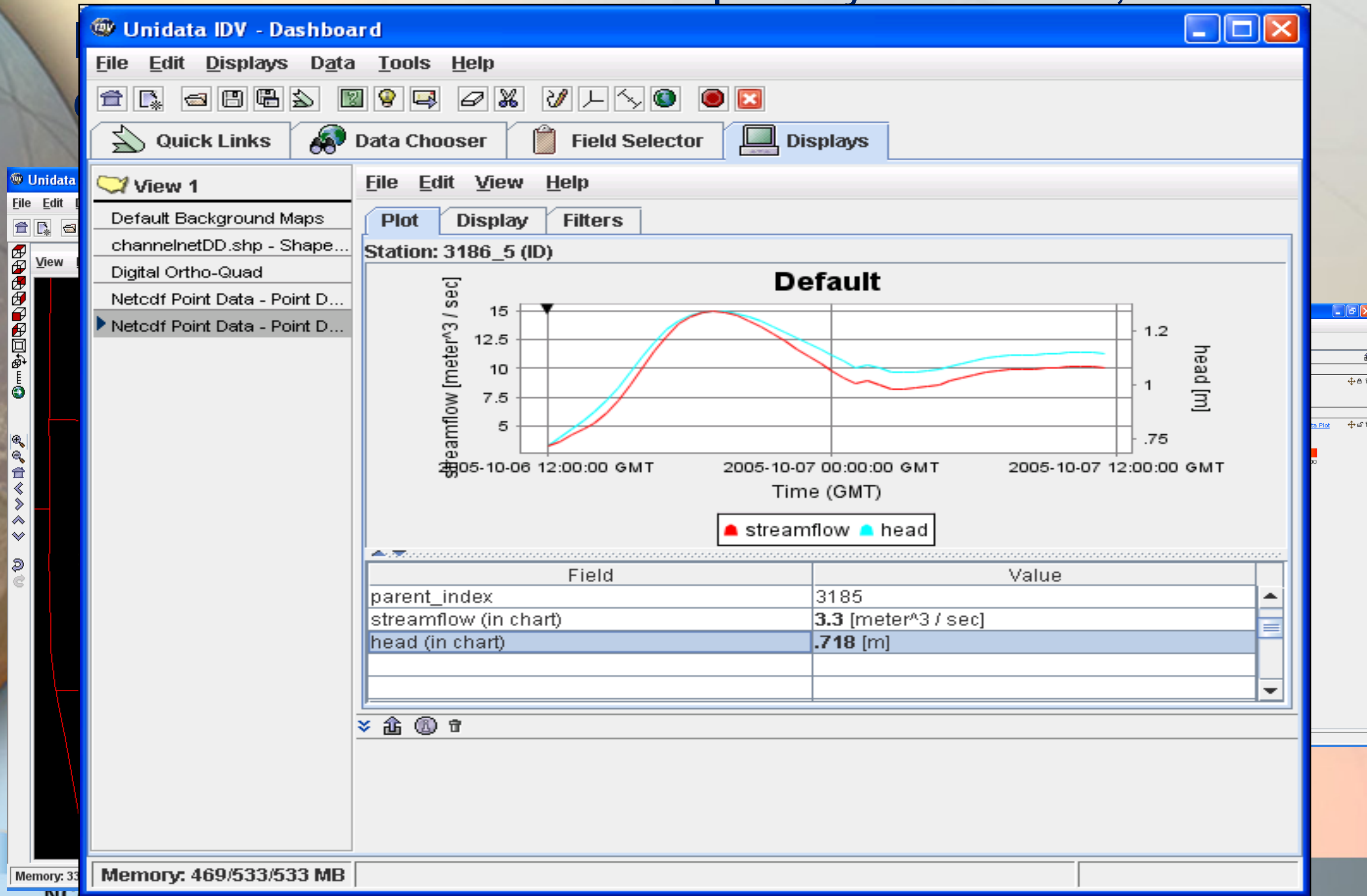


Northern Alps : Germany Domain: ~140x220 km



Distributed Output:

Quantitative information on spatially distributed,



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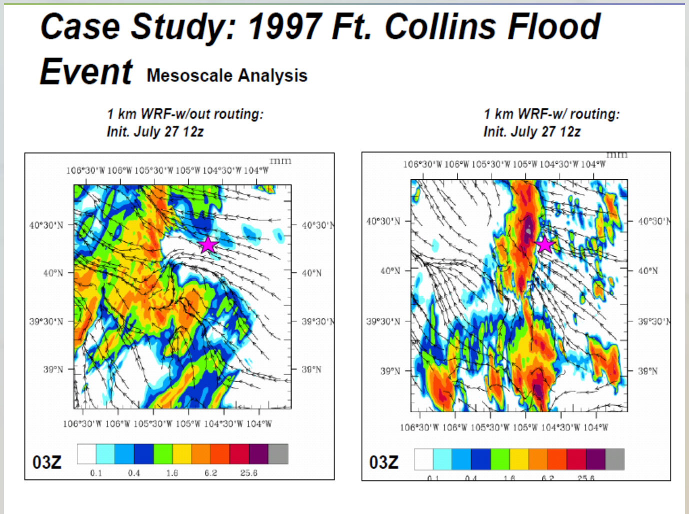
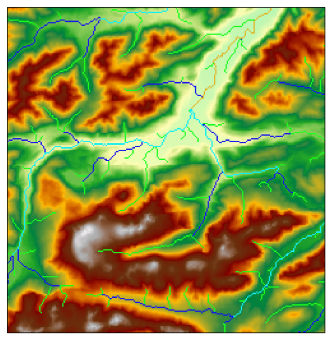
WRF-Hydro: Coupled mode applications and support:

- Progress:
  - Under several projects we have finalized upgrade and coupling of distributed hydrology model with WRF
  - Used to predict front range flooding (2008-2011)
  - Component of Romanian national model development
  - Snowmelt in C. Rockies
  - Climate-hydrology interactions in (Turkey, Germany, Mexico)

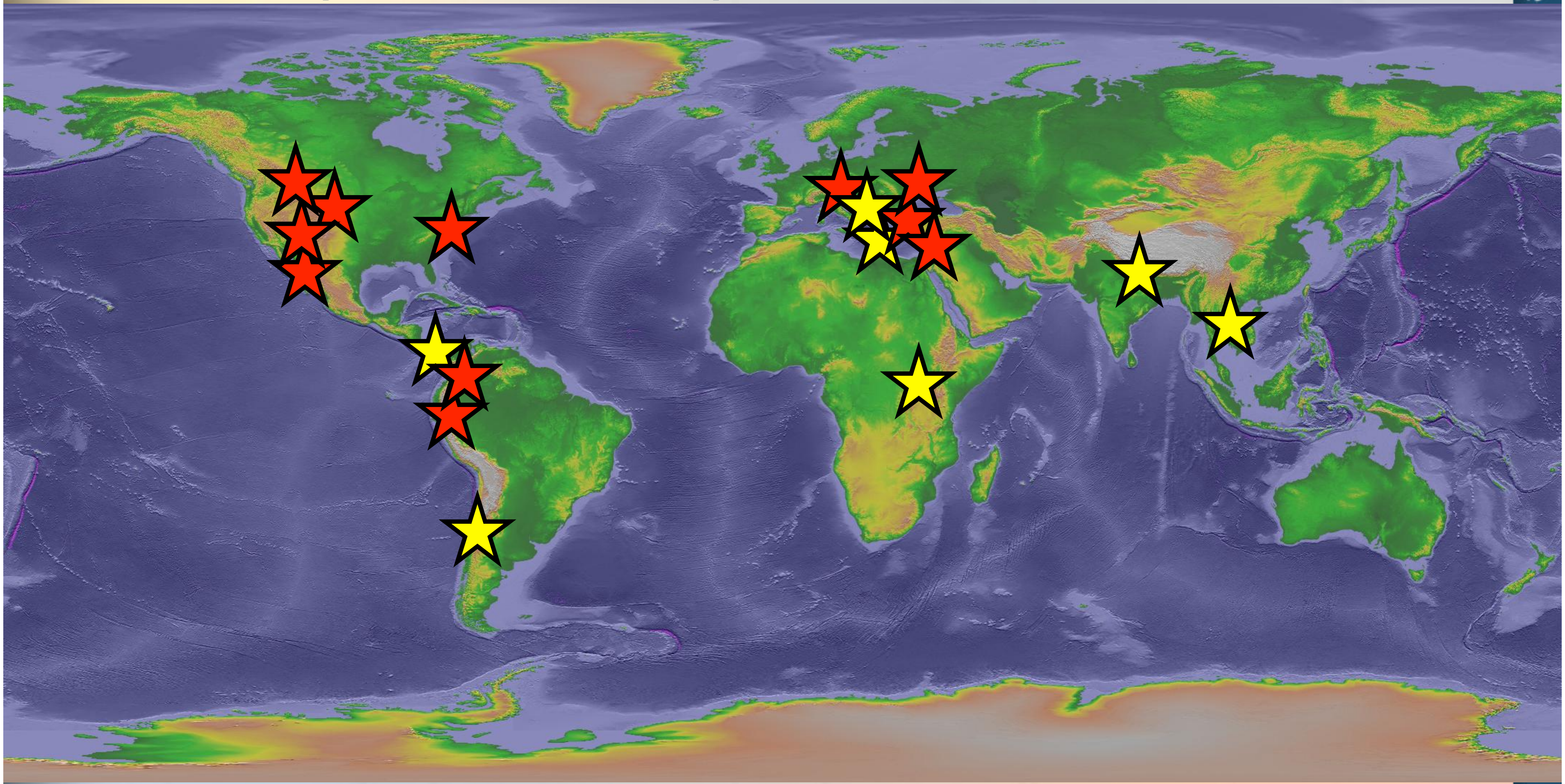


Coupled WRF-Hydro in the Col. Front Range



Regional climate impacts in N. Alps

Existing or Recently Proposed WRF-Hydro ('Noah'-based) Implementations



★ Past or current implementations

★ Recently proposed implementations

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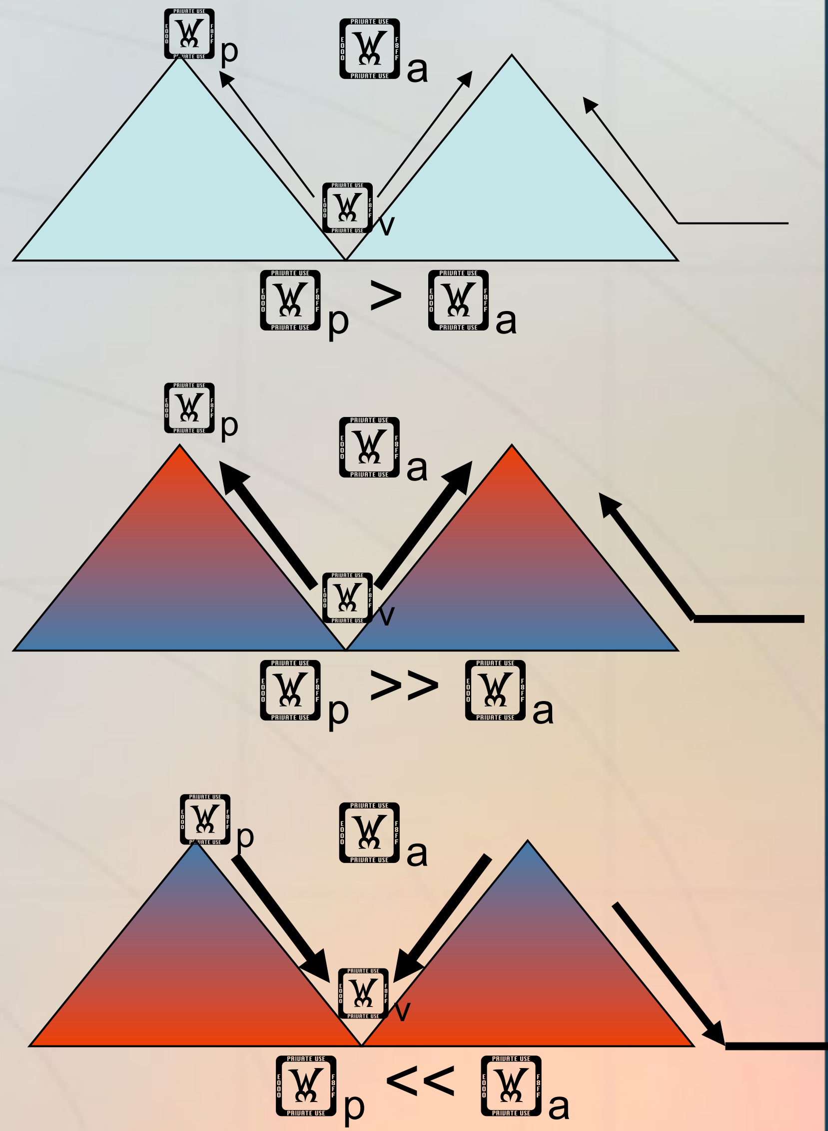
Terrain circulations:

- Background circulation
- Increased circulation (dry peaks)
- Suppressed circulation (wet/snow peaks)



Terrain circulations: Complications

- How do routing processes influence these circulations?
  - How do wet valley-dry peak or dry valley-wet peak conditions influence the terrain circulation? Similarly for mountain-plain circulations?
  - At what spatial and temporal scales do these processes become significant?
  - Is there a detectable difference from an NWP/QPF perspective?
  - What are the potential reasons for such differences?

