The coupling of meteorological and hydrological models and its applications

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Future Outlook of NWP

- Frontier Research in NWP:

  → Data Assimilation

  Ensemble Forecast

  Coupled Model

Part I: A High-Resolution Hydrometeorological Forecast System for Mountainous Watersheds

Reference:

Westrick K. J., and C. F. Mass, 2001: An evaluation of a high-resolution hydrometeorological modeling system for prediction of a cool-season flood event in a coastal mountainous watershed. J. Hydrometerology, 2, 161-180.

Westrick K. J., P. Storck, and C. F. Mass, 2002: Description and evaluation of a hydrometeorological modeling system for mountainous watershed. Wea. Forecasting, 17, 250-262.

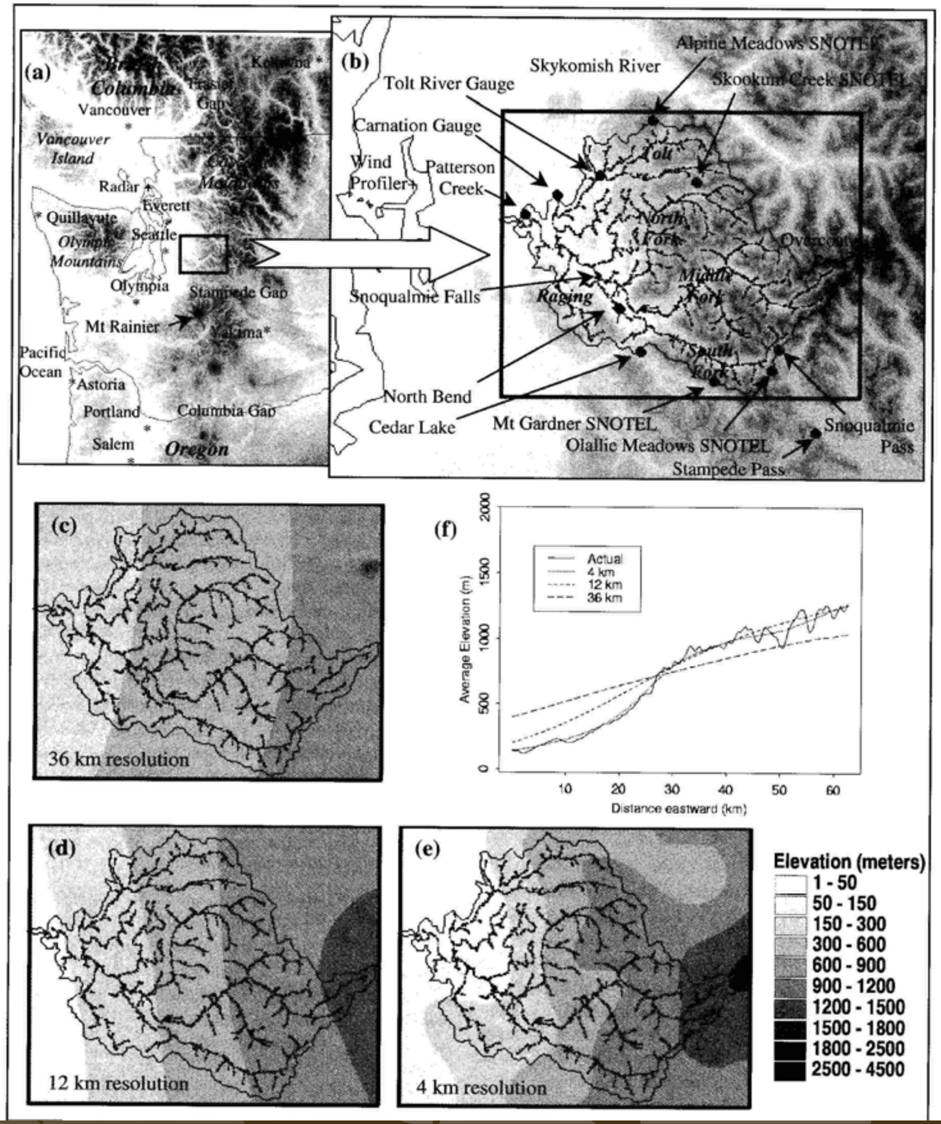
Methodology:

To forecast flooding events with mixed snow and rain over mountainous watersheds using a coupled hydrometeorological modeling system.

Motivation:

- Mesoscale meteorological model can provide a hydrological model with four-dimensional dynamically-consistent meteorological variables.
- The coupled hydrometeorological model can expand the typical coverage area of a hydrological model.
- The coupled model can increase the lead time of flooding event, if the QPF from the meteorological model is accurate enough.

Snoqualmie River watershed over western Washington



Meteorological Model: MM5

- Terrain-following sigma coordinate
- “Nonhydrostatical” mode
- 32 vertical layers with increased resolution in PBL
- NCEP Eta Model “104” grids (80km/25hpa)
- Outer grid (36 km) and two inner nested grids (12 km and 4 km)

MM5 physics options:

- Simple-ice microphysics scheme (Dudhia 1989)
- Blackadar high-resolution PBL scheme (Zhang and Anthes 1982)
- Kain-Fritsch (1993) cumulus scheme on the 36- and 12-km grids, and no cumulus scheme on the 4-km grid
- Longwave and shortwave radiation schemes (Dudhia 1989)

Initialization

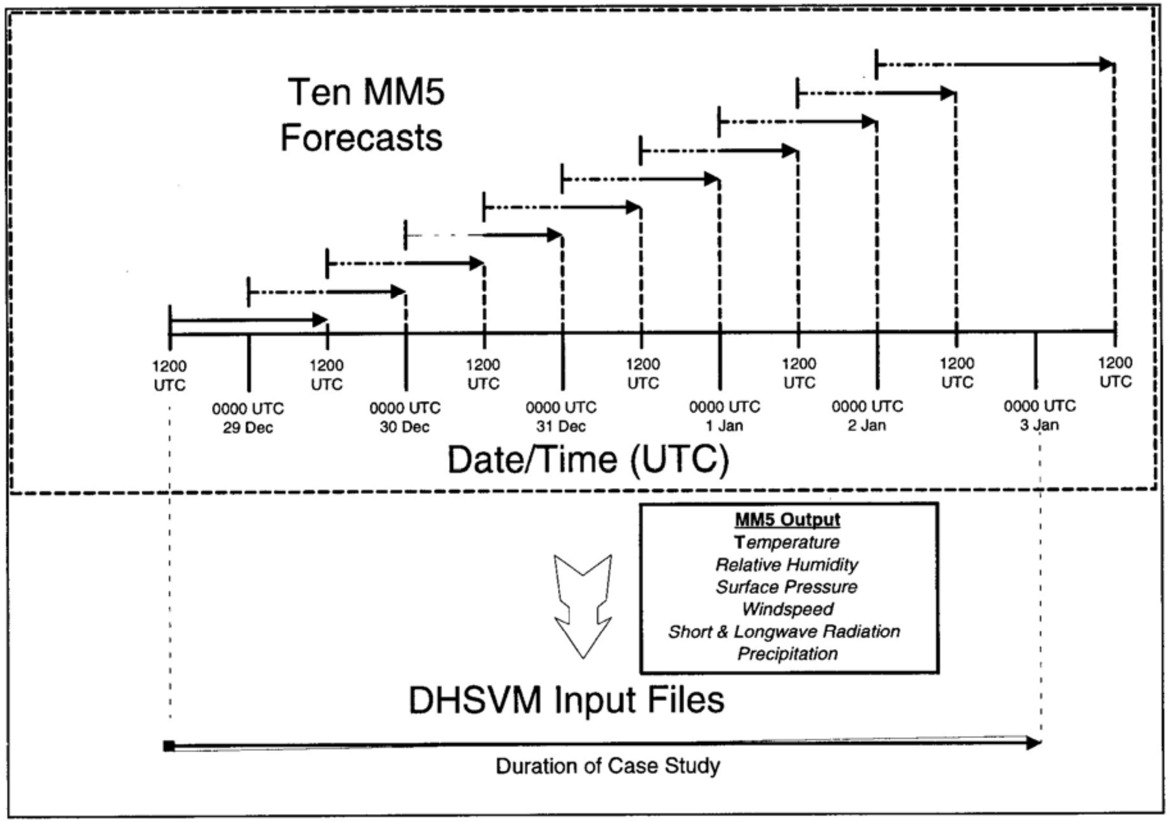


Fig. 3. Schematic describing how the MM5 simulations were used to create input fields for DHSVM. Ten MM5 simulations initialized every 12 h between 1200 UTC 28 Dec 1996 and 0000 UTC 2 Jan 1997 were used to create the DHSVM input data. To allow for the "spinup" of the MM5 precipitation fields, the 13–24-h forecasts were used (solid portion of arrows at top of schematic).

Hydrological Model：DHSVM

- Distributed Hydrology-Soil-Vegetation Model (DHSVM; Wigmosta et al. 1994)

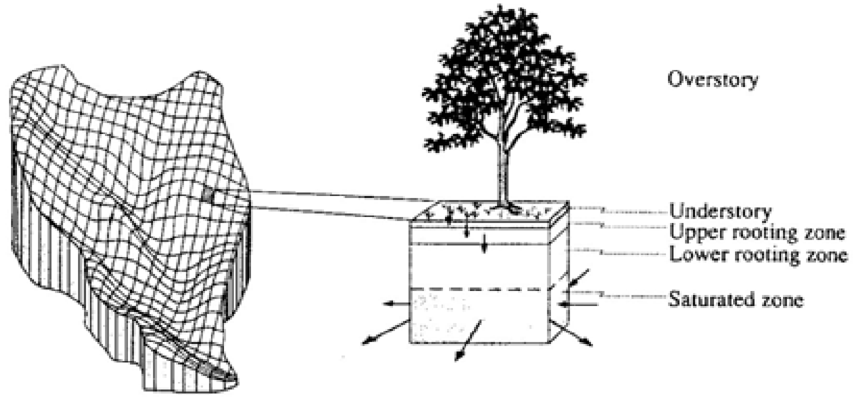


Figure 1. Model representation of a drainage basin. Digital elevation data are used to model topographic controls on incoming solar radiation, precipitation, air temperature, and downslope water movement. Linked one-dimensional moisture and energy balance equations are solved independently for each model grid cell. Grid cells are allowed to exchange saturated subsurface flow with their eight adjacent neighbors.

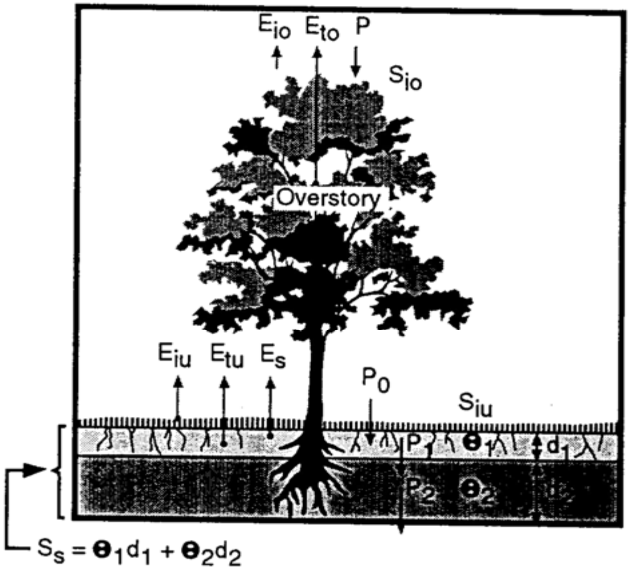


Figure 2. Simulated vegetation and rooting zone water balance for a model grid cell. Water leaving the lower rooting zone (P_2) recharges the local water table.

Coupled-Model Interface

- Meteorological variables required as inputs to the DHSVM:

→temperature, humidity, wind speed and direction, long-wave radiation, short-wave radiation, surface pressure, and precipitation

→ these variables are all interpolated to the 100-m DHSVM grid using a bi-parabolic interpolation.

→ the MM5-forecasted rainfall is interpolated to the 100-m DHSVM grid using the Cressman (1959) interpolation method.

Note: For a watershed with quick flooding response, the feedback from hydrological processes upon meteorological variables can be ignored.

Cases examined

- A complex rain-on-snow flooding event from 1200 UTC 28 Dec 1996 to 0000 UTC 3 January 1997
- The cool seasons of 1998~1999 over six watersheds in western Washington.

