Regional Climate Modeling Using WRF

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Formosat-3/COSMIC Science Summer Camp
Central Weather Bureau, Taipei, Taiwan
May 30 – June 3, 2005

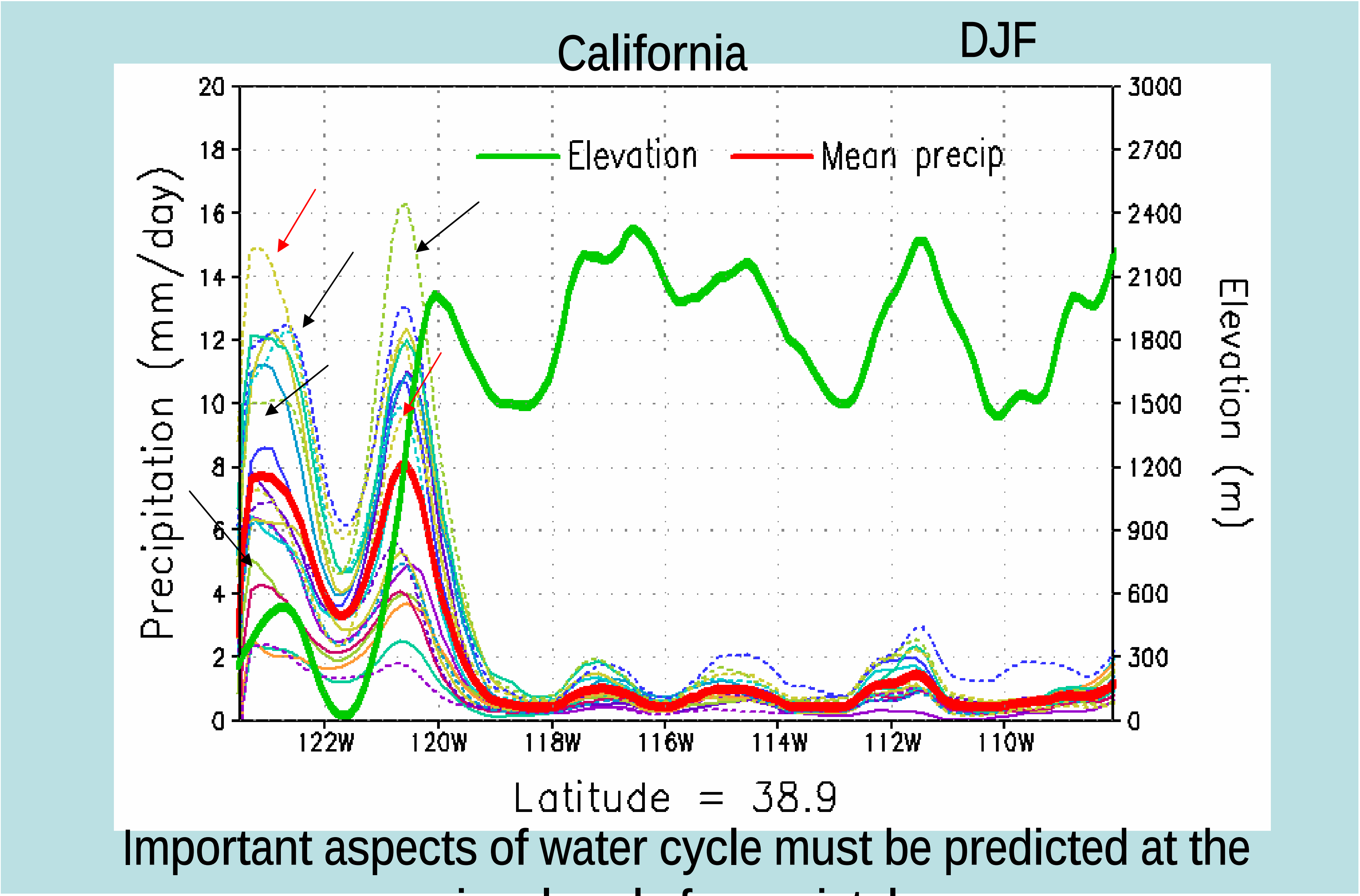
Overview

- Why regional climate modeling?
- Regional climate model development with WRF
- A workshop report
- Recommendations and future directions

Why Regional Climate Modeling?