1. Ft. Collins Flood Model Experiments

- July 28, 1997 Fort Collins flood event

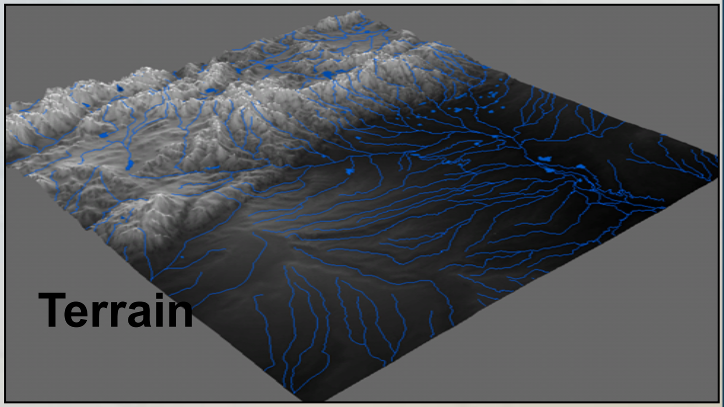
   1. Spin up land surface initial conditions with and without terrestrial routing (2mo. spin-up, avoiding snowmelt)

   2. Compare/contrast fully-coupled WRF simulations with spun-up land surface conditions (w/ and w/out routing) but no routing during simulation

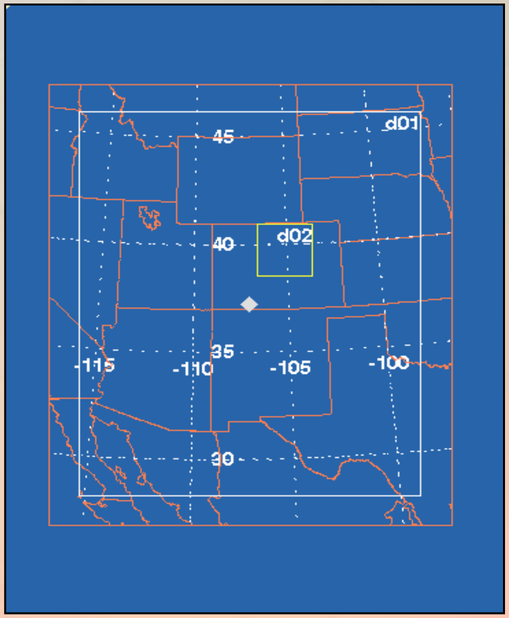
- Aim: Assess the impact of land surface initializations on simulated storm event

1. Coupled WRF-Hydro Flash Flood Forecasting in the Colorado Front Range:

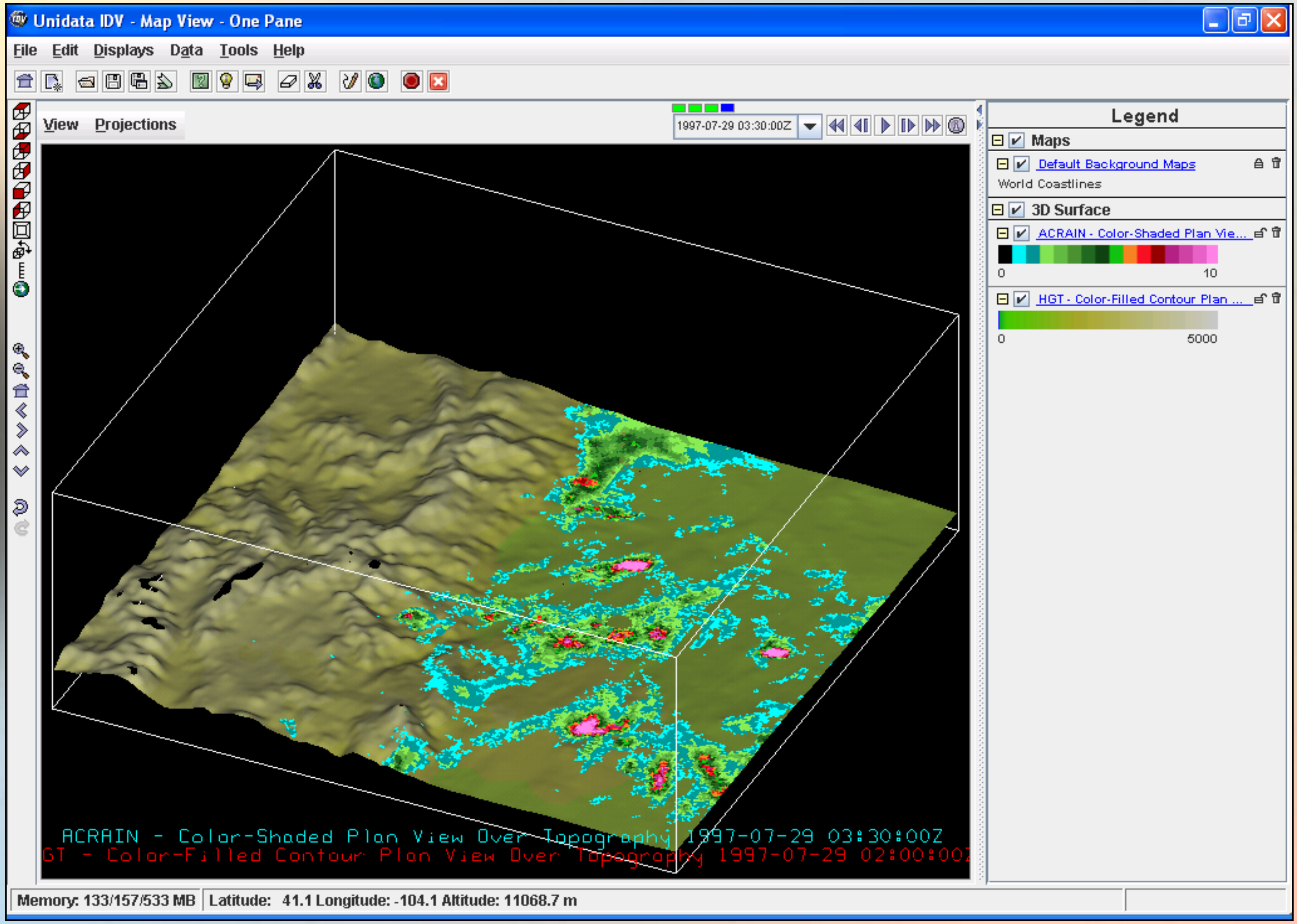
- WRF Model Options
  - No convection parameterization
  - Purdue/Lin 6-class microphysics
  - RRTM LW, Dudhia SW
  - Yonsei PBL, M-O sfc lyr
  - Noah land surface model w/ and w/out coupled Noah-distributed routing
  - Operational runs from 00z (research run from 12z)



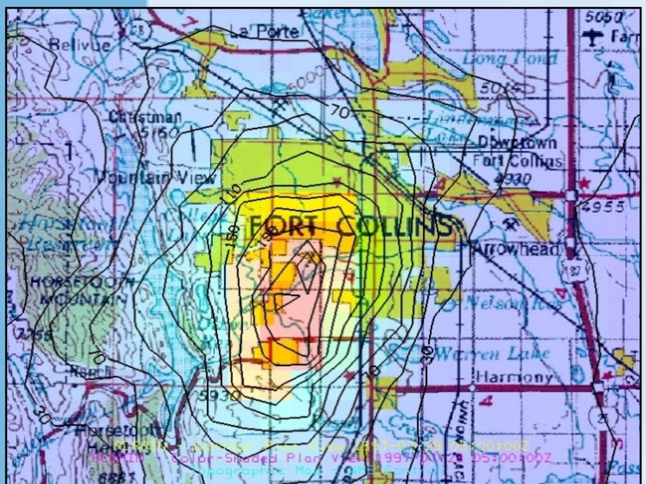
4 km and 1 km WRF Domains

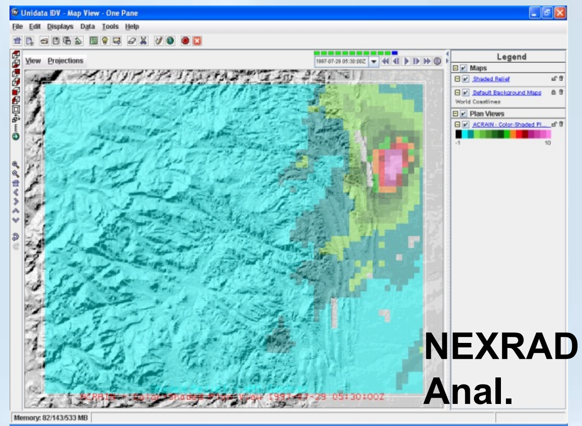


1. The 1997 Forth Collins Flood:

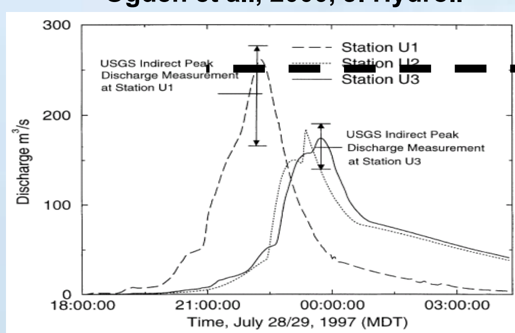


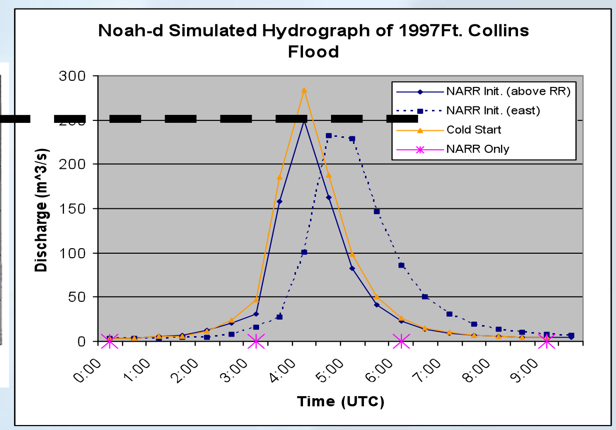
Coupled WRF-Hydro Flash Flood Forecasting in the Colorado Front Range:





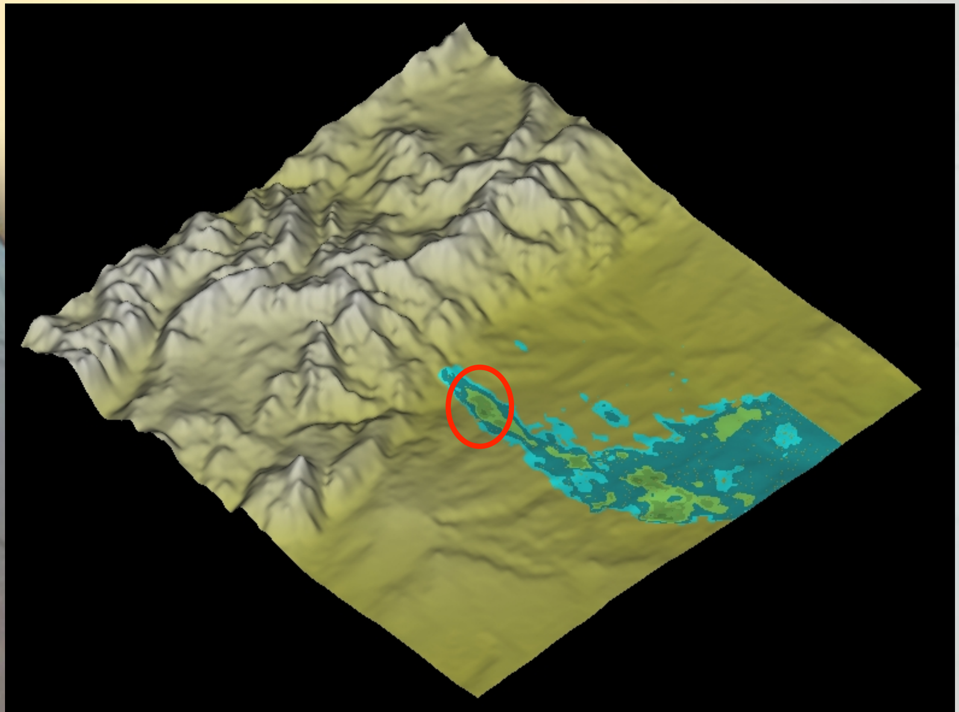
Ogden et al., 2000, J. Hydrol.