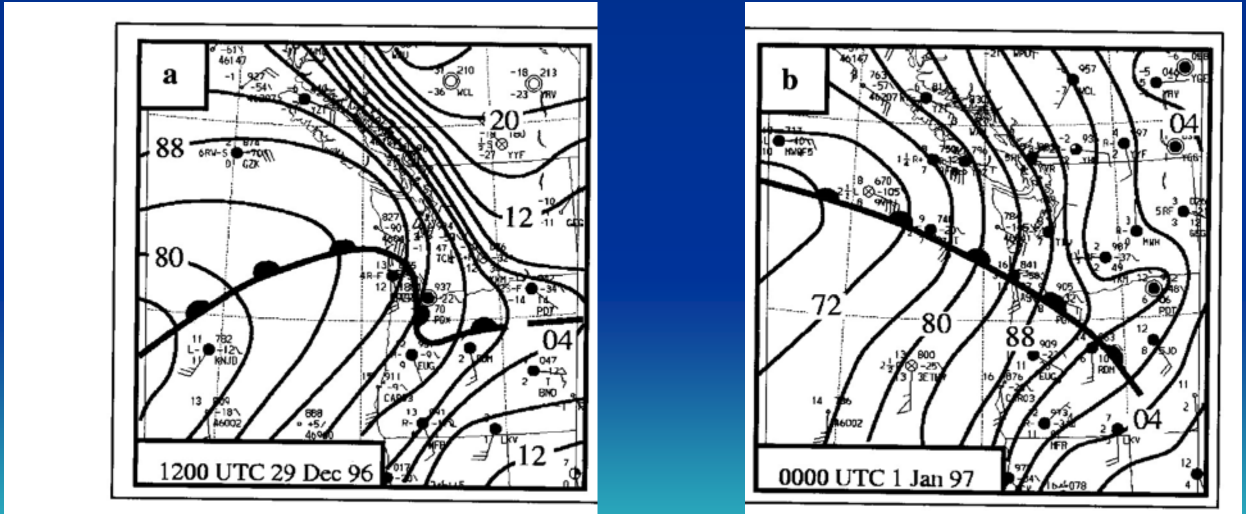


FIG. 4. Surface analysis for (a) 1200 UTC 2

9 Dec 1996 and (b) 0000 UTC 1 Jan 1997.

MM5 Model assessment

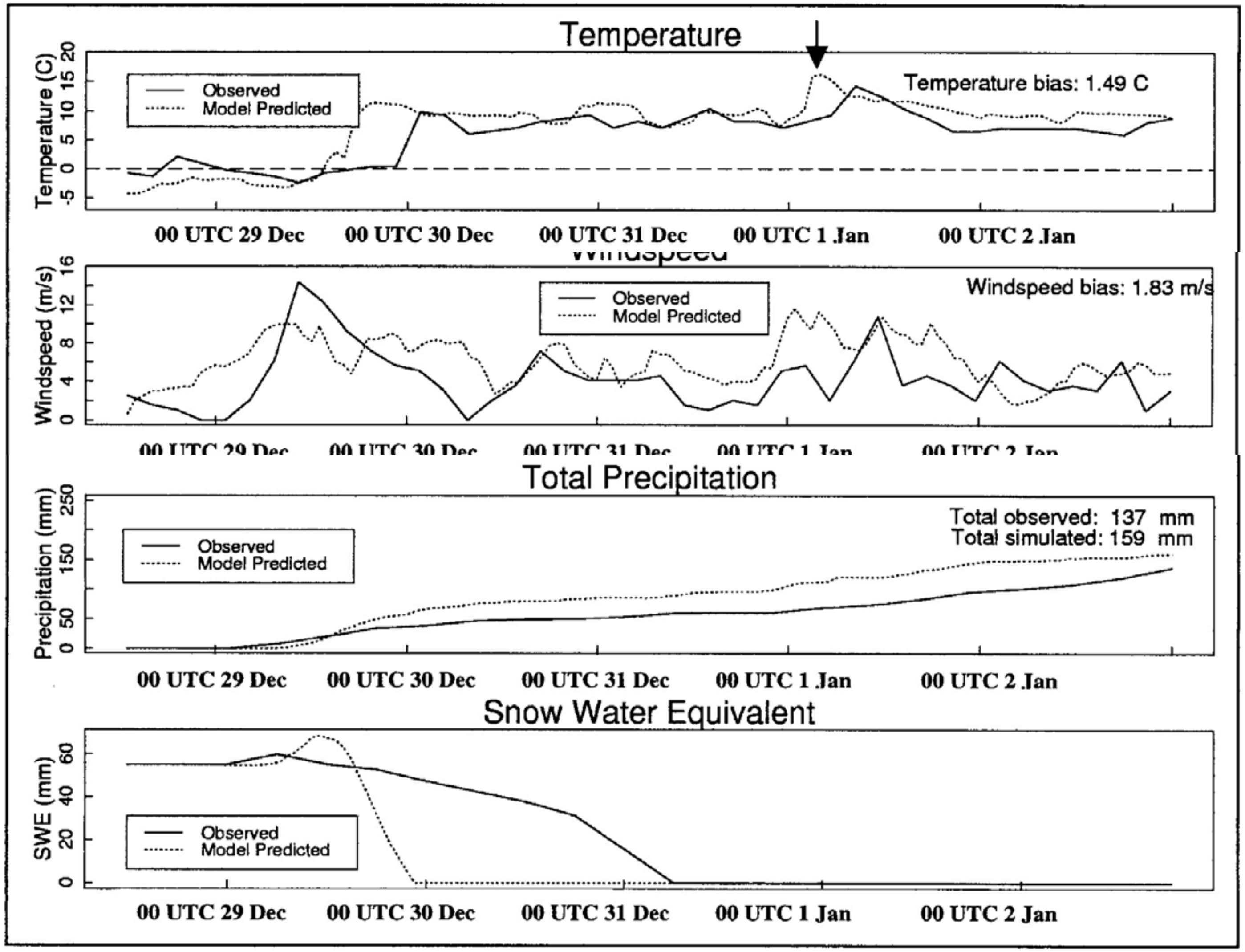
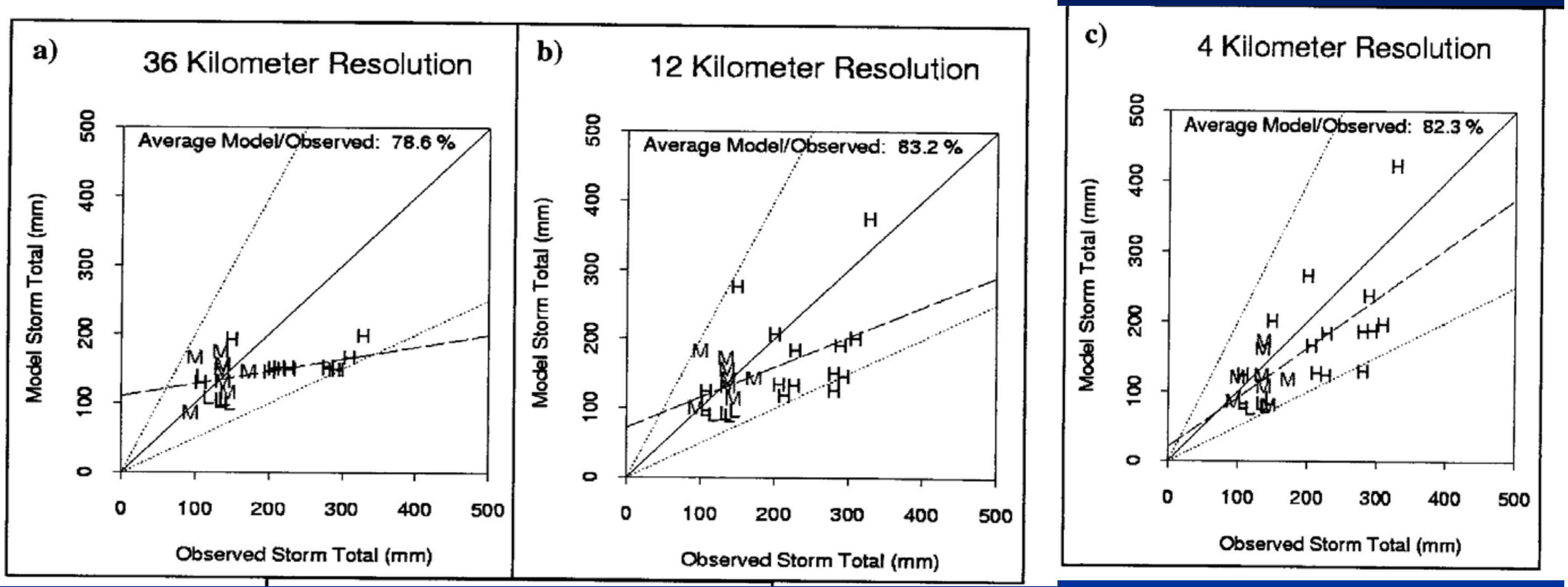


FIG. 7. Time series of temperature, wind speed, precipitation, and SWE for North Bend, WA. SWEs were based on snow-depth observations and assumed snow densities. The arrow denotes the model-simulated warm-frontal passage on 1 Jan 1997.

MM5 always under-predicts the rainfall !



- 36-km MM5,12-km MM5, and 4-km MM5 can simulate 79%, 83%, and 82% of observed rainfall.

Rain gauge-enhanced precipitation

- The total rainfall can reach to 248 mm, 21% more than the original forecast by 4-km MM5.

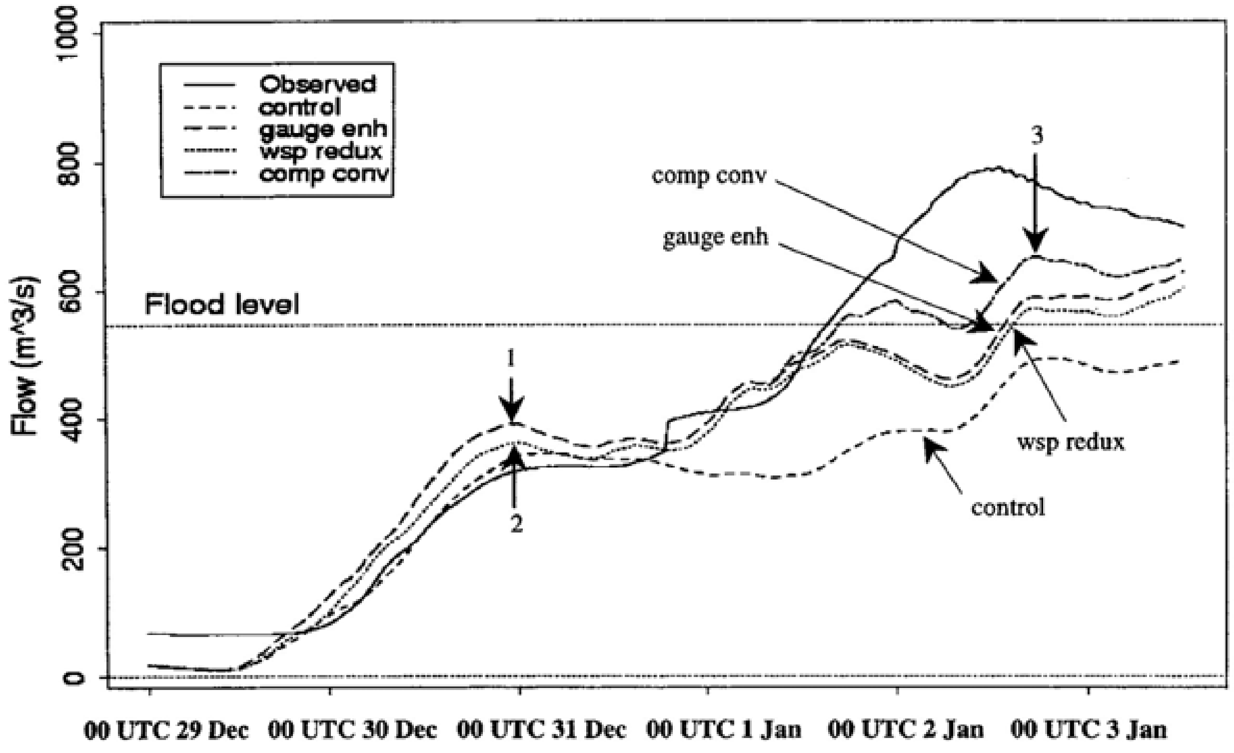


FIG. 13. Observed and simulated river flows for the control, rain gauge–corrected (gauge enh), rain gauge–corrected/30% wind speed reduction (wsp redux), and the rain gauge–corrected/30% wind speed reduction/convective precipitation (comp conv) sensitivity simulations.

Wind speed reduction

- First reduce the low-level wind speed by 30% to remove MM5's wind bias and then rerun the DHSVM

→ It also improves DHSVM's streamflow forecast

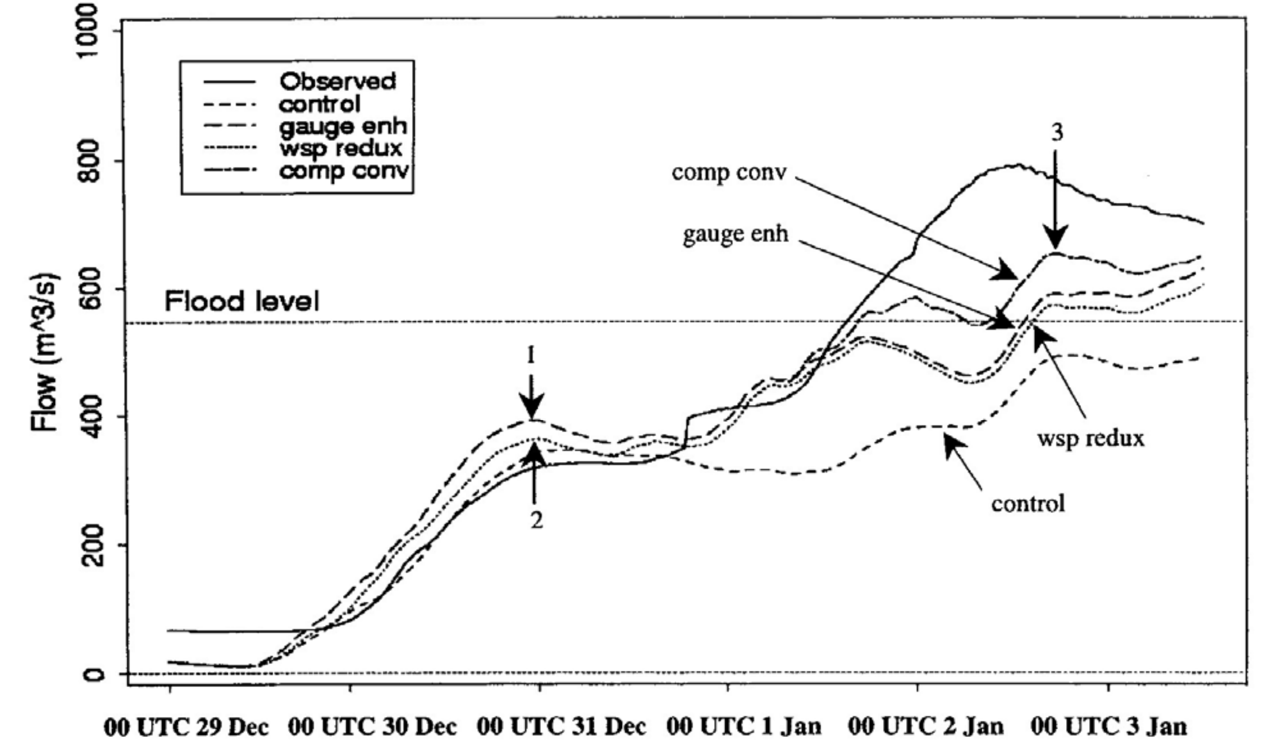


FIG. 13. Observed and simulated river flows for the control, rain gauge–corrected (gauge enh), rain gauge–corrected/30% wind speed reduction (wsp redux), and the rain gauge–corrected/30% wind speed reduction/convective precipitation (comp conv) sensitivity simulations.