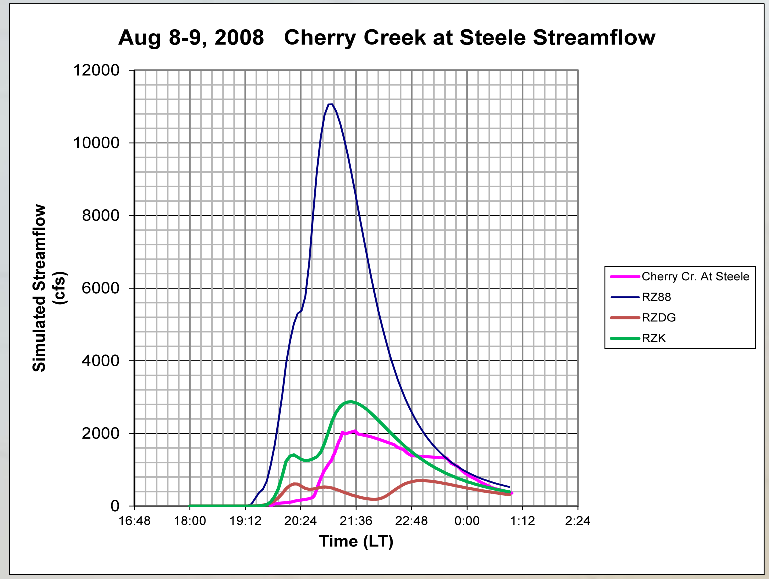


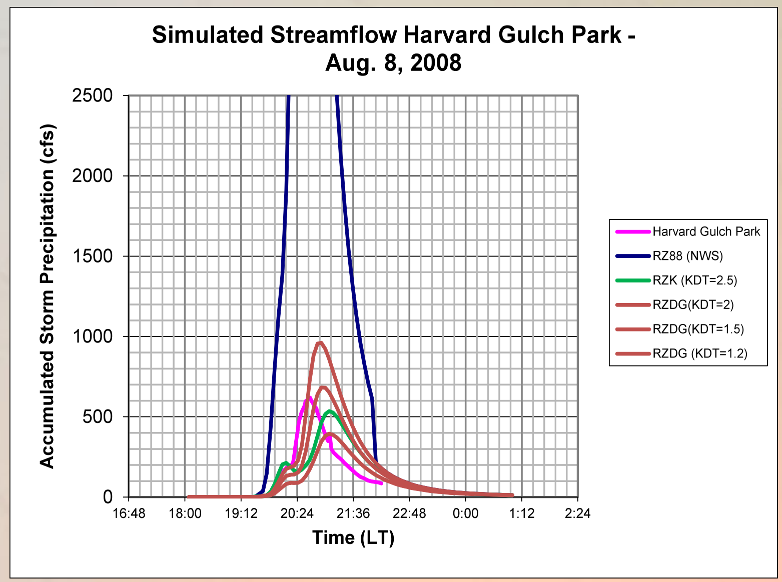


– Development of Front Range QPE and QPF

– Flash flood simulation of 1997 Fort Collins flood







Above: Map of Aug. 8, 2008 storm total precipitation. Red circle outlines area of flood response on Cherry Creek and Harvard Gulch watersheds in south Denver. Peak rainfall in flood areas was approximately 2-3 inches (dark green).
Right: Flood hydrographs for observed (pink) and simulated flows where blue, light blue and green lines show runoff sensitivity to soil infiltration.

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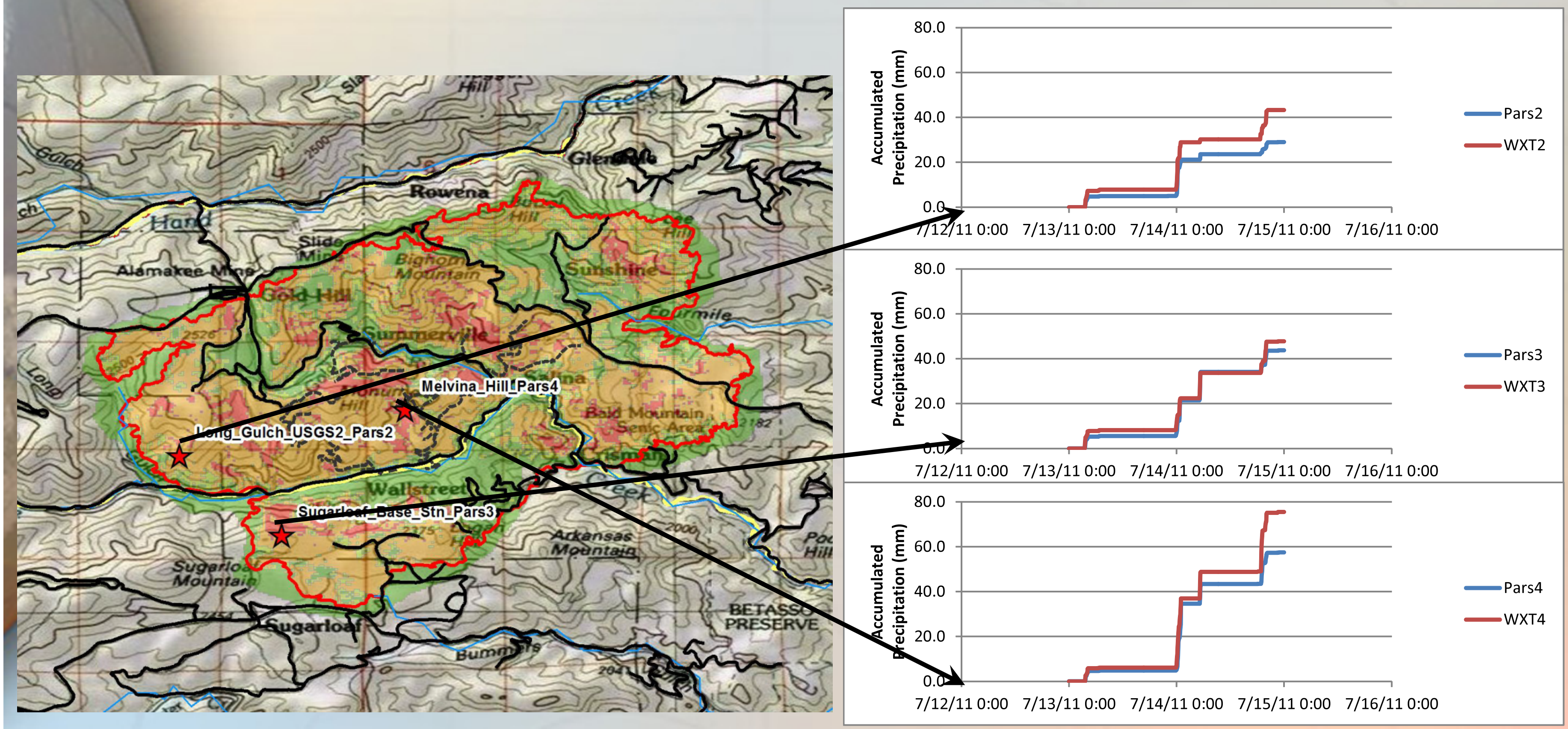
July 13, 2011 Fourmile Canyon Flood Event:

1. Description and animation…



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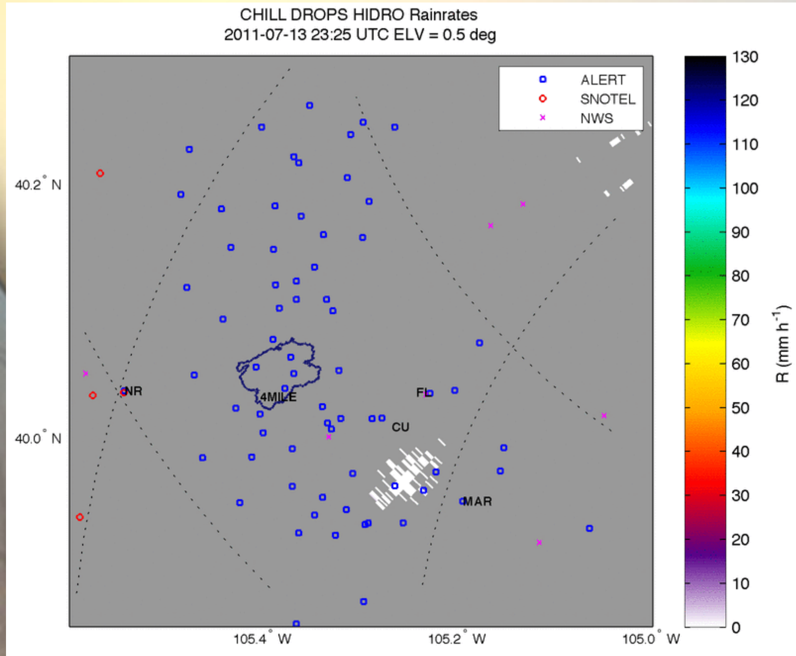

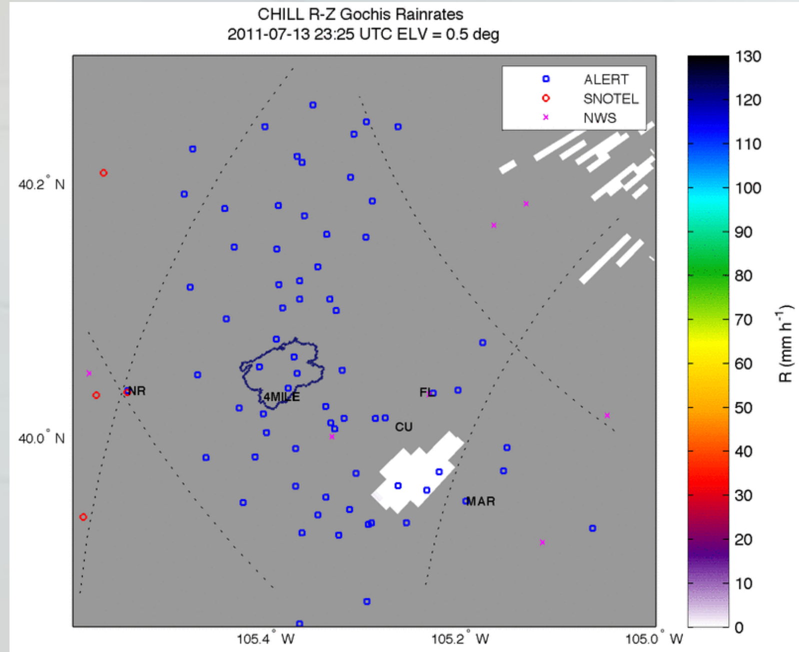

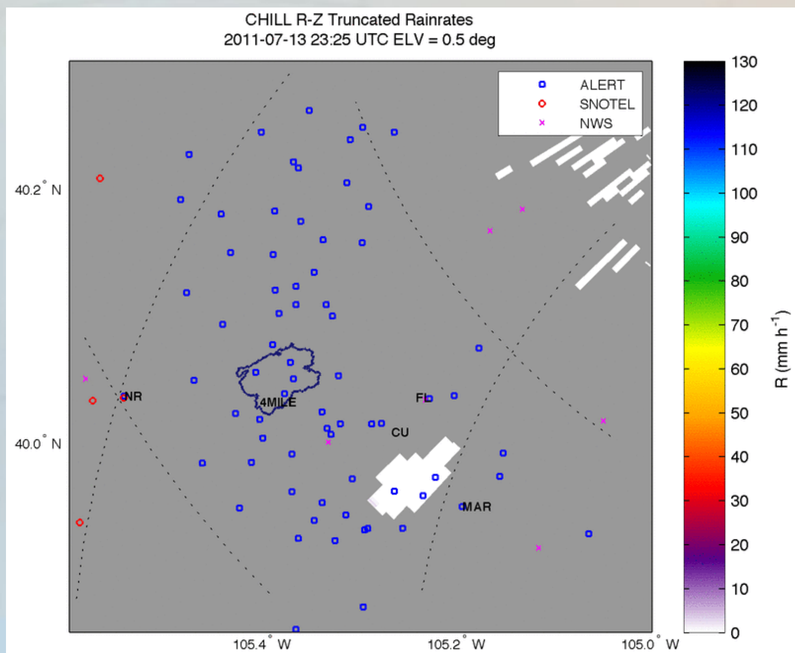

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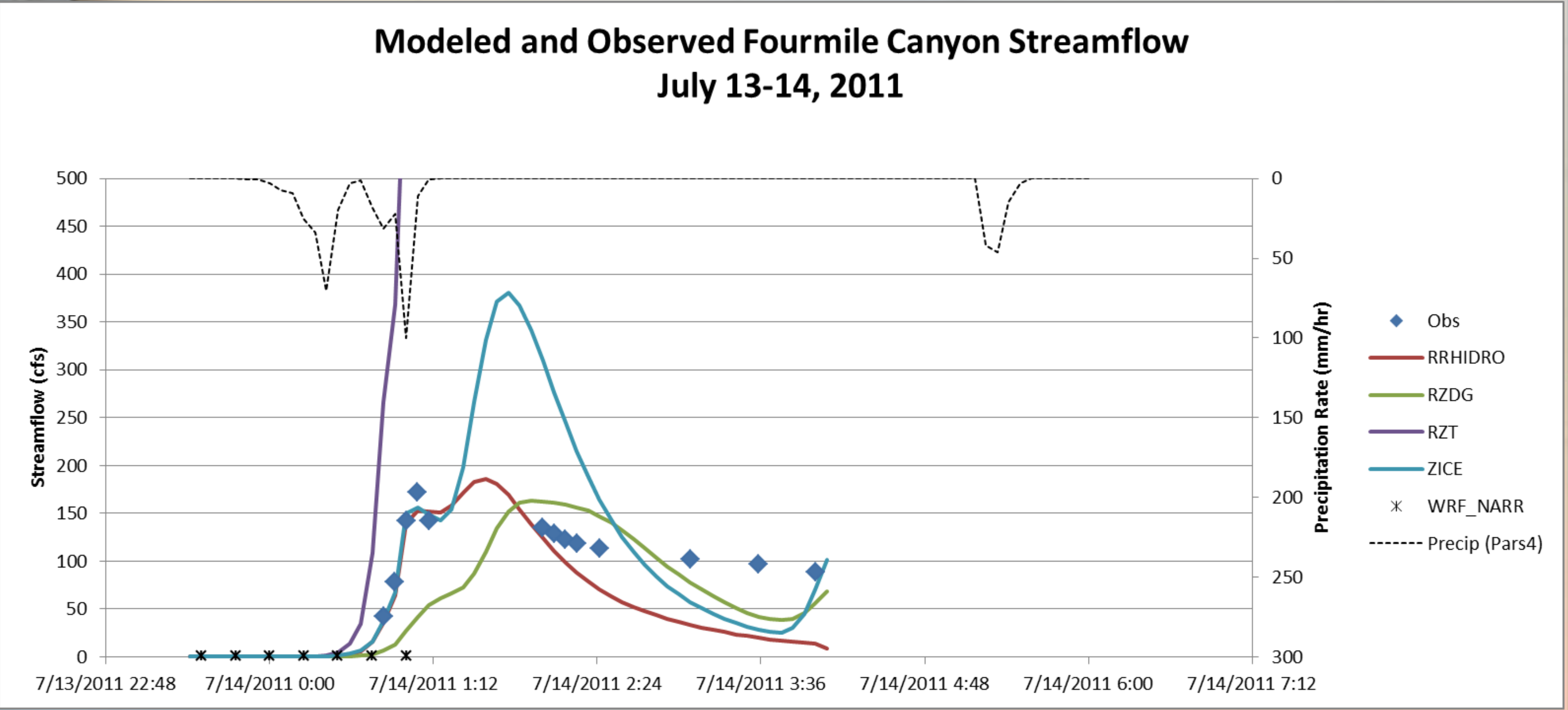
July 13, 2011 Fourmile Canyon Flood Event: Hydrologic Simulation



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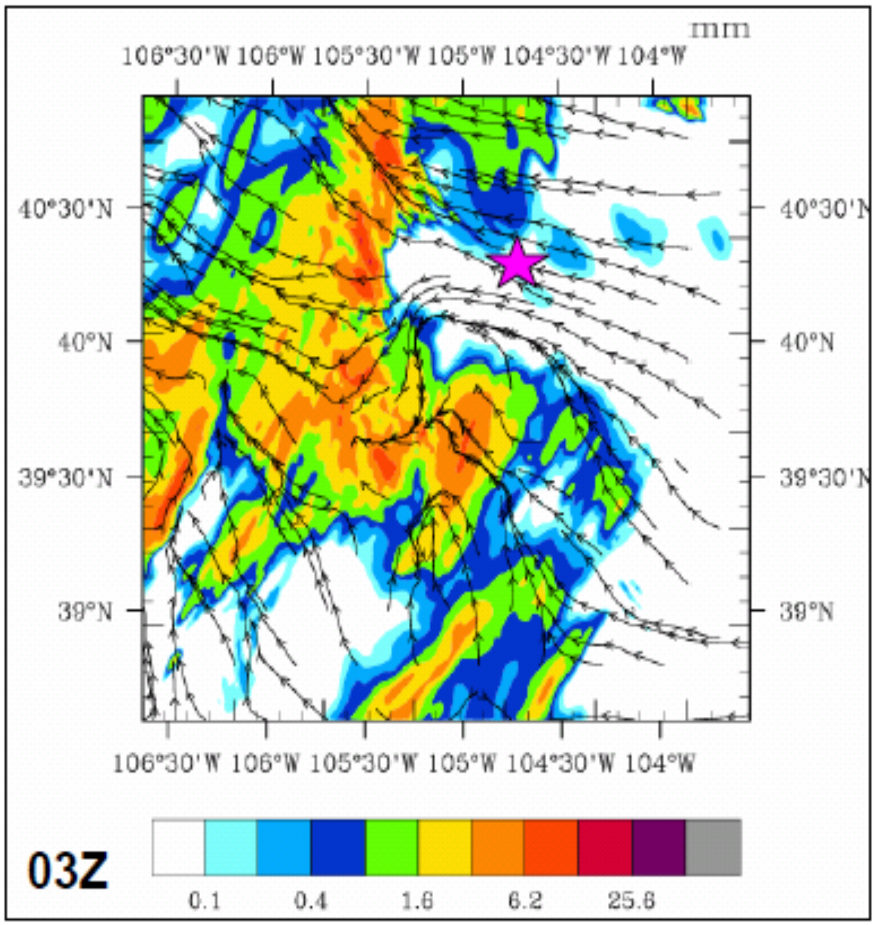
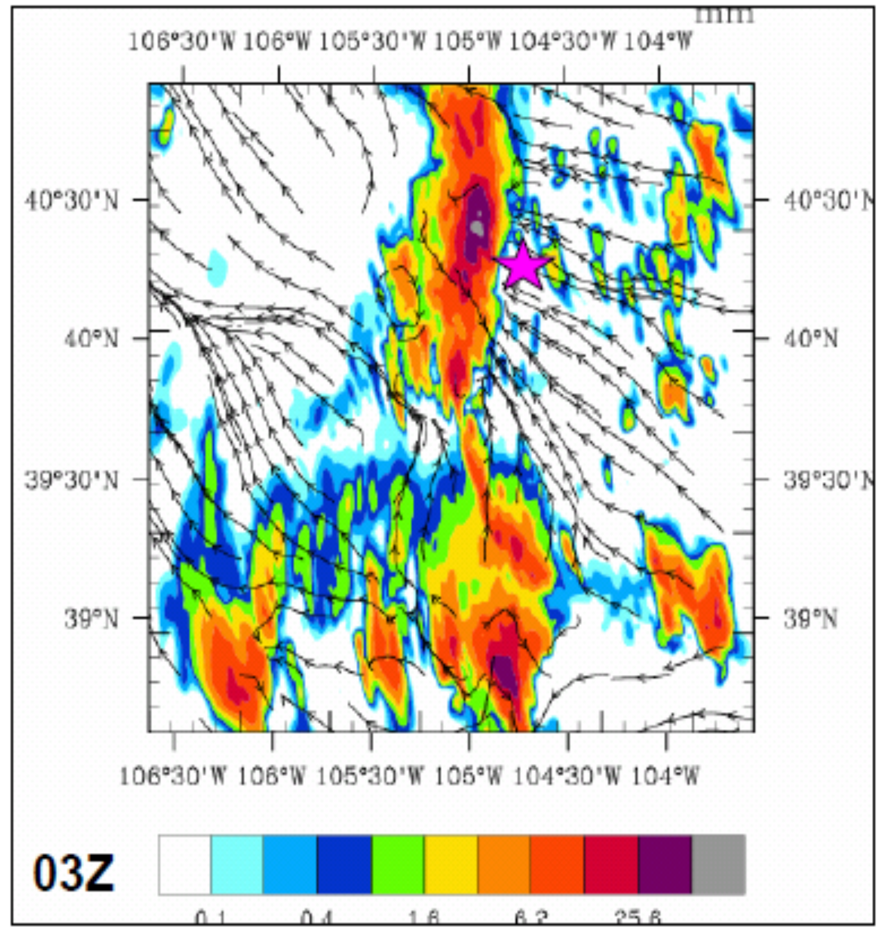
Case Study: 1997 Ft. Collins Flood Event