Convective precipitation modification

- Assimilating a convective rainfall event based on the WSR-88D radar data

→ It also improves DHSVM's streamflow forecast

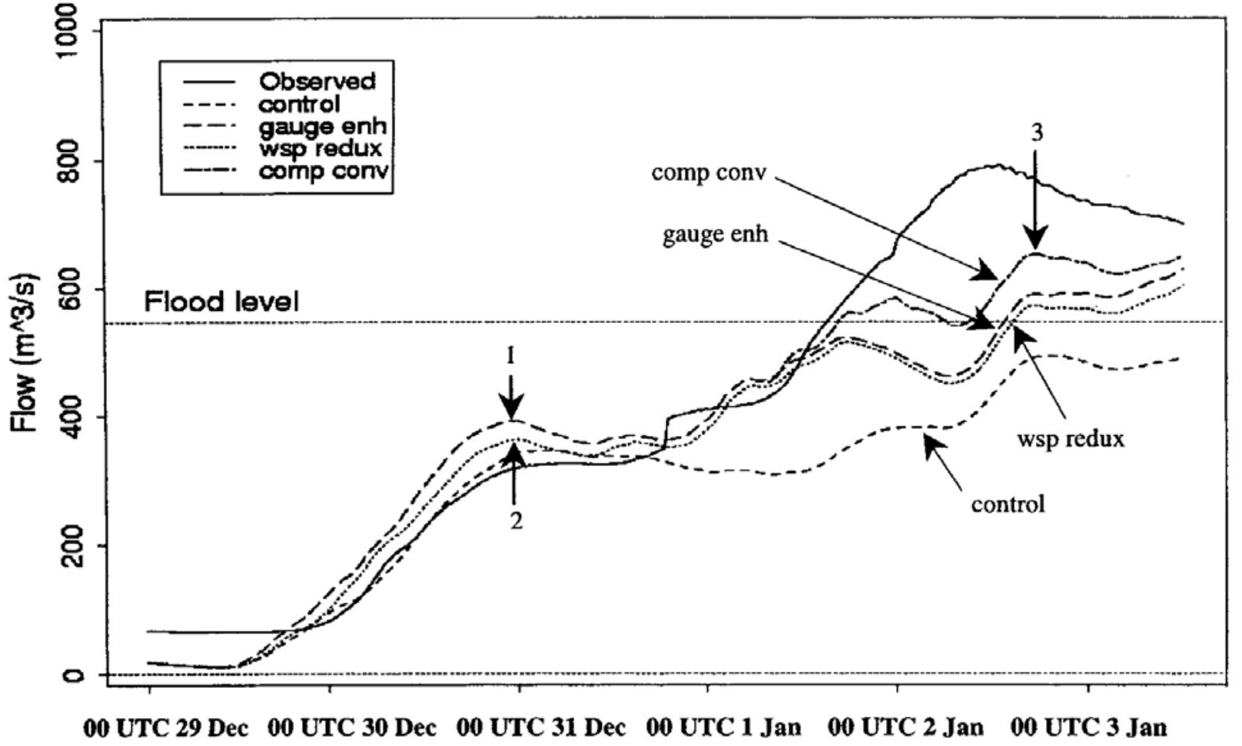


FIG. 13. Observed and simulated river flows for the control, rain gauge–corrected (gauge enh), rain gauge–corrected/30% wind speed reduction (wsp redux), and the rain gauge–corrected/30% wind speed reduction/convective precipitation (comp conv) sensitivity simulations.

Summary

- For the rain-on-snow flooding event, the coupled model system can simulate 93% of total stream flow, and 82% of extreme runoff, with 4-h timing error.
- The MM5 can simulate the stratiform precipitation reasonable well, but has less accuracy on the convective rainfall. It may be because 36-km and 12-km MM5 do not have enough resolution to represent the convective rainfall over the rugged Cascade Range.
- The MM5 tends to over-forecast the low-level wind speed over regions of complex terrain.

Summary

- With proper model resolution to represent the topographic effect and microphysical processes, the MM5 can simulate the rain-on-snow flooding event with reasonably-well accuracy.
- The coupled system can improve the flooding forecast by including the rain gauge observation and radar-derived precipitation features.
- A timely flood prediction can be done by linking the high-resolution MM5 with the DHSVM hydrological model.

Part II: River Runoff Simulations for Typhoon Invading Taiwan

Reference:

Li, M.-H., M.-J. Yang, R. Soong, and H.-L. Huang, 2005: Simulating typhoon floods with gauge data and mesoscale modeled rainfall in a mountainous watershed. *J. Hydrometeor.*, **6**, 306–323.

Objectives

- To investigate the applicability of distributed basin-scale runoff modeling, driven by rainfall data from either ground-based observations or MM5 simulations, in response to typhoons invading Taiwan.

Approaches

- Domain: upstream basin of Shihmen Reservoir
- Models:
  - Hydrological model: FLO-2D (O'Brien et al., 1998)
  - Meteorological model: MM5 (Grell et al., 1994)
- Events:
  - Calibration: Typhoon Herb (1996)
    - Property damages ≈ US$ 1 billion
  - Validation: Typhoon Zeb (1998)
    - Property damages ≈ US$ 250 millions

    Typhoon Nari (2001)
    - Property damages > US$ 1 billion

Input Data

- Rainfall
  - Rain gauge observation
  - MM5 simulated rainfall
  - MM5 rainfall assimulated with radar data
- Stream discharge
- Digital terrain model (200 m x 200 m)
- Digital landuse map
- Digital soil map

The continuity and depth-averaged momentum equations in the FLO-2D runoff model are:

$$\frac{\partial h}{\partial t}+\frac{\partial hV_x}{\partial x}+\frac{\partial hV_y}{\partial y}=I_e$$

$$\frac{\partial V_x}{\partial t}=-V_x\frac{\partial V_x}{\partial x}-V_y\frac{\partial V_x}{\partial y}-g\frac{\partial h}{\partial x}+g\left(S_{ox}-S_{fx}\right)$$

$$\frac{\partial V_y}{\partial t}=-V_x\frac{\partial V_y}{\partial x}-V_y\frac{\partial V_y}{\partial y}-g\frac{\partial h}{\partial y}+g\left(S_{oy}-S_{fy}\right)$$

where h = river depth

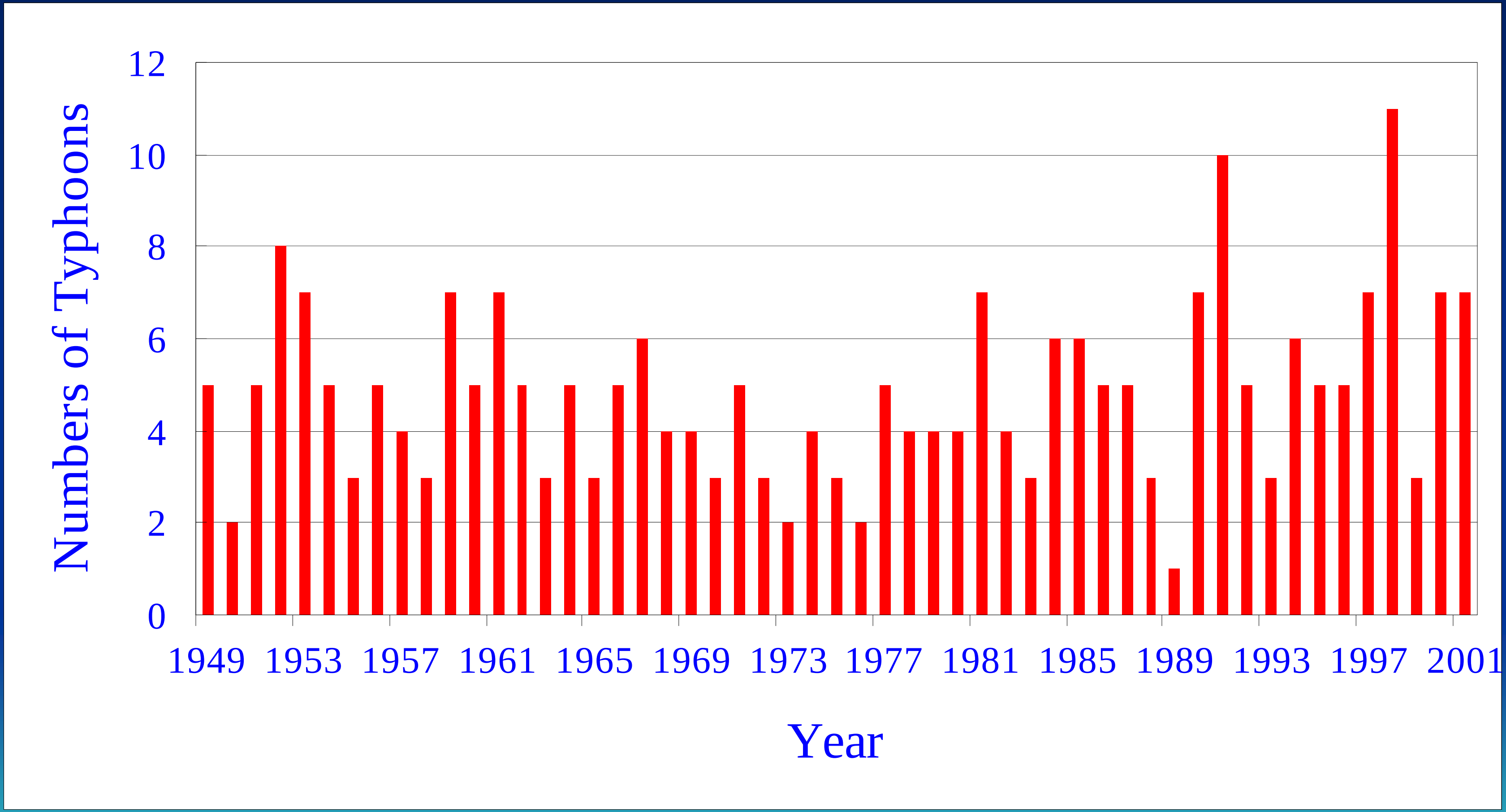
I_e= rainfall (Ps) excess over infiltration,

V_x, V_y = the depth-averaged velocity in x- and y-dir.,

S_{ox}, S_{oy} = the bed-slope components in x- and y-dir.,

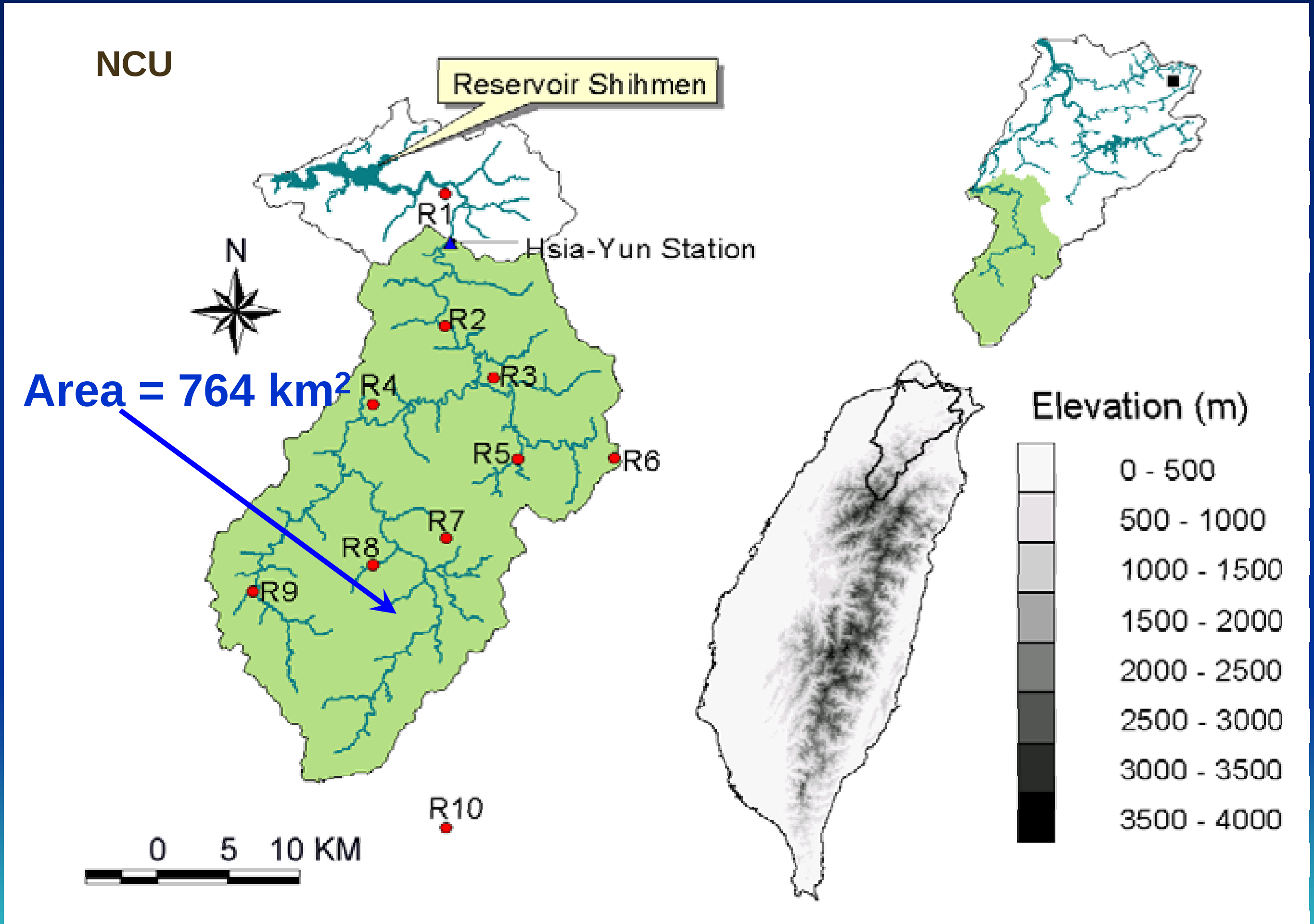
S_{fx}, S_{fy} = the friction-slope components in x- and y-dir.