Mesoscale Analysis

1 km WRF-w/out routing:
Init. July 27 12z



1 km WRF-w/ routing:
Init. July 27 12z



Case Study: 1997 Ft. Collins Flood Event

Mesoscale Analysis

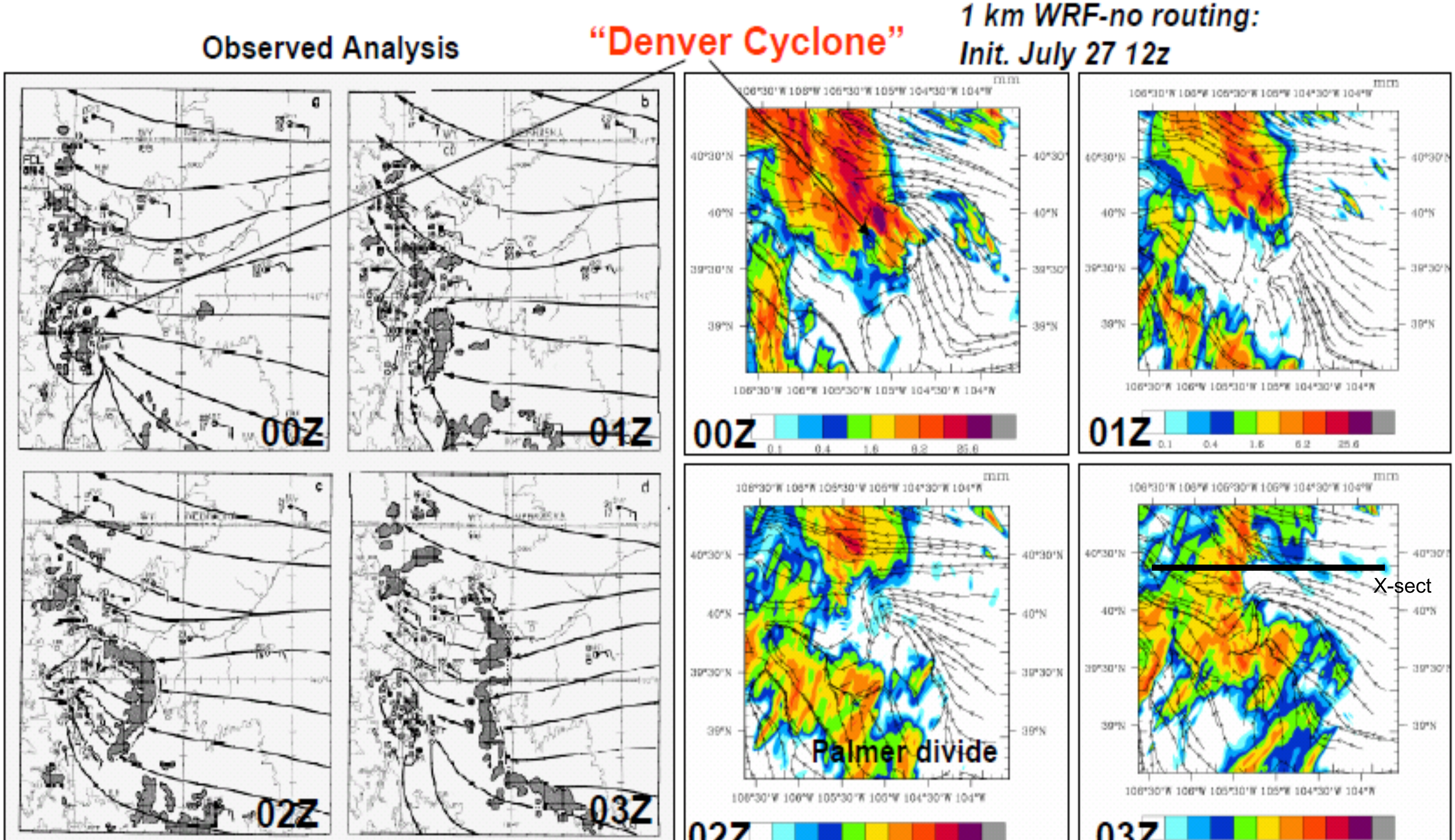


FIG. 7. Hourly mesoscale analyses for 1800–2100 MDT 28 July 1997 (0000–0300 UTC 29 July 1997). Surface streamlines are in solid arrows. Wind barbs plotted as in Fig. 6; temperature and dewpoints in °C. Mesoscale boundaries are indicated as in Fig. 5. Regions of radar reflectivity ≥ 35 dBZ are shaded: (a) 1800 (0000), (b) 1900 (0100), (c) 2000 (0200), and (d) 2100 MDT (0300 UTC).

Confidential
and

Case Study: 1997 Ft. Collins Flood Event

Mesoscale Analysis

Observed Analysis

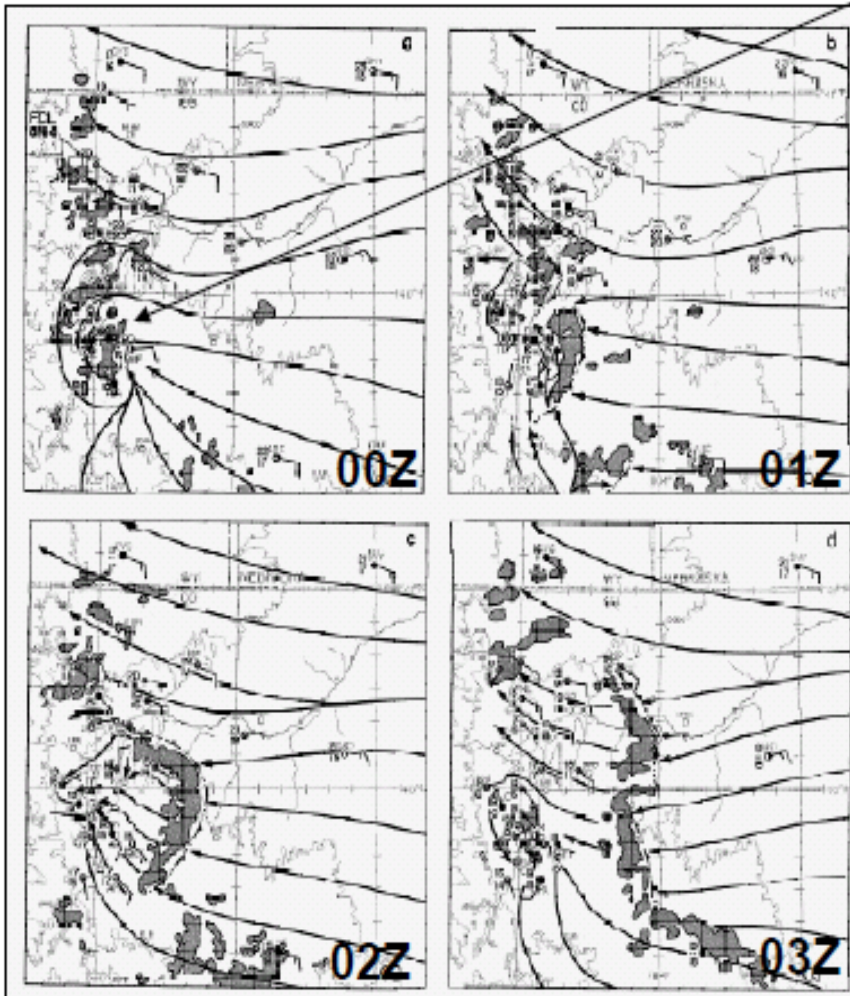
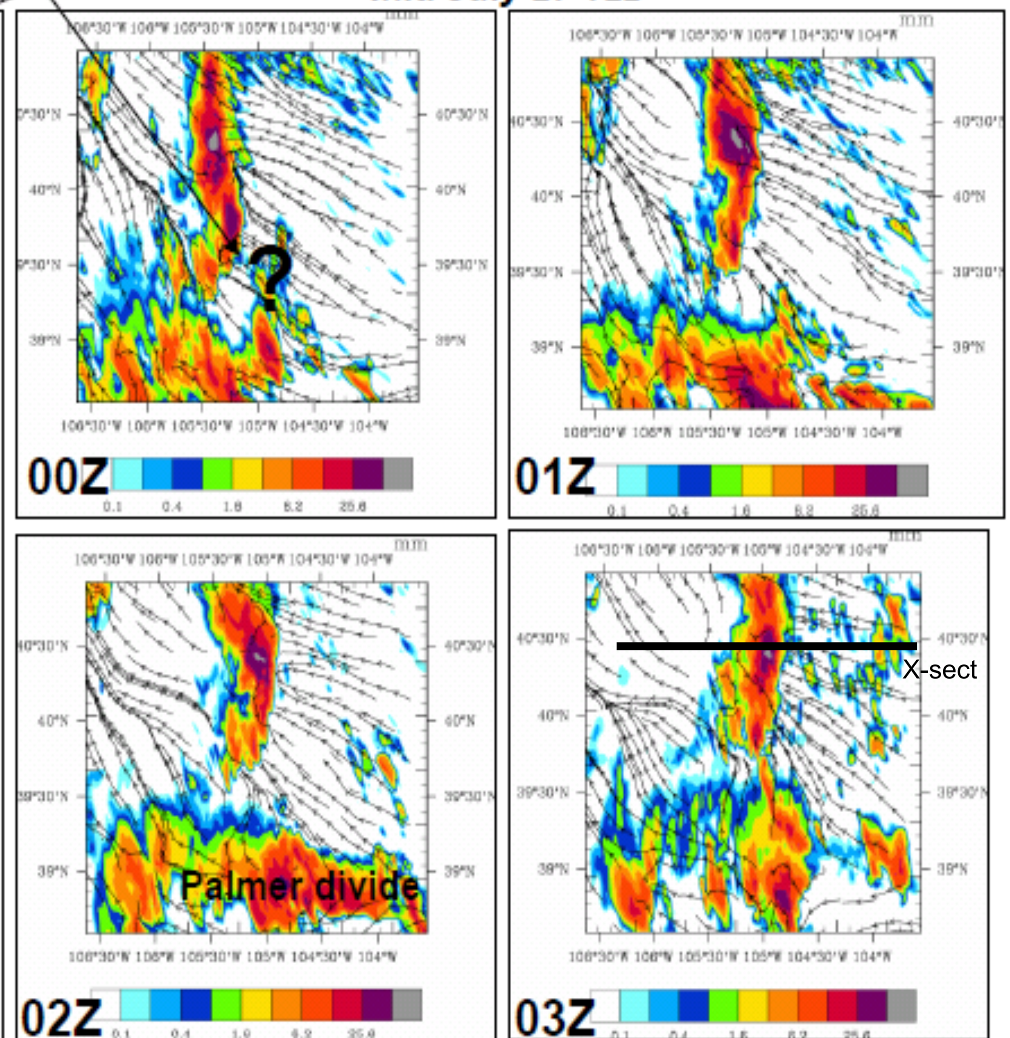


FIG. 7. Hourly mesoscale analyses for 1800–2100 MDT 28 July 1997 (0000–0300 UTC 29 July 1997). Surface streamlines are in solid arrows. Wind barbs plotted as in Fig. 6; temperature and dewpoints in °C. Mesoscale boundaries are indicated as in Fig. 5. Regions of radar reflectivity ≥ 35 dBZ are shaded: (a) 1800 (0000), (b) 1900 (0100), (c) 2000 (0200), and (d) 2100 MDT (0300 UTC).

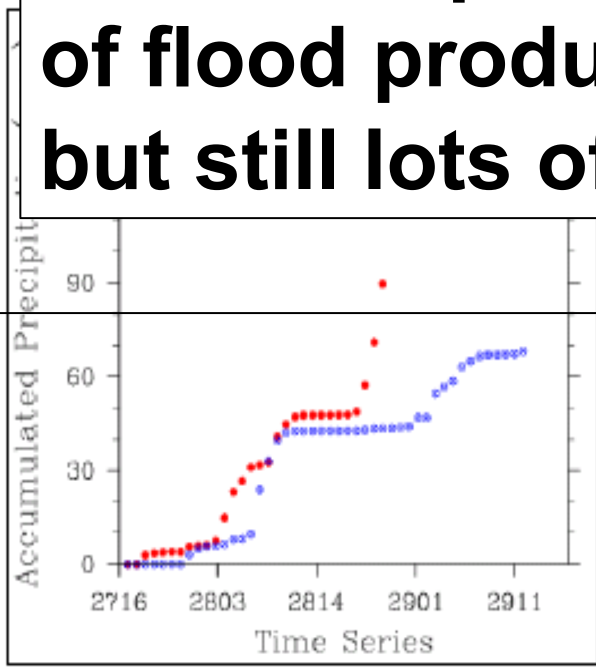
"Denver Cyclone"

1 km WRF-w/ routing:
Init. July 27 12z

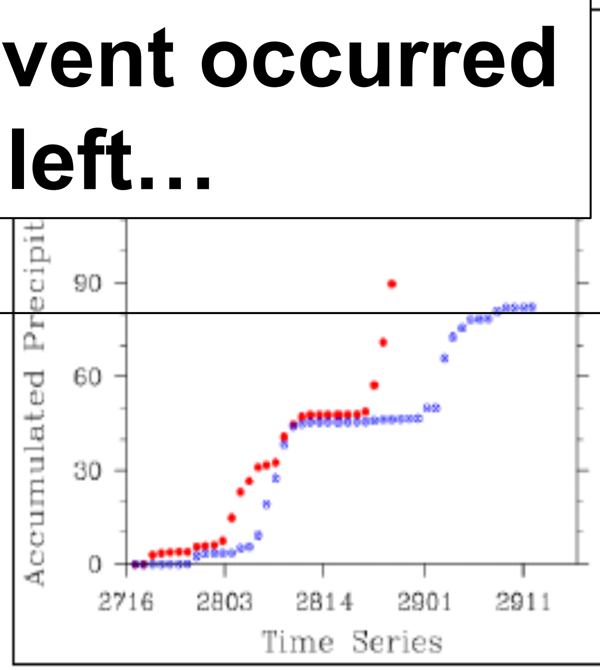


Case Study: 1997 Ft. Collins Flood Event Accumulated Precipitation

Result: Improvement in simulation of flood producing event occurred but still lots of work left…

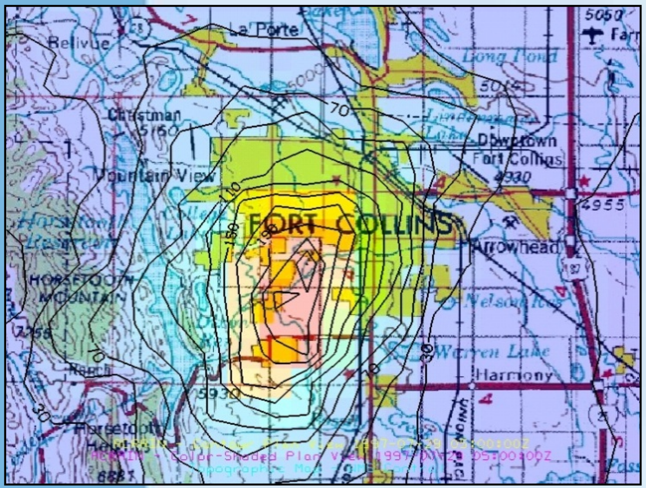


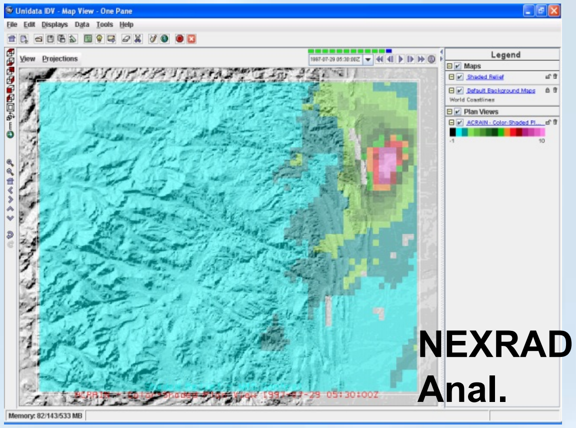
1 km WRF-no routing: Init. July 27 12z

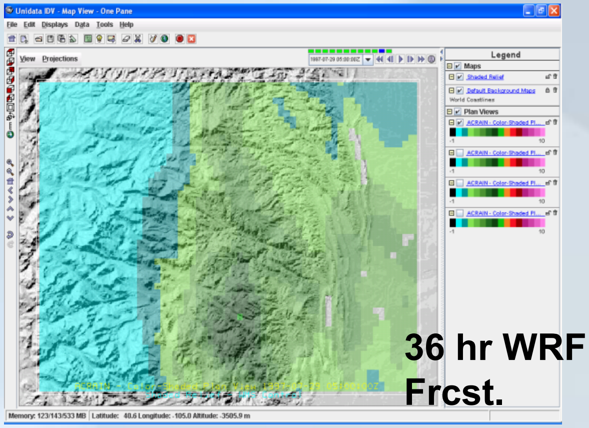


1 km WRF-with routing: Init. July 27 12z

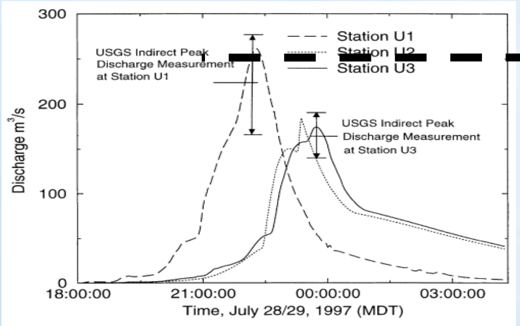
Coupled WRF-Hydro Flash Flood Forecasting in the Colorado Front Range:

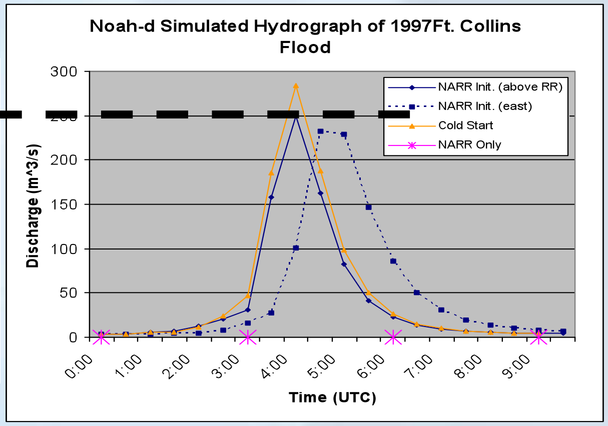






Ogden et al., 2000, J. Hydrol.

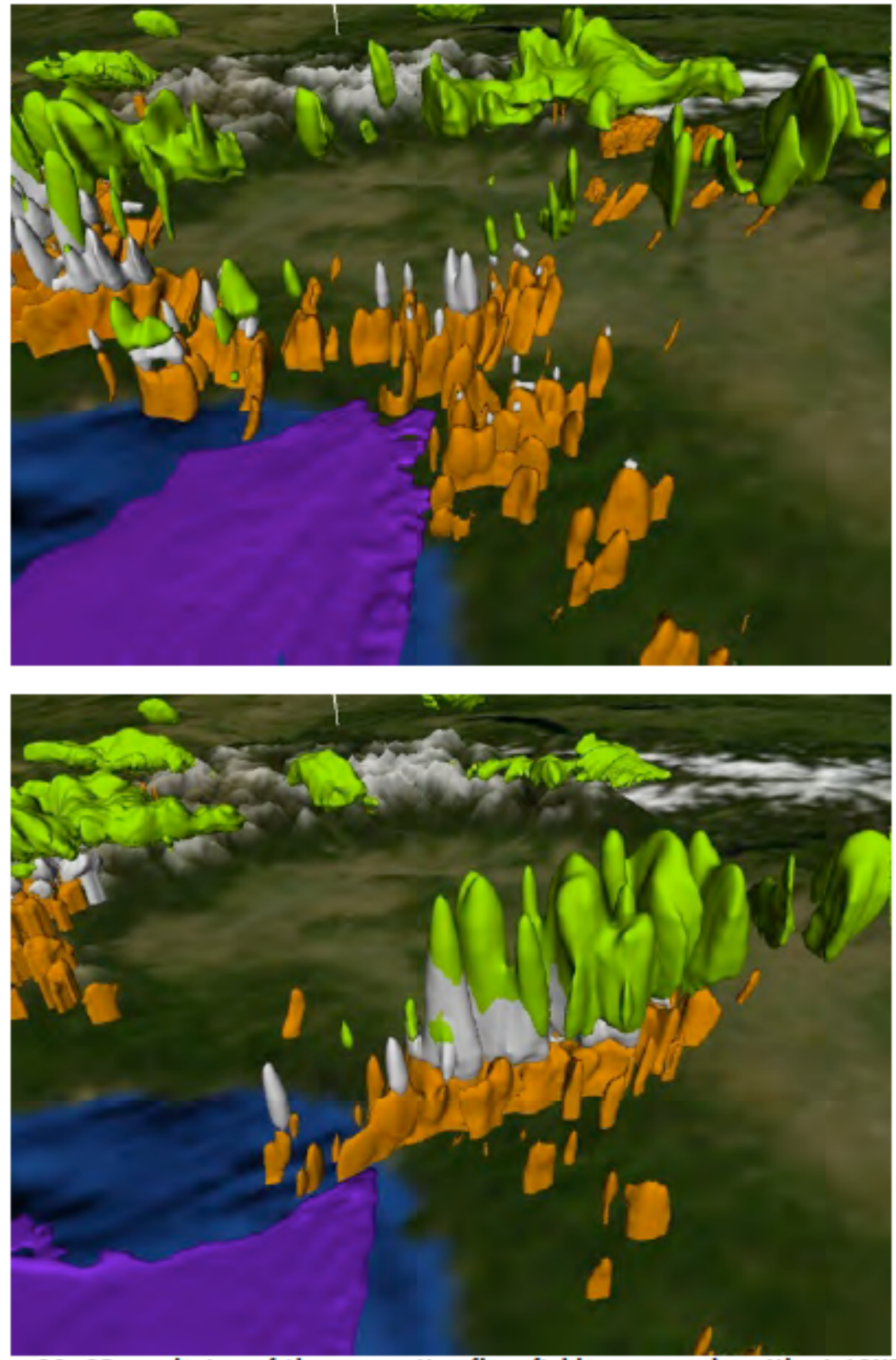




– Development of Front Range QPE and QPF

– Flash flood simulation of 1997 Fort Collins flood

2011 Genoa Flood (4 Nov.)



ure 20: 3D rendering of the convective flow field on november 4th at 12UT

The National Center for Atmospheric Research

NCAR

2. WRF-Hydro regional hydroclimate study for the Ammer Catchment, Bavaria, Germany (Thomas Rummler & Harald Kunstmann, KIT Garmisch-P., Ger.)

Discretization
D01: dx= 15km
D02: dx= 5km
D03: dx= 1km
Routing subgrid dx=100m
44 vertical layers
p_{top}=10hPa

Global Driving
ERA-INTERIM

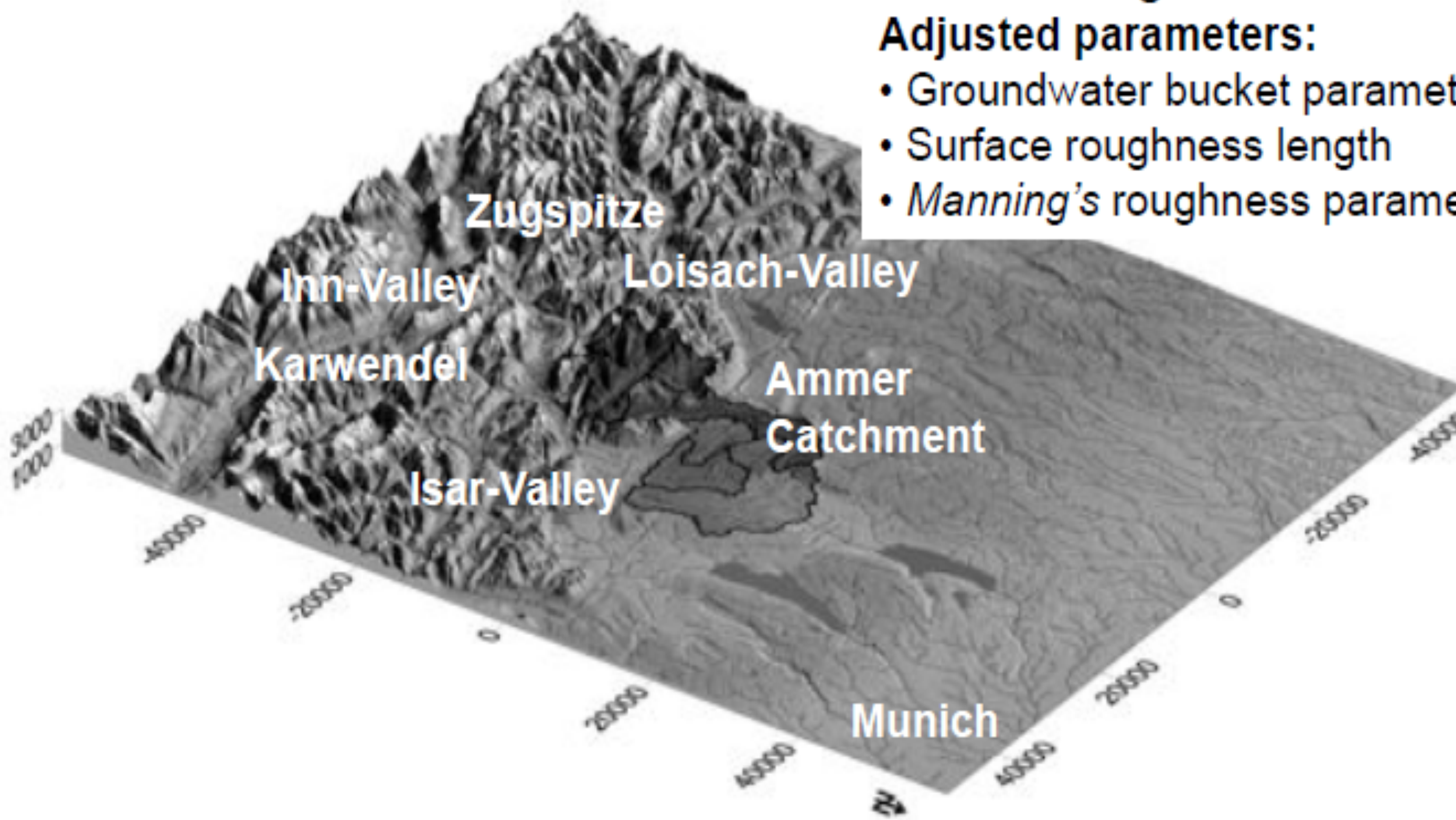
Period
Jun-Aug 2005
➔ *Century-Flooding Event*
(20.-23.8.2005)