Numbers of typhoons invading Taiwan from 1949 to 2001

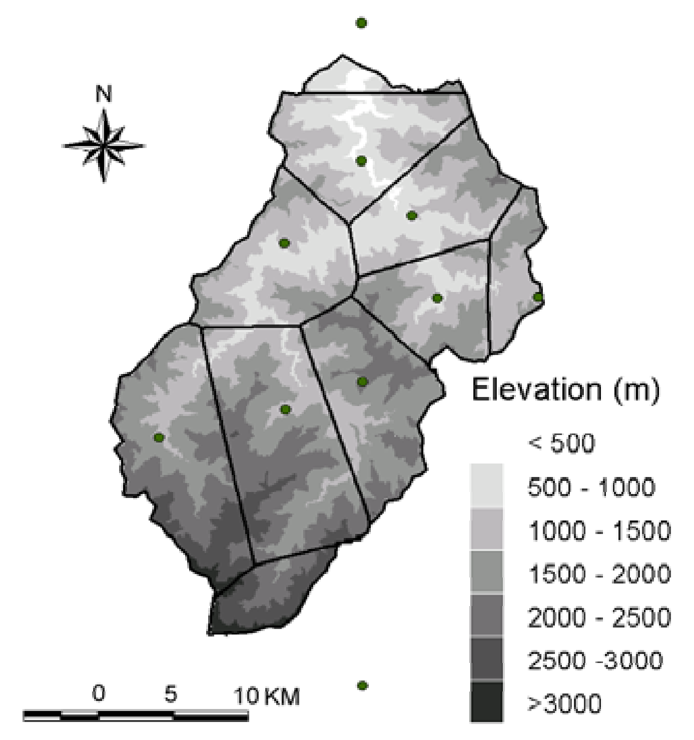


(Source: CWB)

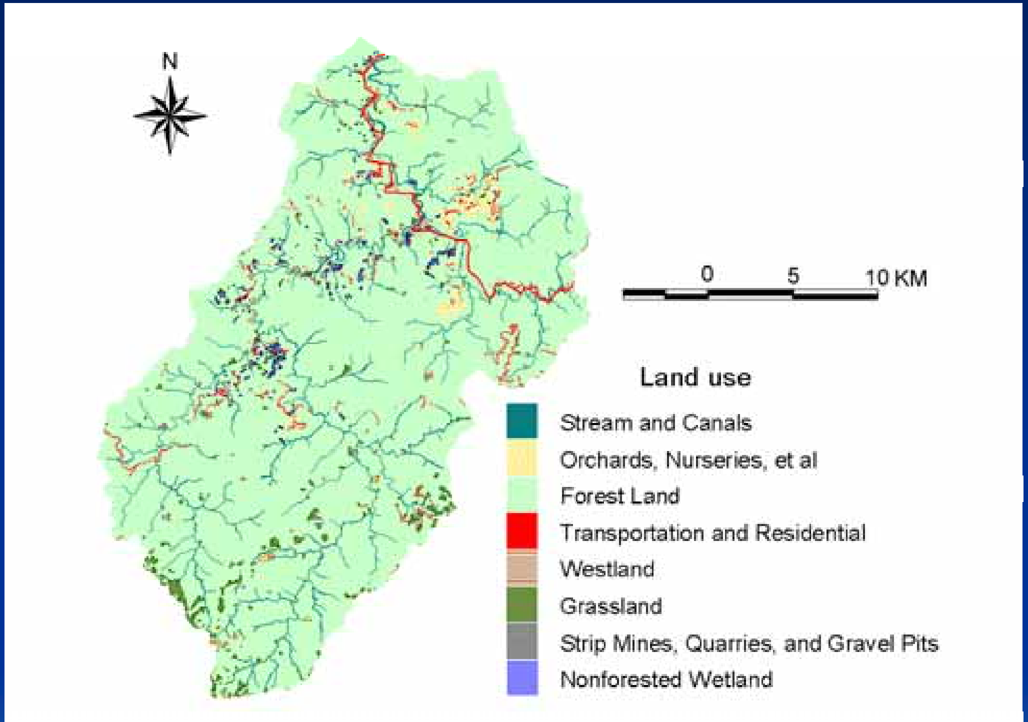
Simulation domain of Reservoir Shihmen



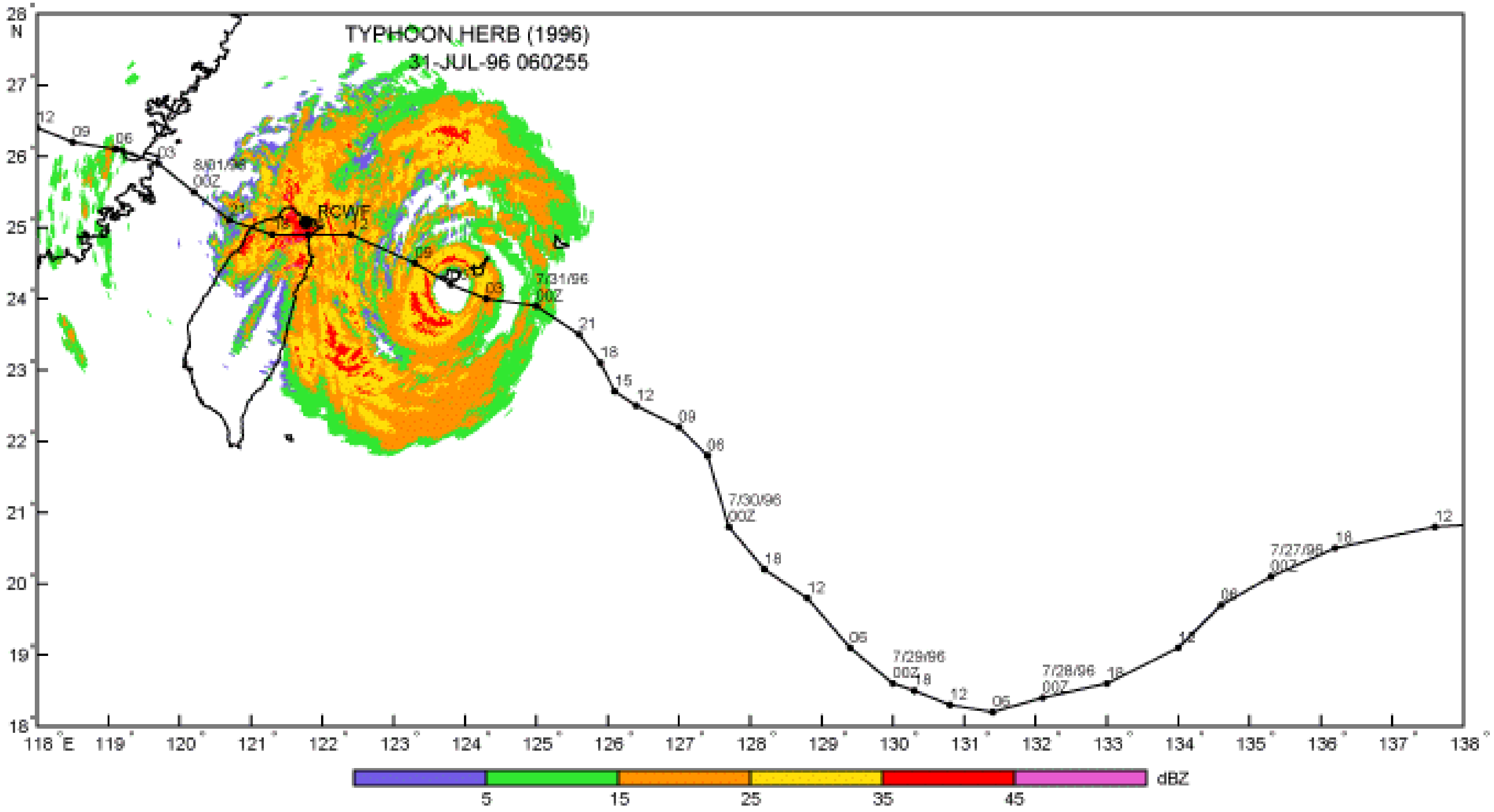
Terrain Height (DTM)



Landuse map


N
0
5
10 KM
Land use
Stream and Canals
Orchards, Nurseries, et al
Forest Land
Transportation and Residential
Westland
Grassland
Strip Mines, Quarries, and Gravel Pits
Nonforested Wetland

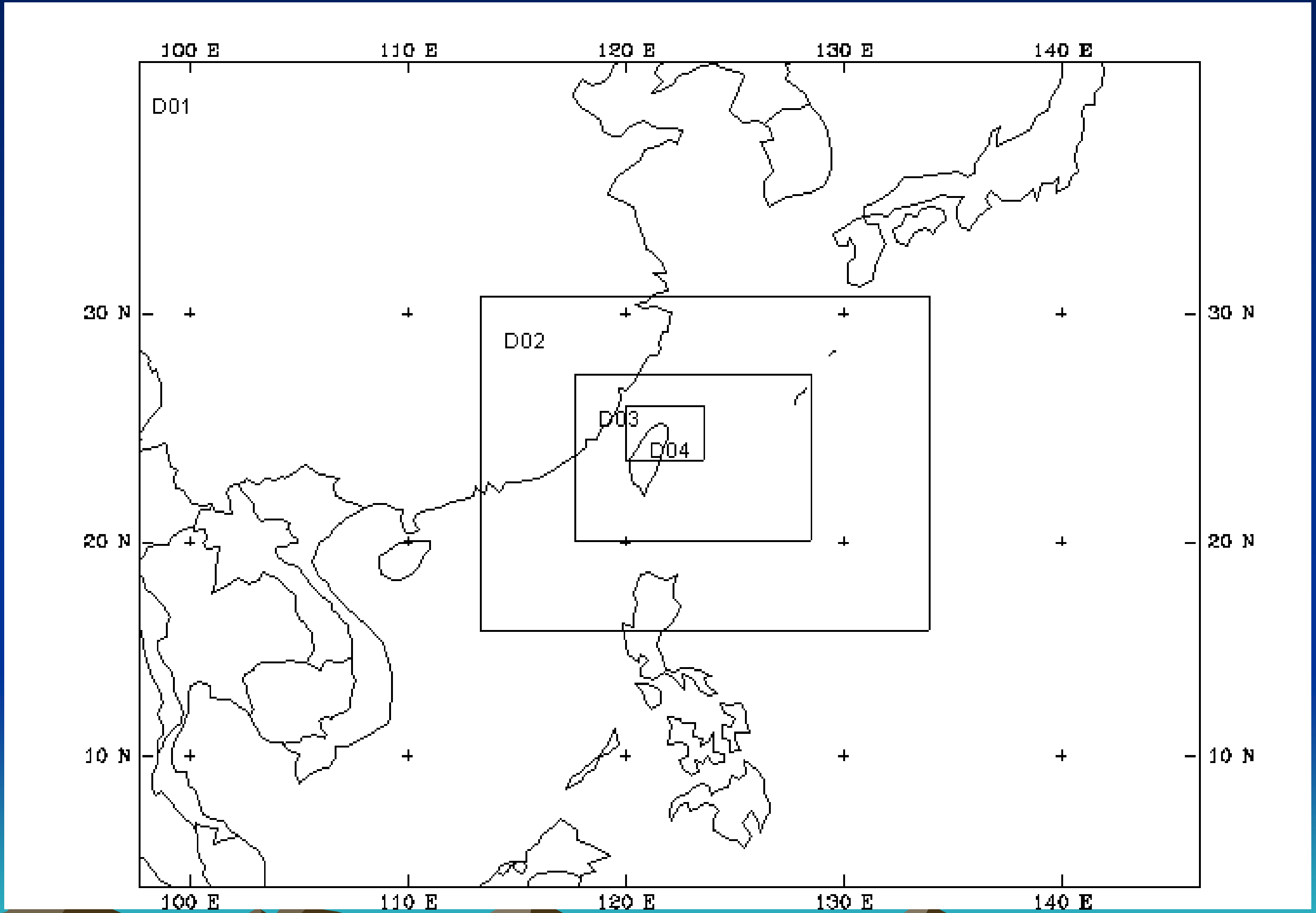
Track of Typhoon Herb (1996)