Rummler et al., 2012

2. WRF-Hydro regional hydroclimate study for the Ammer Catchment, Bavaria, Germany

Model Elevation for D03 (dx=1km)

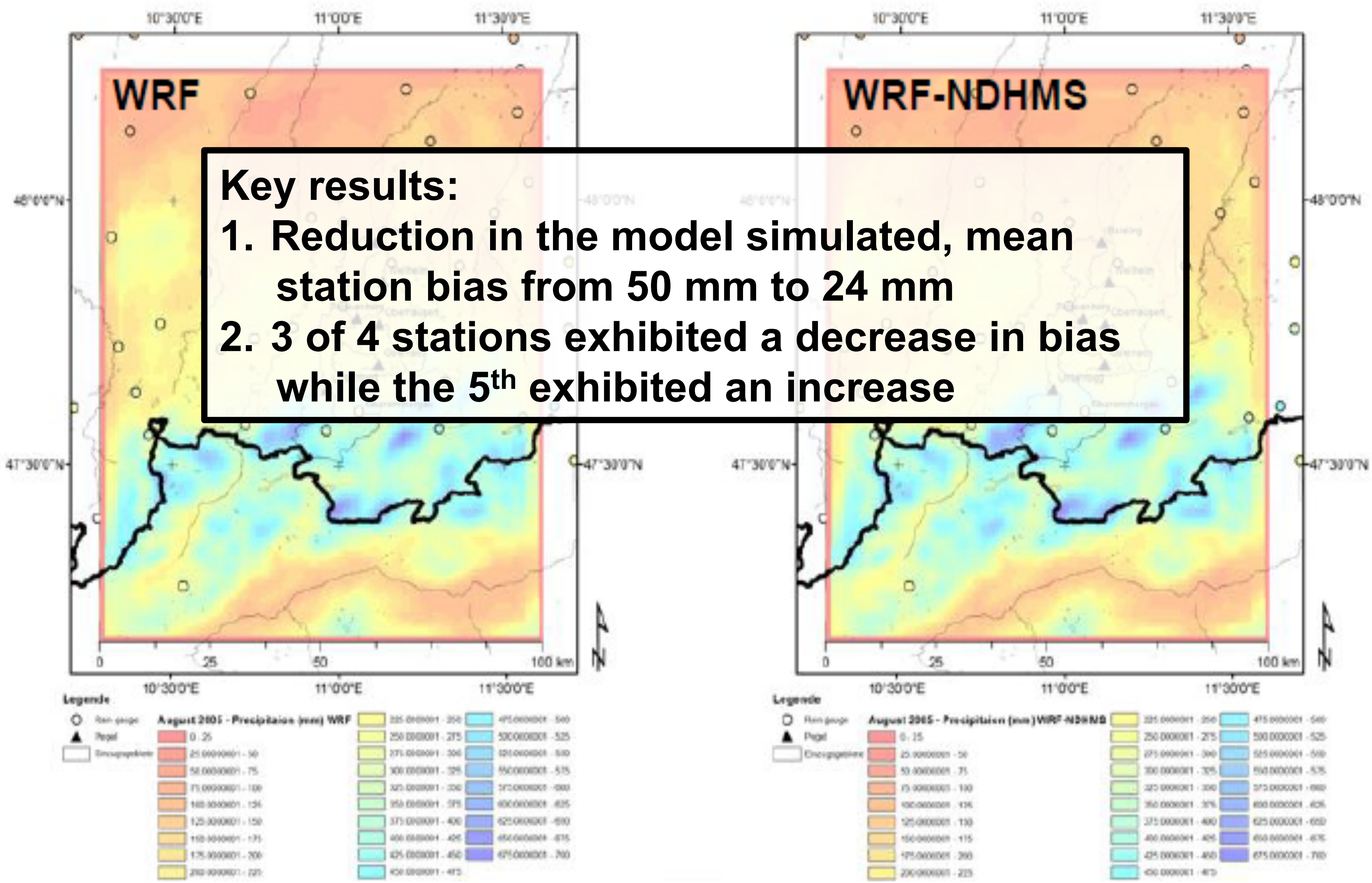
NDHMS: subgrid Δx=100m
Adjusted parameters:
- Groundwater bucket parameterization
- Surface roughness length
- *Manning's* roughness parameter



Rummler et al., 2012

2. WRF-Hydro regional hydroclimate study for the Ammer Catchment, Bavaria, Germany

Changes in the spatial distribution of terrain-driven precipitation:

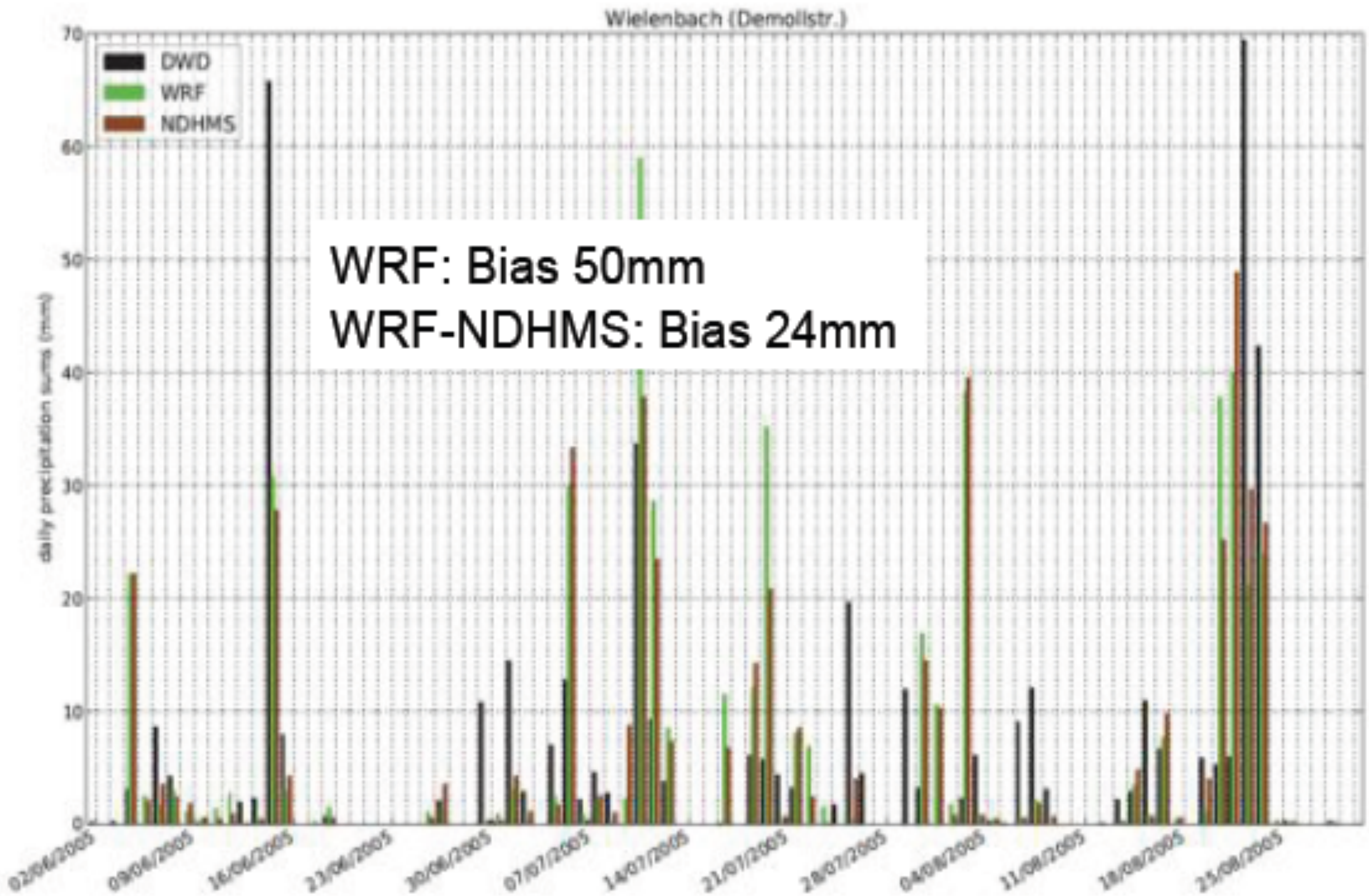


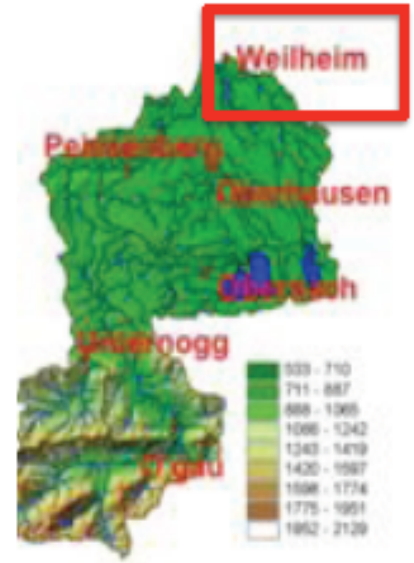
Key results:

1. **Reduction in the model simulated, mean station bias from 50 mm to 24 mm**
2. **3 of 4 stations exhibited a decrease in bias while the 5th exhibited an increase**

2. WRF-Hydro regional hydroclimate study for the Ammer Catchment, Bavaria, Germany

Precipitation [mm]





WRF-NDHMS vs. WRF:

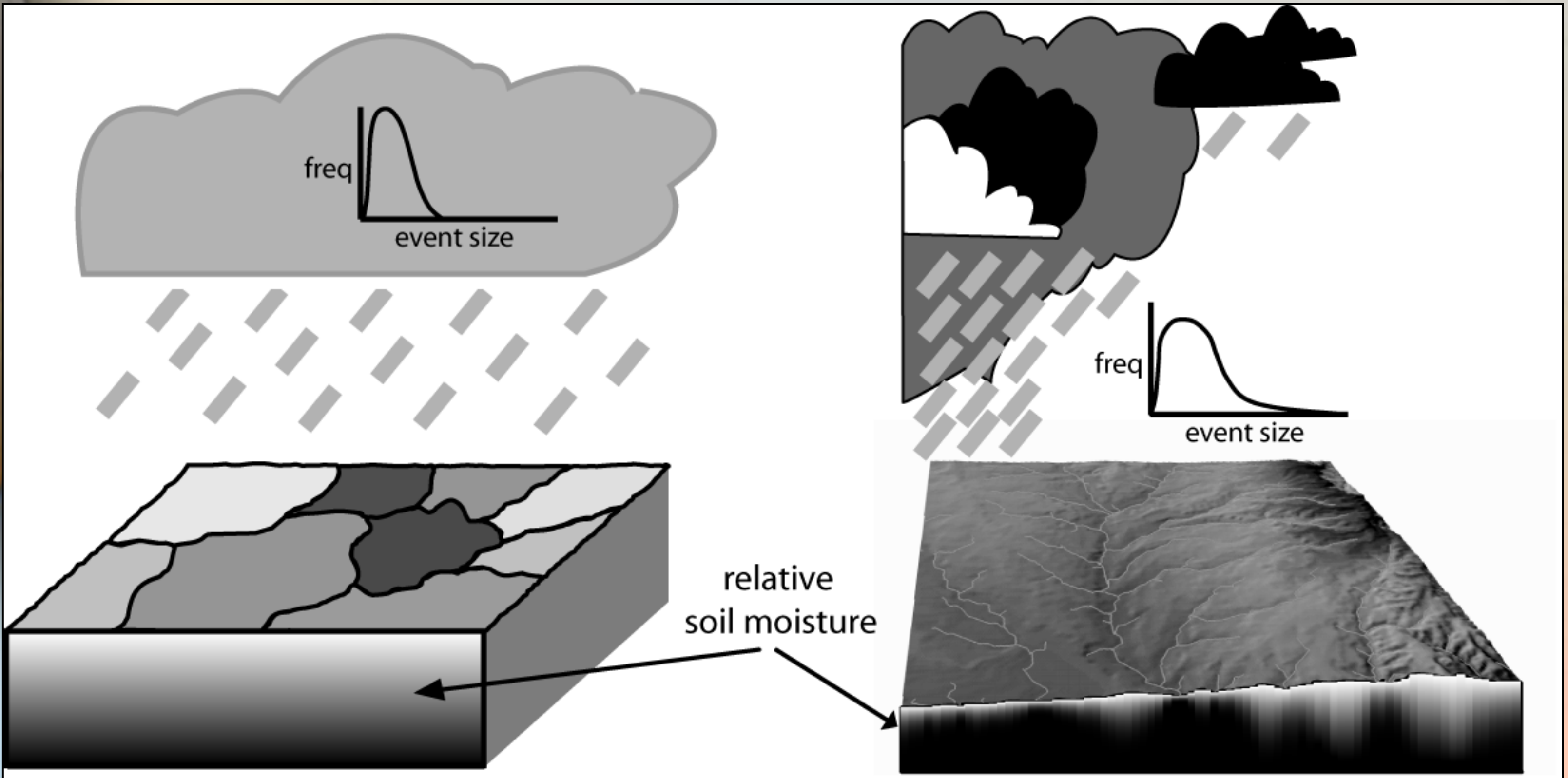
Bias decreases for stations *Wielenbach*, *Hohenpeissenberg*, & *Oberammergau*