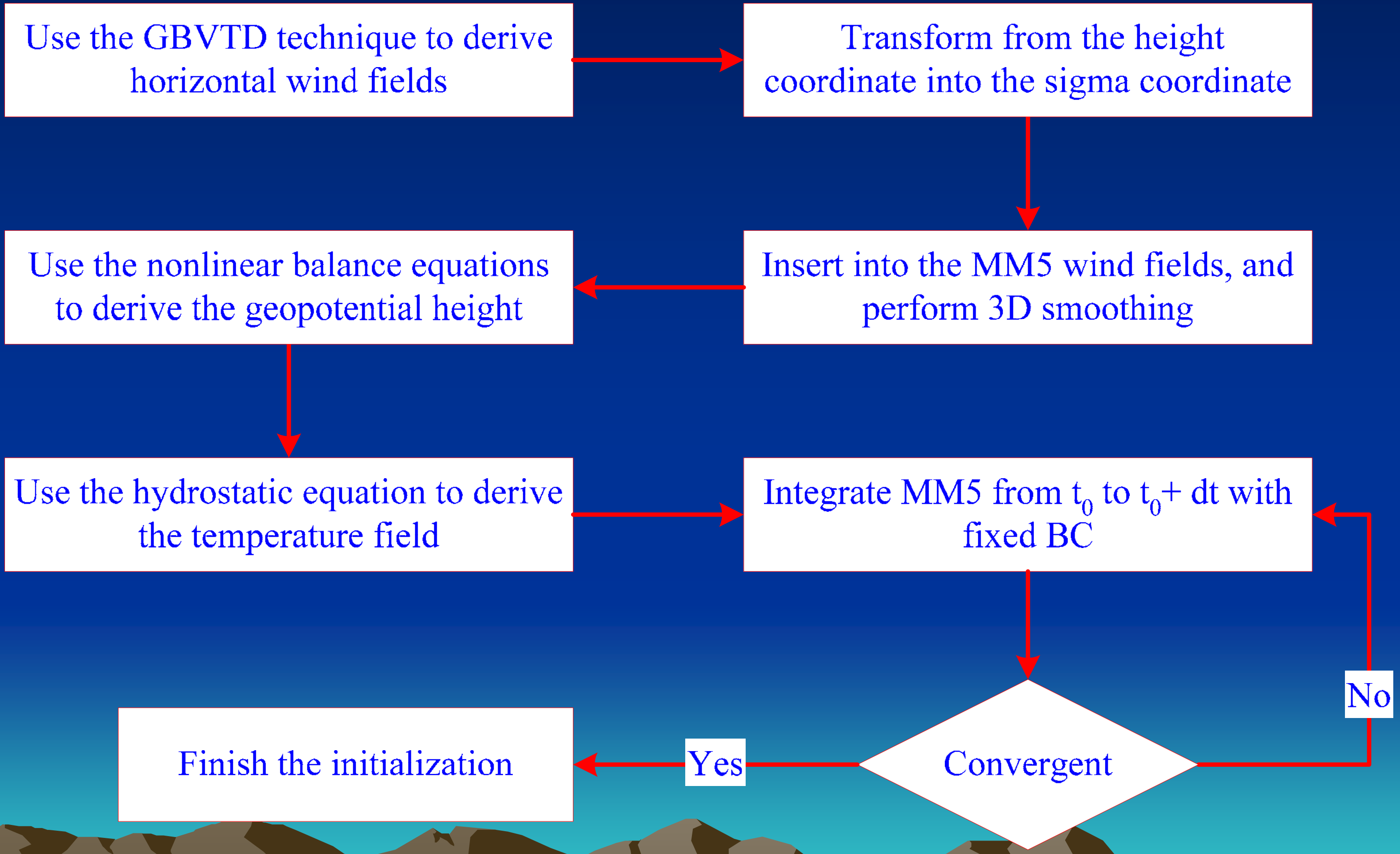
From: Wen-Chau Lee @NCAR

MM5 Domains for Typhoon Herb

D1: 60 km
D2: 20 km
D3: 6.67 km
D4: 2.22 km



Assimulating radar-derived typhoon circulation into MM5



Use the GBVTD technique to derive horizontal wind fields

Transform from the height coordinate into the sigma coordinate

Insert into the MM5 wind fields, and perform 3D smoothing

Use the nonlinear balance equations to derive the geopotential height

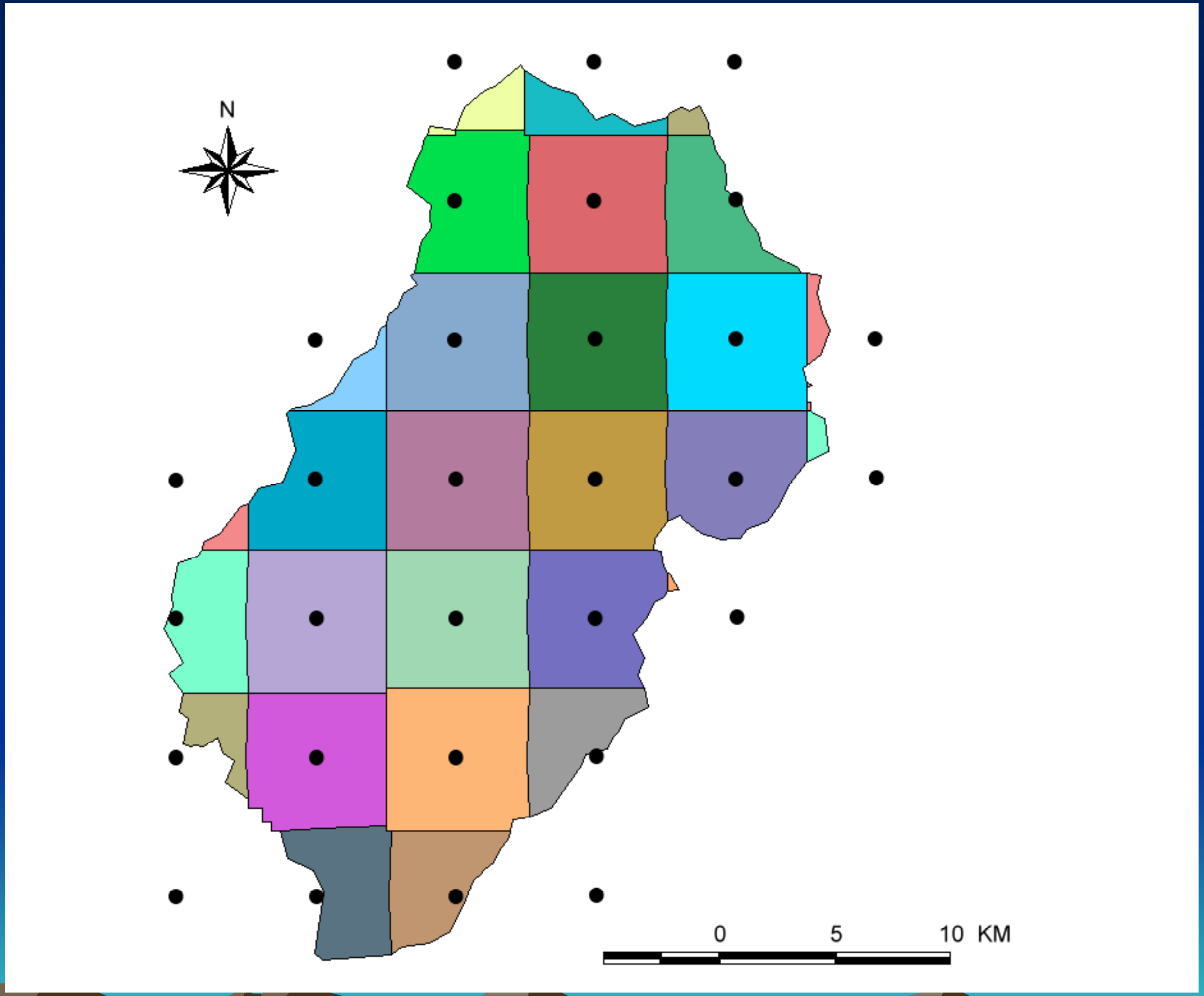
Use the hydrostatic equation to derive the temperature field

Integrate MM5 from t_0 to t_0+ dt with fixed BC

Convergent

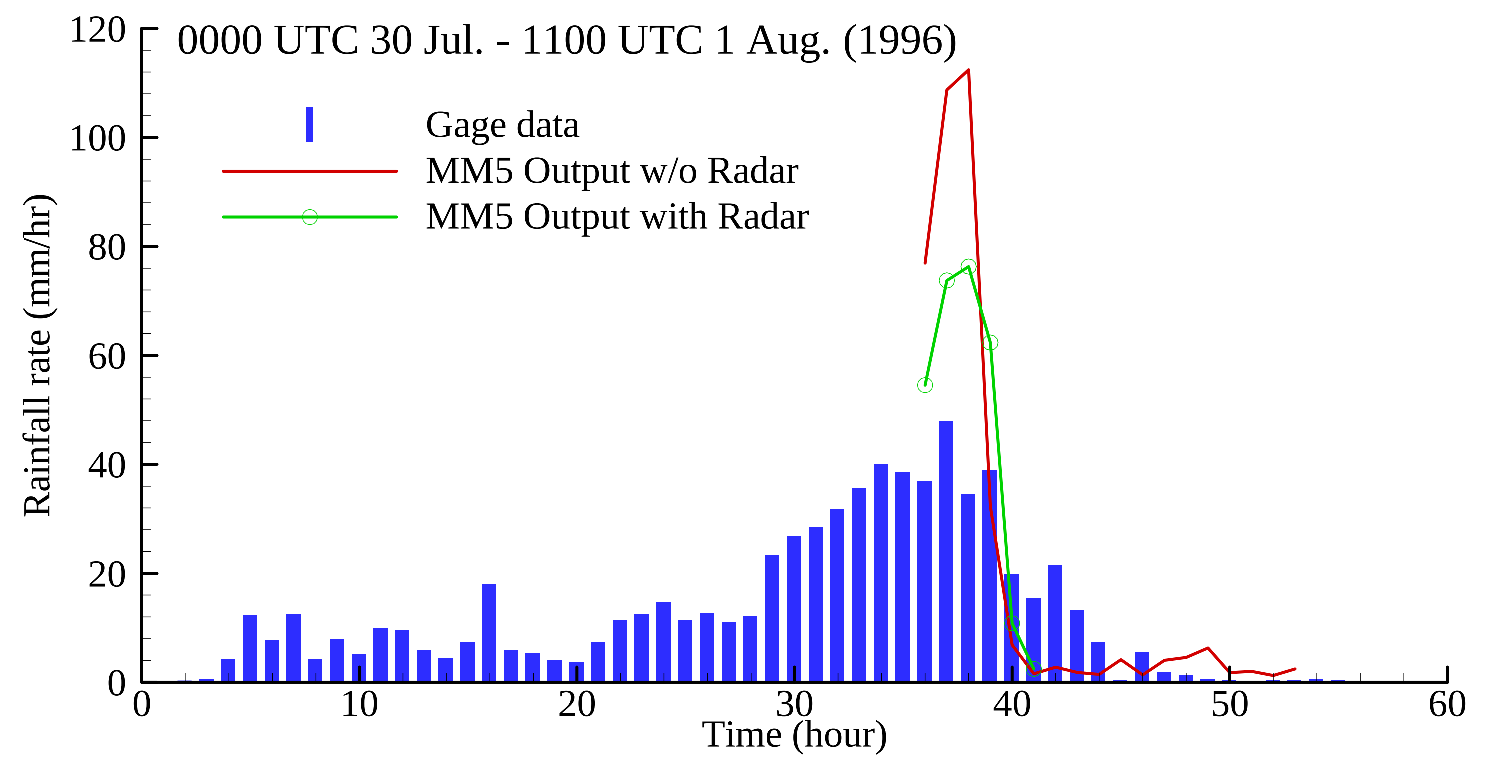
Finish the initialization

Thiessen Polygons for MM5 grids

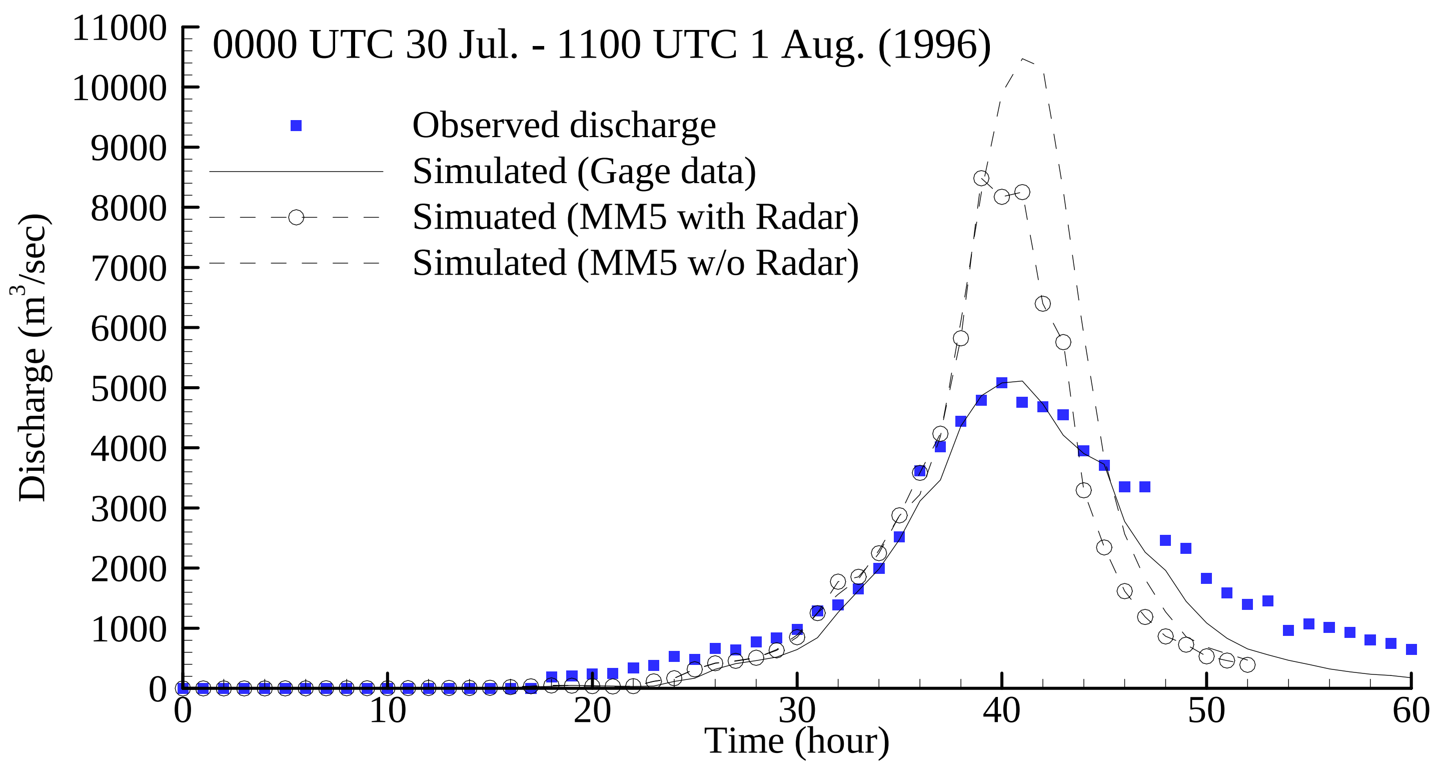


*6.67-km MM5 grids in black dots

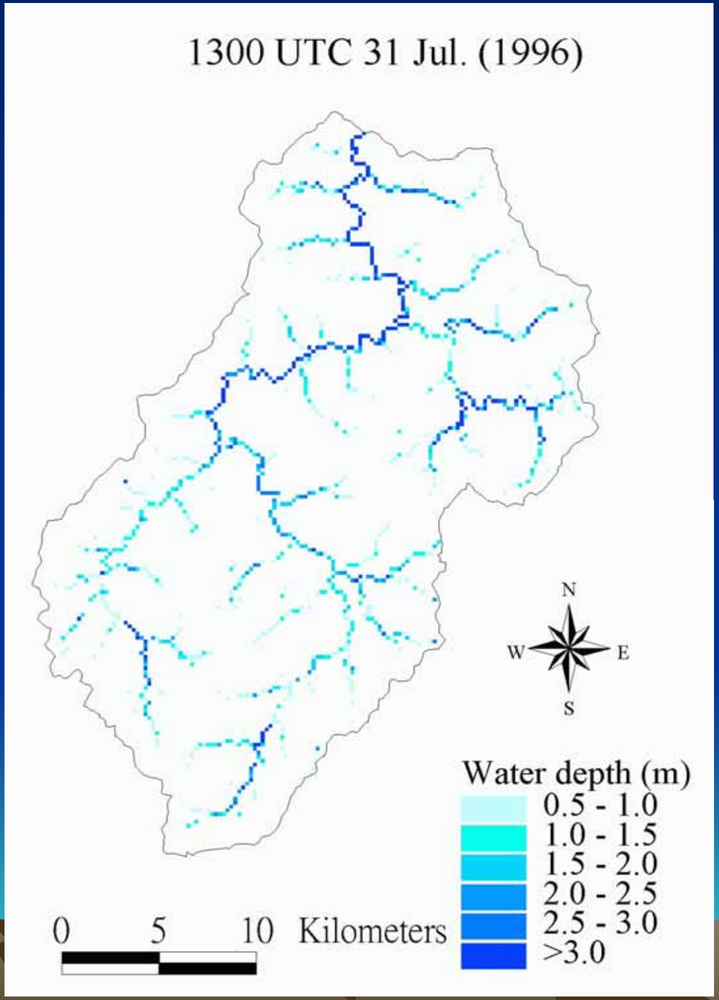
Basin-averaged rainfall for Typhoon Herb (1996)

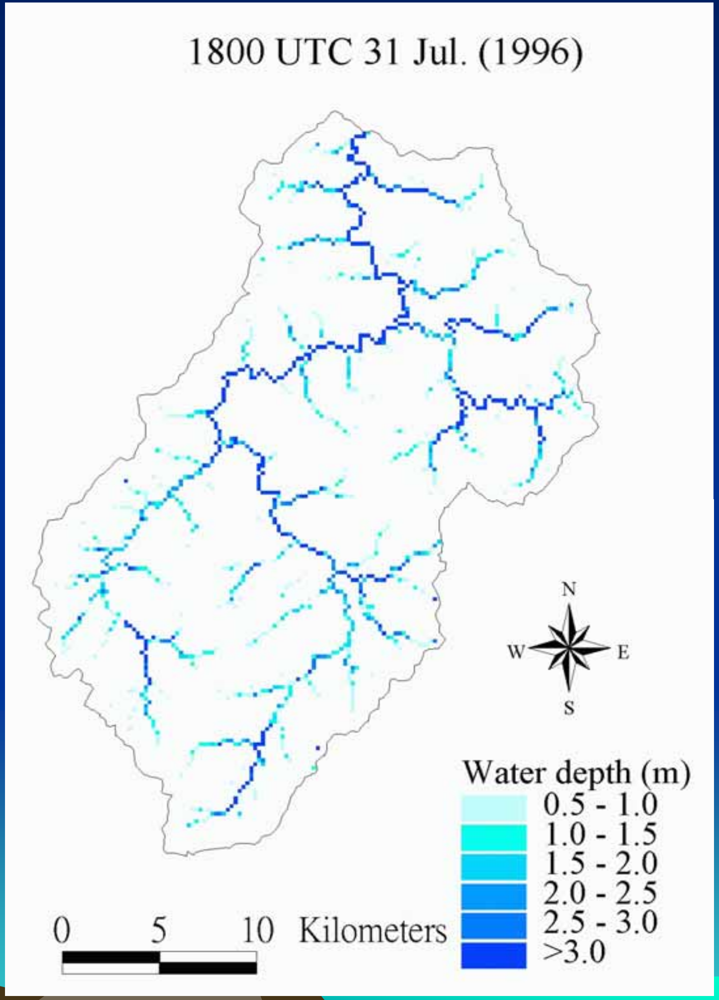


Simulated and Observed Hydrographs for Typhoon Herb (1996)

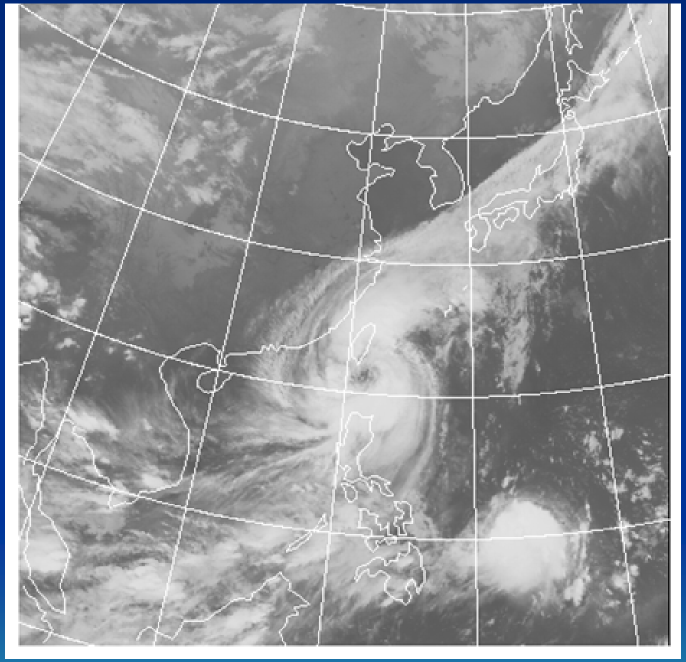


Simulated flood water depth for Typhoon Herb (1996)



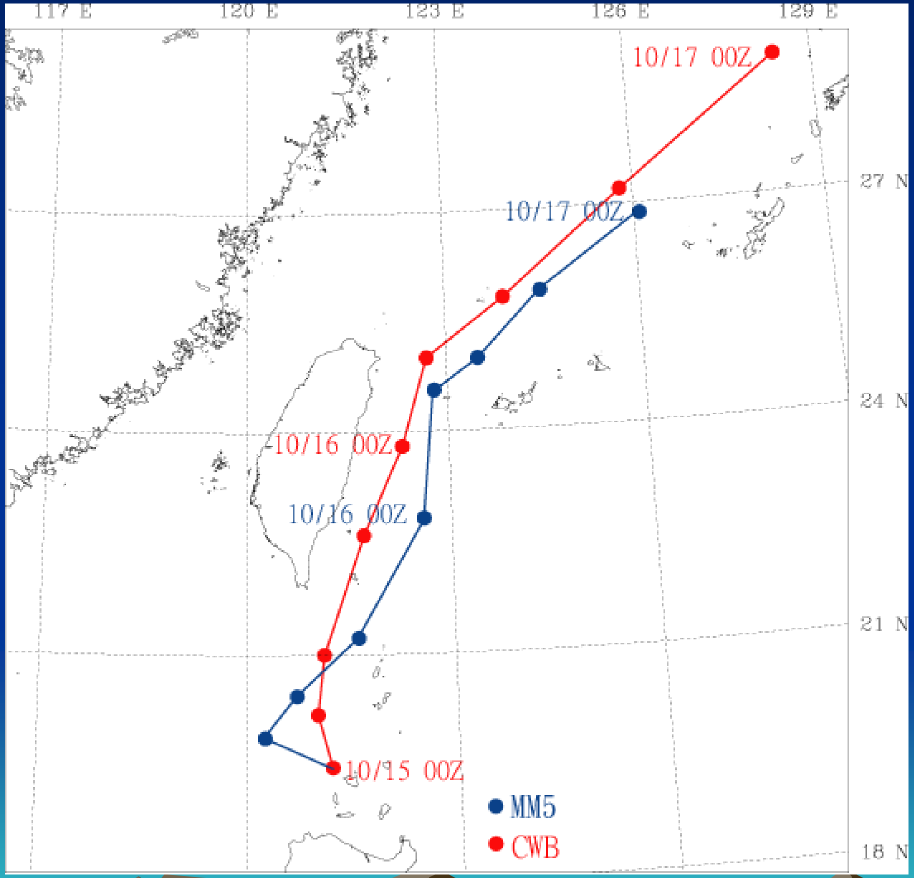


Satellite Image of Typhoon Zeb (1996)



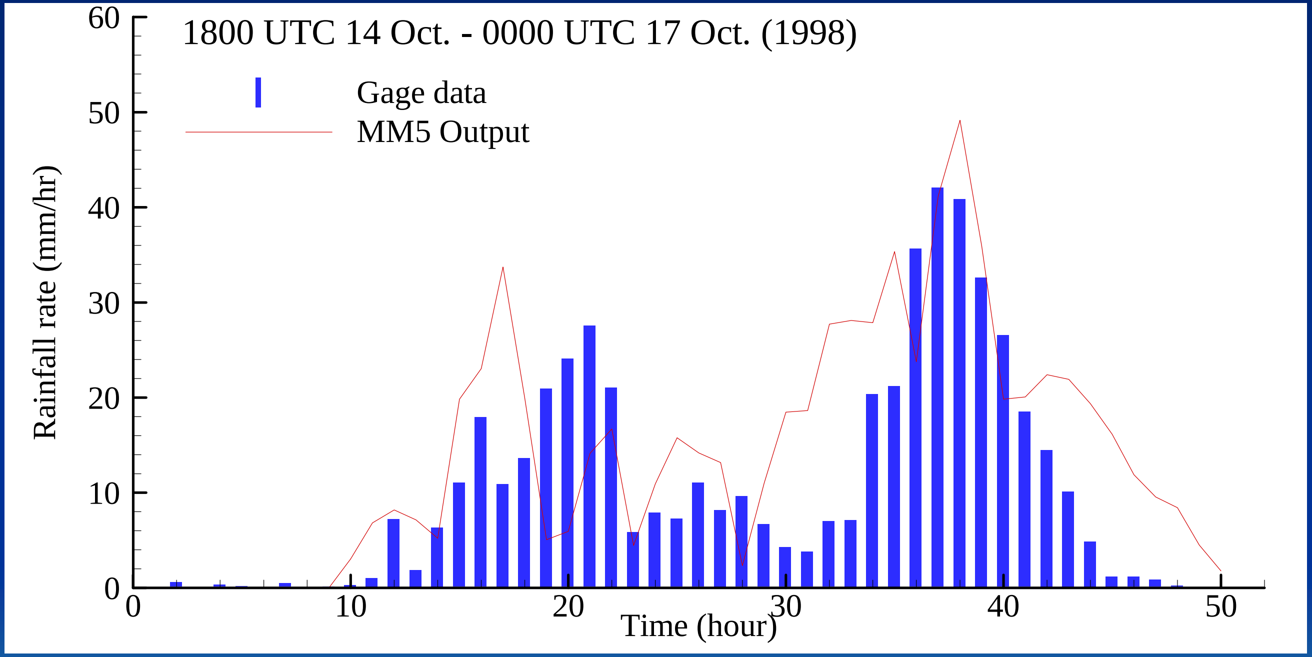
IR image @ 1998/10/15 1200 UTC

Track of Typhoon Zeb (1996)

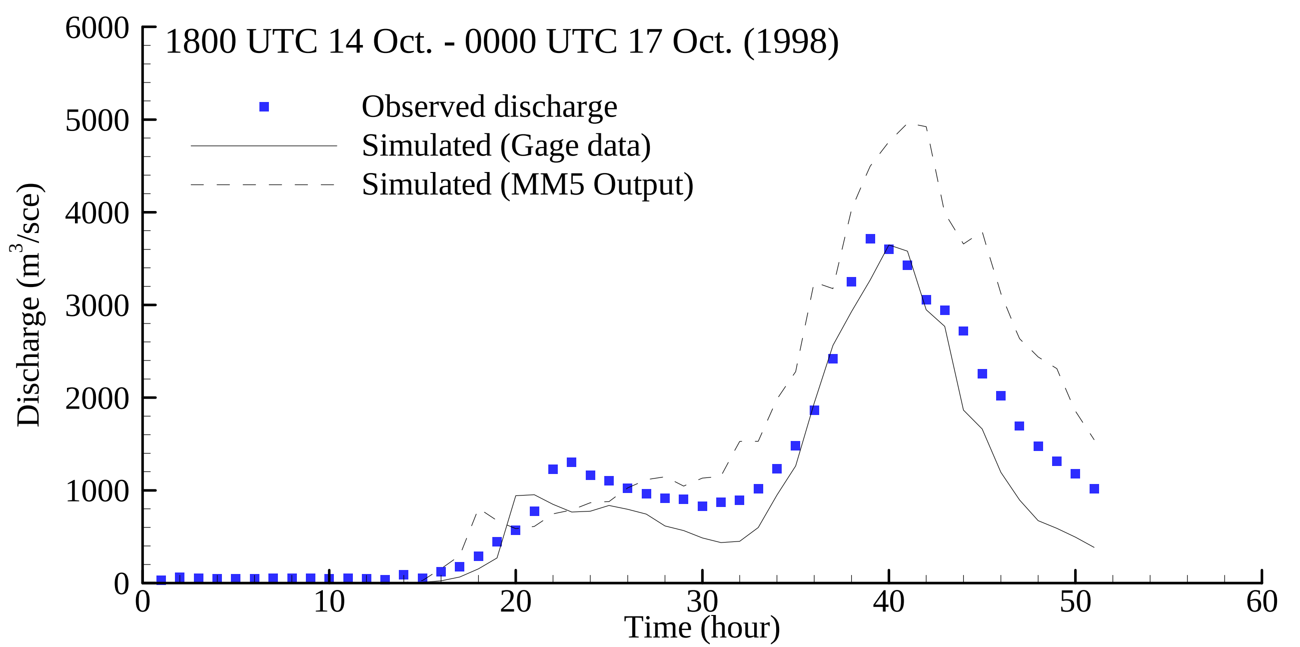


Triply-Nested MM5 (60, 20, 6.67 km)