… but increases for station *Ettal*

Rummler et al., 2012

The NCAR Distributed hydrological Modeling System (NDHMS)

- Goal: To linking multi-scale process models in a consistent Earth System Modeling framework

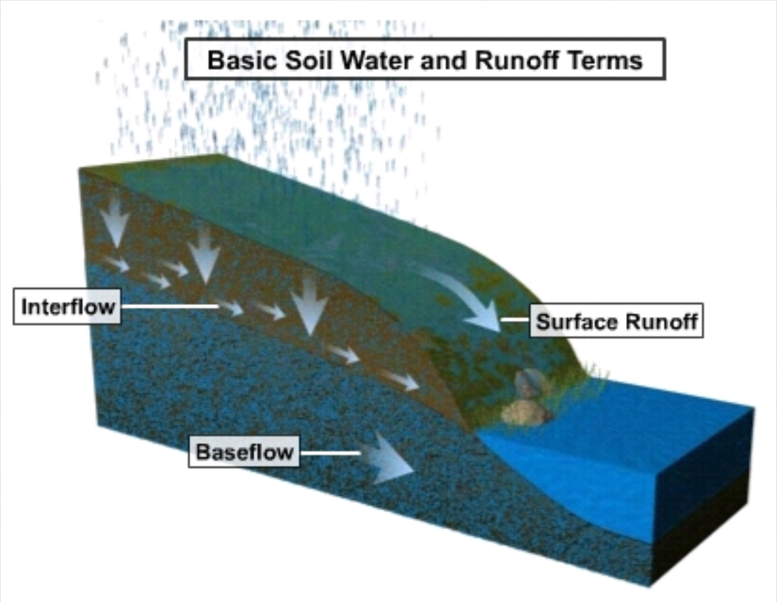


a. Existing climate models

b. Conceptualization of nature

Scale and process issues:

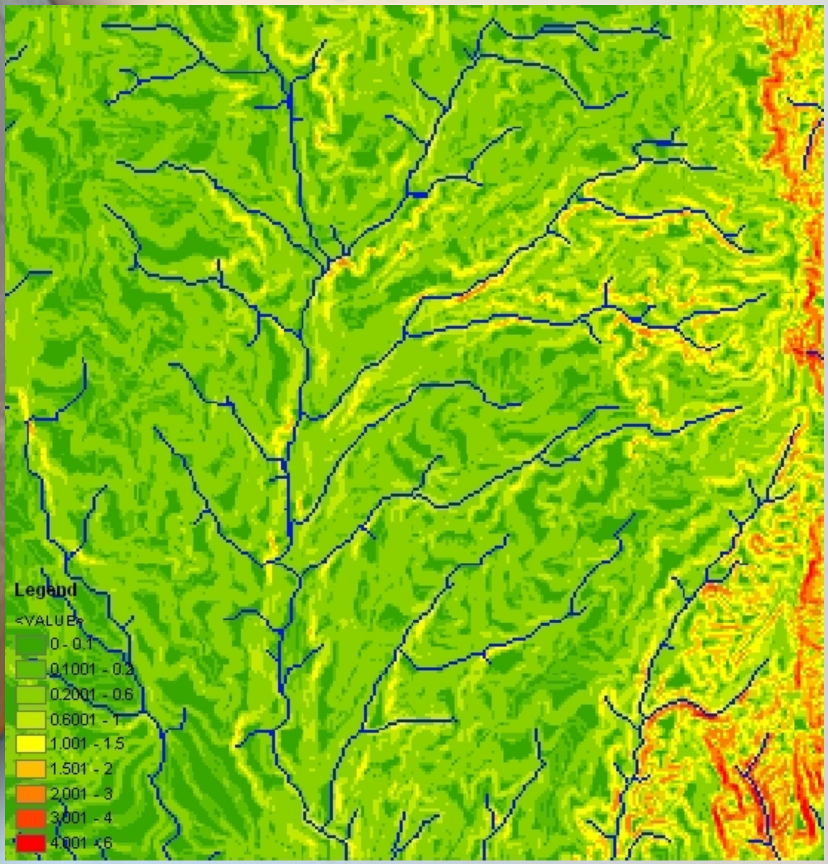
- Landscape features affecting moisture availability (scales ~1km)
  - Routing processes: the redistribution of terrestrial water across sloping terrain
  - Groundwater processes
  - Channel processes
  - Built environment/infrastructure
  - Water management



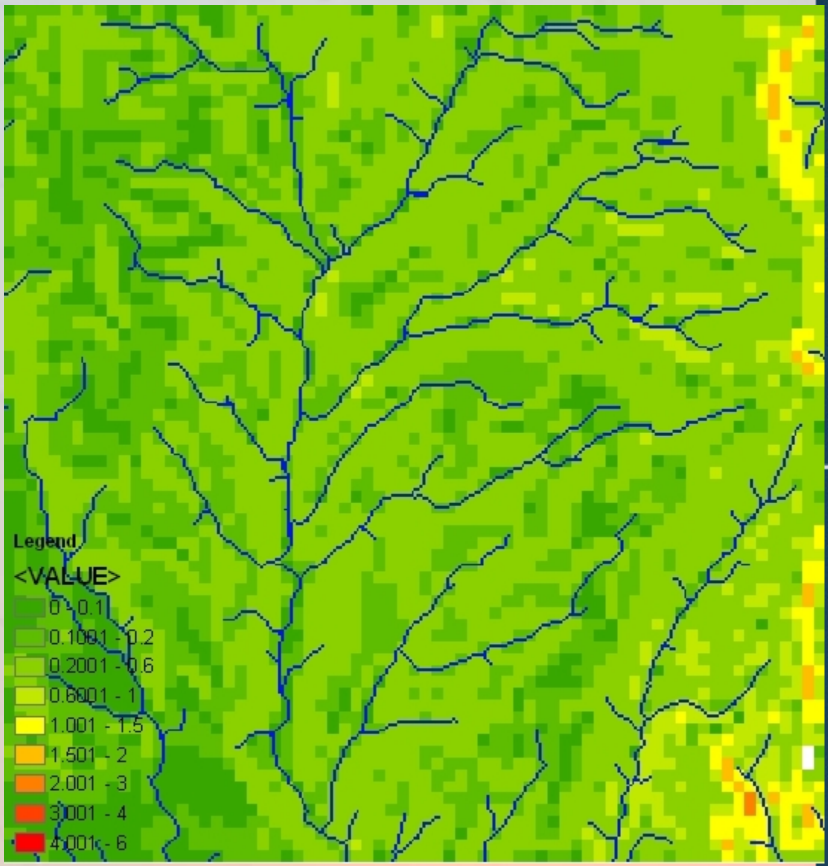
Courtesy the COMET Program

Motivation: Terrain controls on hydrologic processes:

Slope: 250 m



Slope: 1000 m



Scale dependence of Terrain Slope

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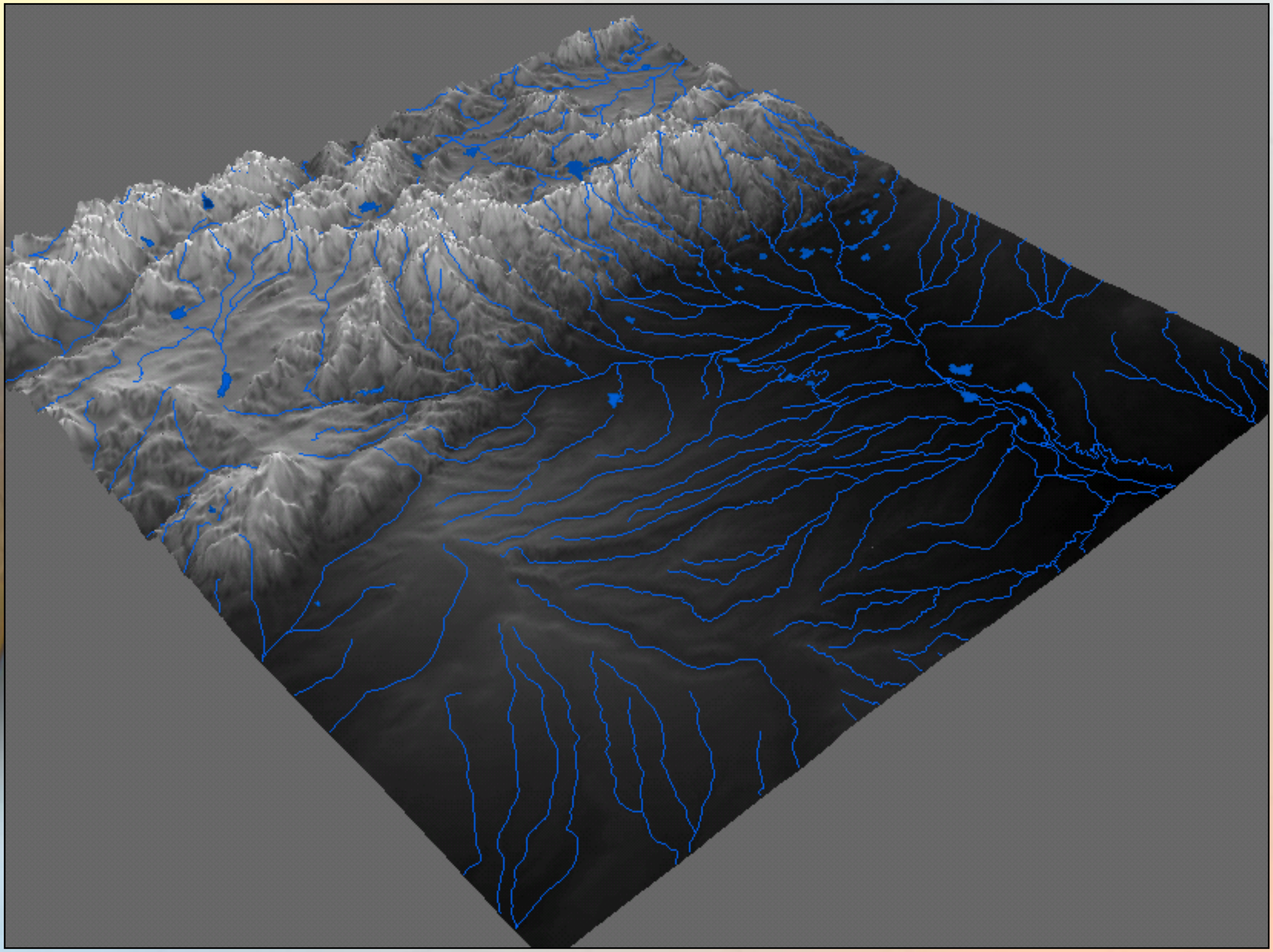

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