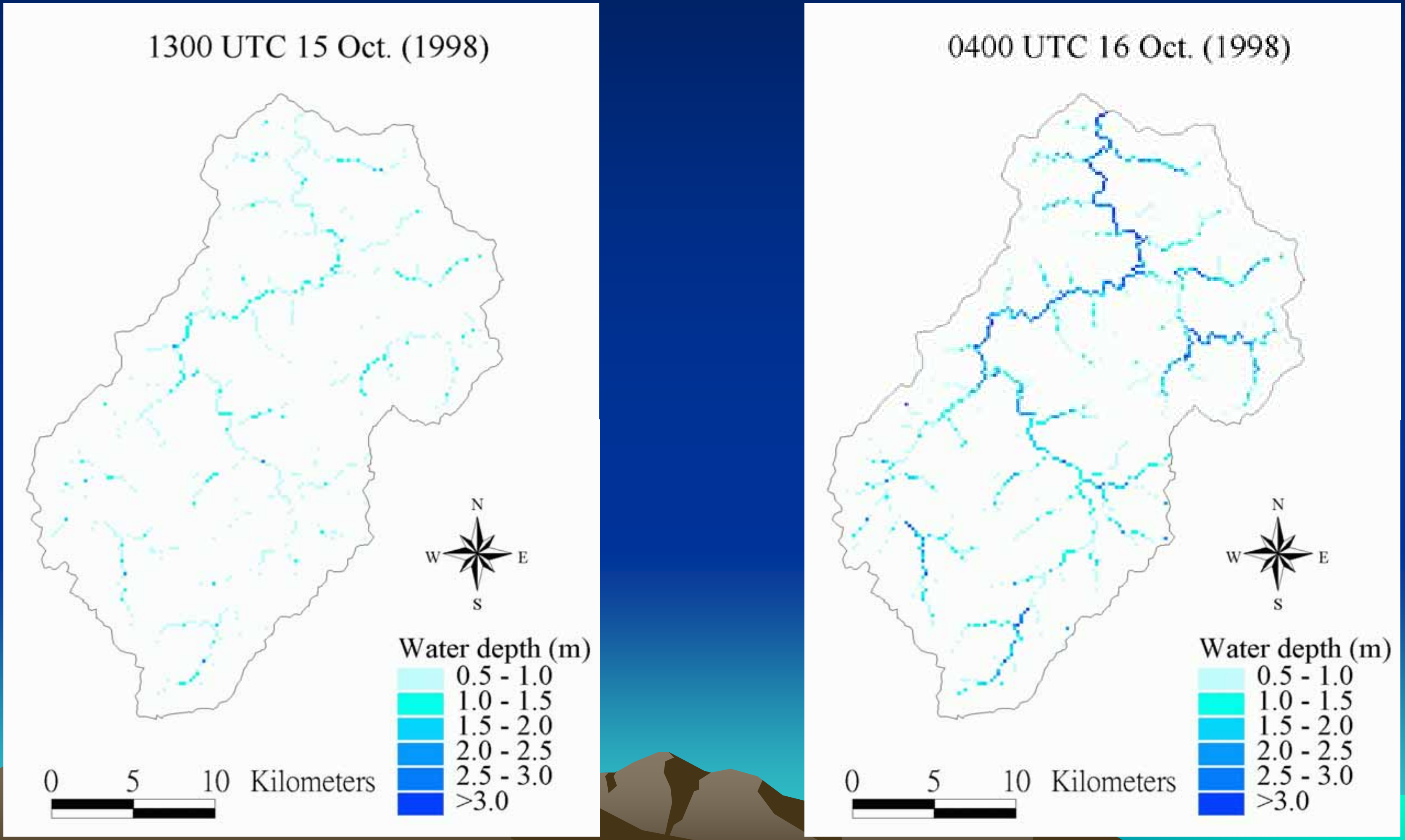
Basin-averaged rainfall for Typhoon Zeb (1998)



Comparisons of discharge for Typhoon Zeb (1998)



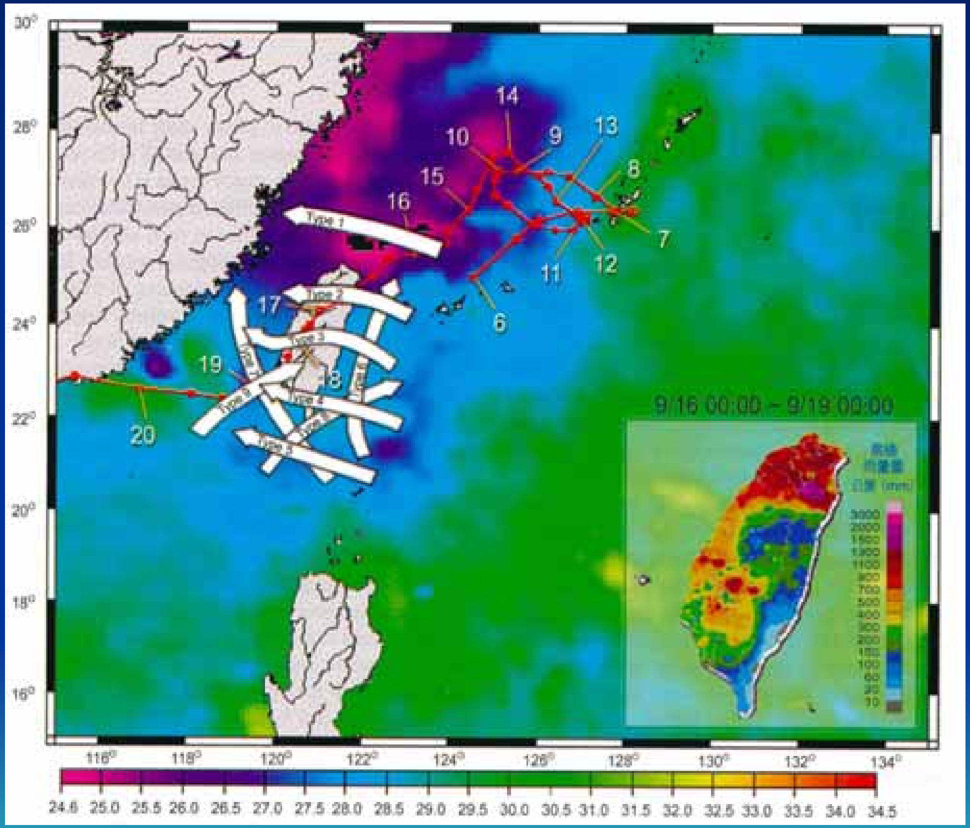
Simulated flood water depth for Typhoon Zeb (1998)



1300 UTC 15 Oct. (1998)

0400 UTC 16 Oct. (1998)

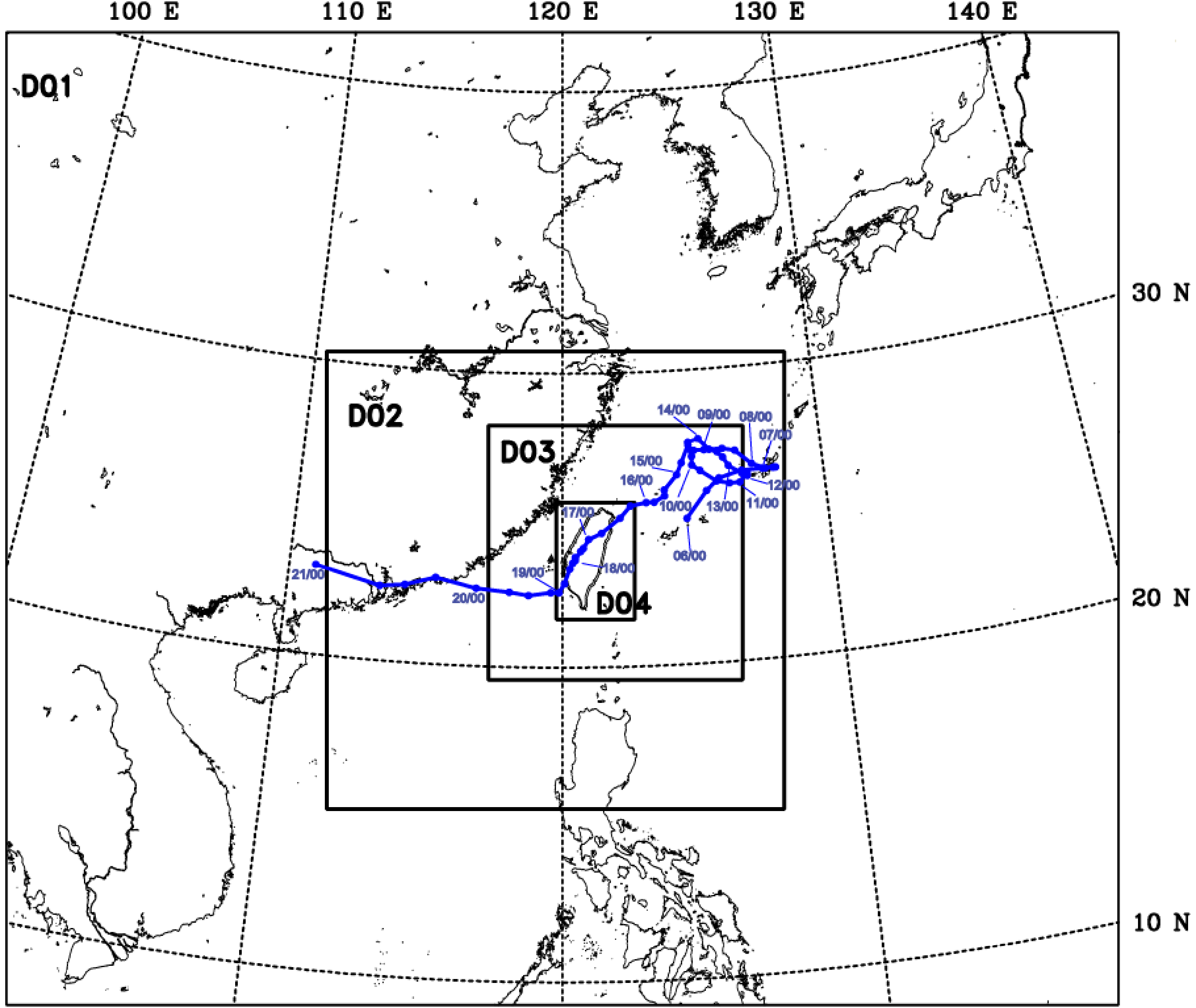
Track and SST for Typhoon Nari (1996)



Sui et al. (2002; EOS)


90
50


阿彌陀佛

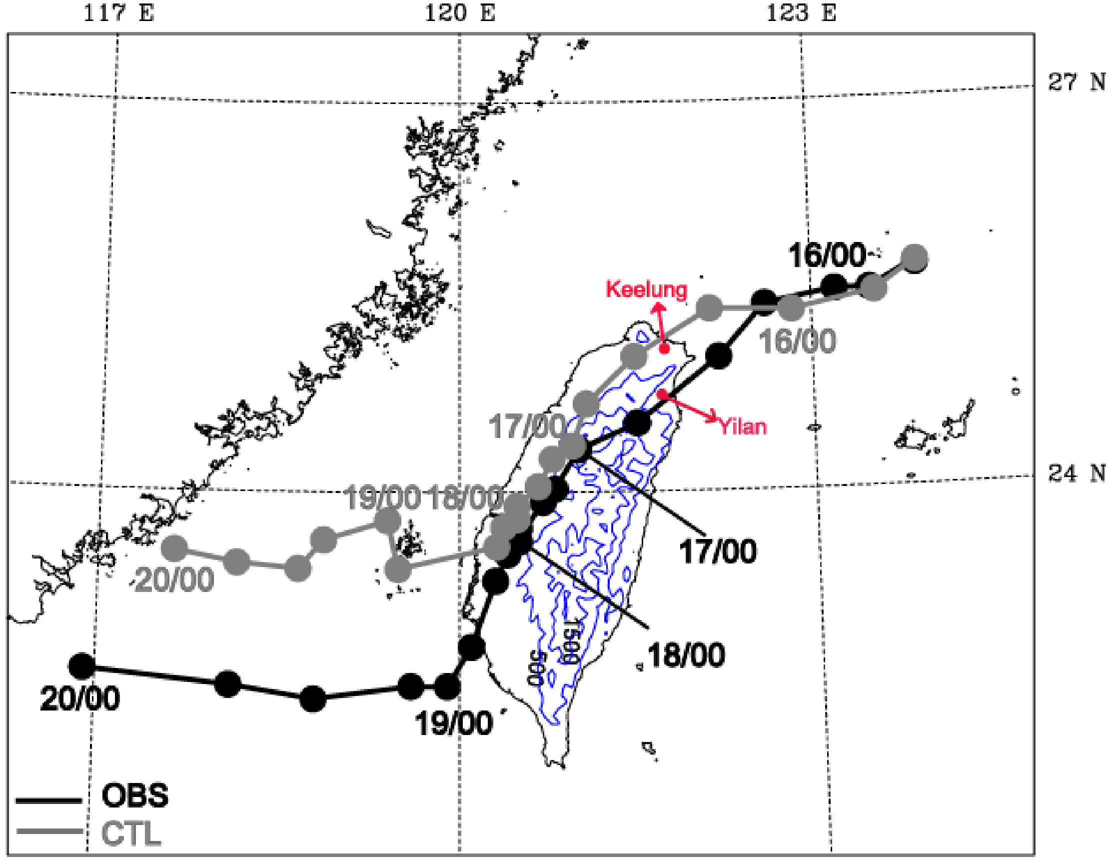


MM5 Domains

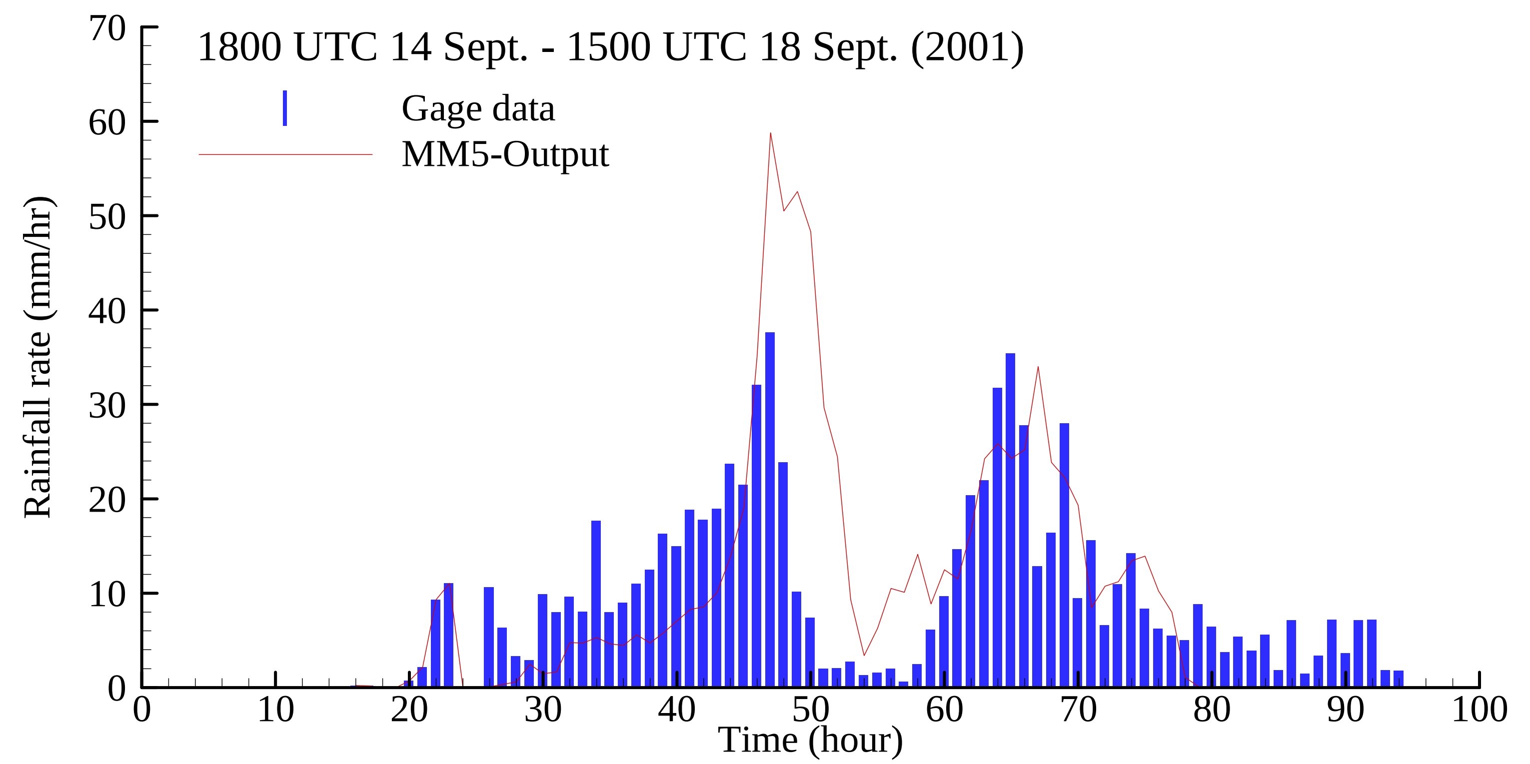
D1: 54 km
D2: 18 km
D3: 6 km
D4: 2 km

31 levels
In vertical

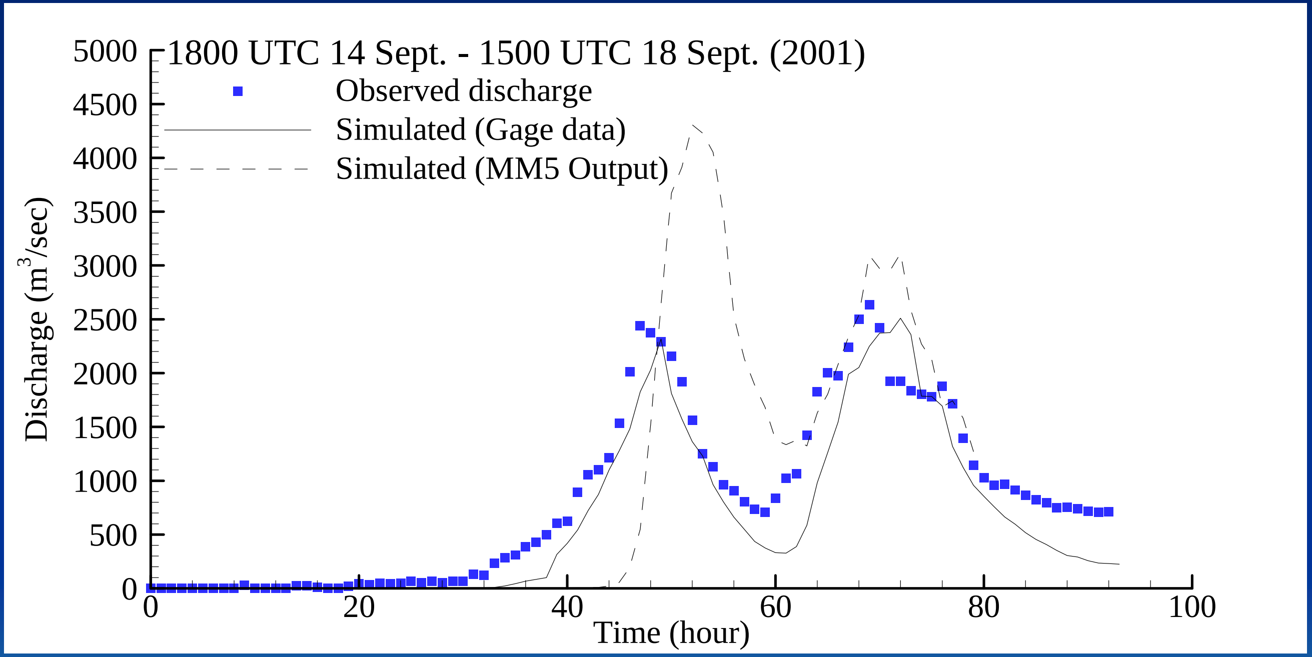
Track of Typhoon Zeb (1996)



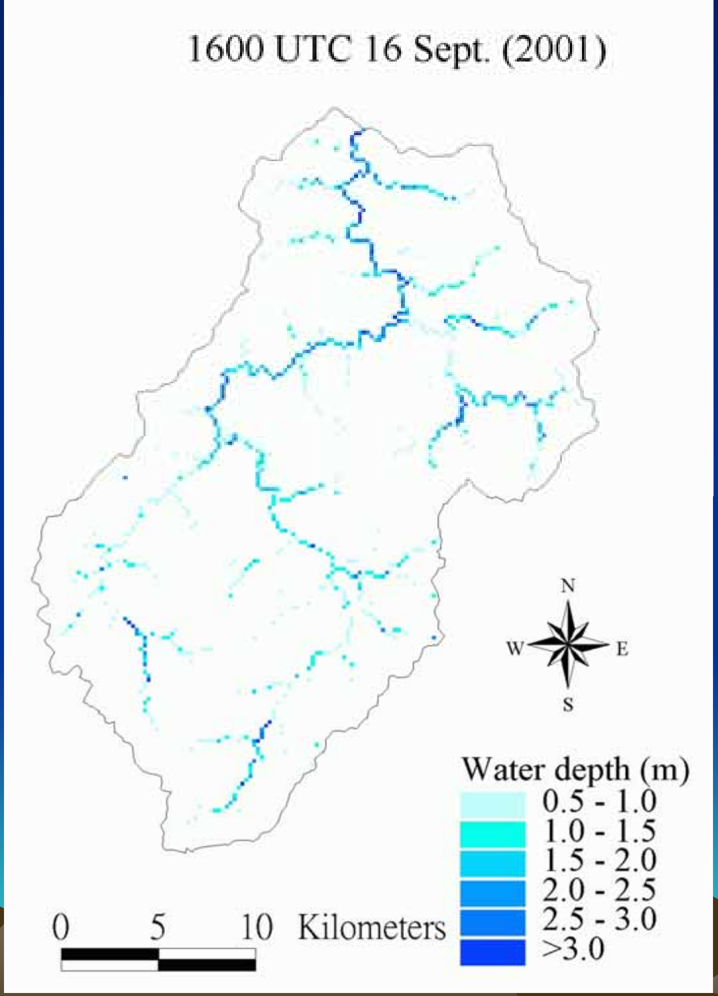
Basin-averaged rainfall for Typhoon Nari (2001)



Comparisons of discharge for Typhoon Nari (2001)



Simulated flood water depth for Typhoon Nari (2001)


1600 UTC 16 Sept. (2001)

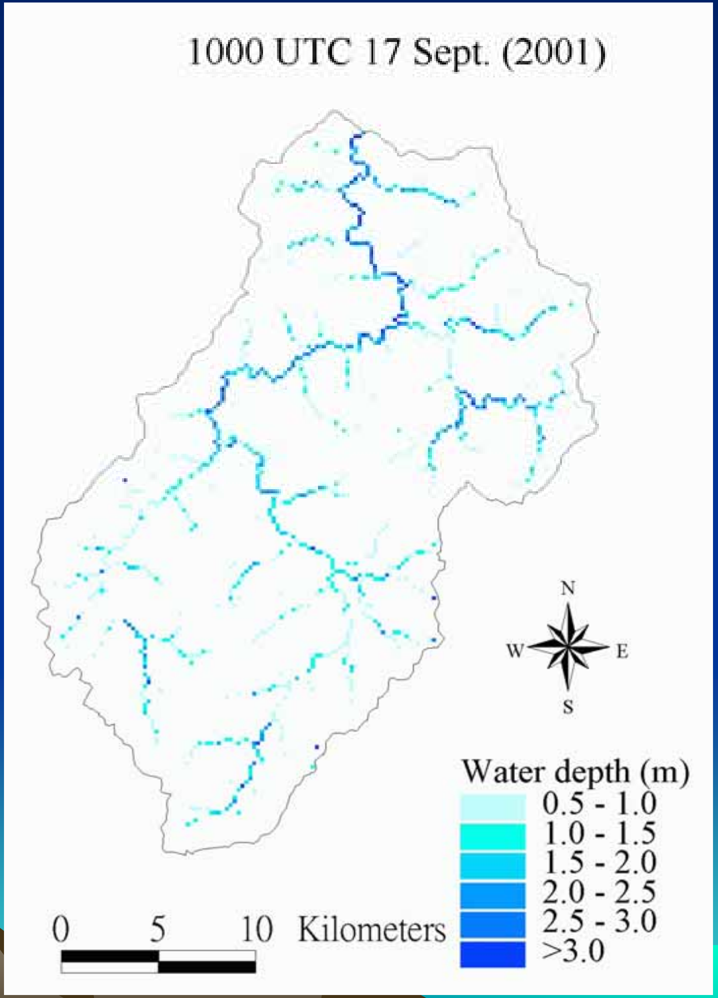

1000 UTC 17 Sept. (2001)

Table 1. Comparisons of peak discharge (Q_p; $m^3 s^{-1}$) between the observed and the simulated with gauge data (Q_{pg}) and with MM5 runs (Q_{pM}) and time lag (hour) of peak discharge for Typhoons Zeb, Nari, and Herb. Positive/negative time lag indicates simulated peak discharge is later/earlier than the observed.

Typhoons	Q_p		Q_{pg} (time lage)		Q_{pM} (time lag)	
Zeb	1301	3715	953 (-2)	3647 (+1)	807 (-5)	4961 (+2)
Nari	2439	2639	2316 (+2)	2375 (+2)	4306 (+5)	3095 (0)
Herb	5084		5109 (+1)		10470 (+2)	w/ radar 8482 (-1)

Table 2. Comparisons of total flood (Q), total rainfall (P), and the runoff ratio (R = Q/P) of the observed data and simulated results with gauge data and MM5 rainfall estimates for Typhoons Zeb, Nari, and Herb. The RMSE and GOF are computed with observed and predicted flood hydrographs (Q, P, RMSE, and GOF are all in units of mm).

<table>
<tr><th></th><th>Observed data</th><th>Gauge data</th><th colspan="2">MM5 rainfall estimates</th></tr>
<tr><td>Zeb</td><td>Q = 357
P = 516
R = 0.69</td><td>Q = 267
P = 516
R = 0.52
RMSE = 2.35
GOF = 279.0</td><td colspan="2">Q = 443
P = 703
R = 0.63
RMSE = 4.13
GOF = 173.7</td></tr>
<tr><td>Nari</td><td>Q = 455
P = 782
R = 0.58</td><td>Q = 350
P = 782
R = 0.45
RMSE = 1.86
GOF = 445.7</td><td colspan="2">Q = 459
P = 816
R = 0.56
RMSE = 5.20
GOF = 6407.0</td></tr>
<tr><td rowspan="2">Herb</td><td rowspan="2">Q = 487
P = 696
R = 0.70</td><td rowspan="2">Q = 396
P = 696
R = 0.57
RMSE = 2.35
GOF = 154.4</td><td>Original MM5</td><td>With radar data</td></tr>
<tr><td>Q = 543
P = 870
R = 0.62
RMSE = 9.05
GOF = 197.2</td><td>Q = 446
P = 728
R = 0.61
RMSE = 6.06
GOF = 196.0</td></tr>
</table>

Summary

- With rainfall-gauges data, the FLO-2D model is capable of capturing the basin characteristics in response to typhoons invading Taiwan.
- The fast runoff response of Shihmen watershed is sensitive to severe weather rainfall, which poses a great challenge to quantitative precipitation forecasting (QPF).
- Simulated rainfall bias by MM5 may induce discrepancy in basin-scale runoff predictions in Taiwan.

Summary

- Although the predicted rainfall of MM5 has some uncertainty, it does show a significant QPF improvement by assimilating radar data.
- For future work, other hydrological models will be used to implement spatially-varied rainfall distributions, rather than basin-averaged rainfall currently used in the FLO-2D model.