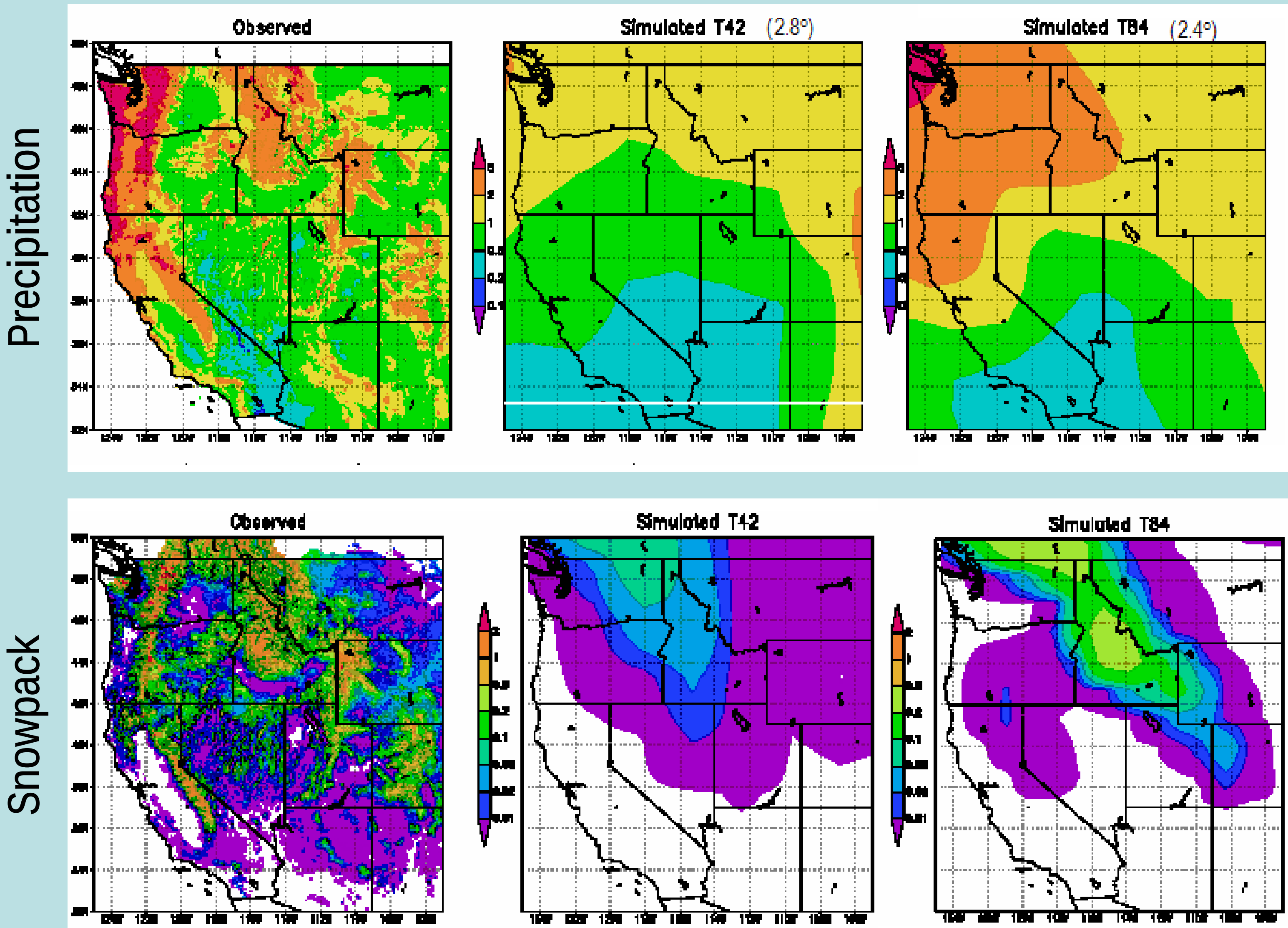
- *Downscaling* of climate variability and change at the regional scale (e.g., climate change effects on water resources, ecosystem, extreme weather; hurricane frequency; storm track; distribution of MCS and warm season precipitation; use of seasonal forecasts for water management)
- *Process studies* (e.g., Amazon biomass burning and aerosol effects; orographic effects; land-atmosphere interactions; ocean-atmosphere interactions; sea ice; cloud-radiation feedbacks)
- *Upscaling* of regional phenomena with global consequences (e.g., subtropical and tropical eastern boundary upwelling regimes; subgrid-scale clouds; organized convection; gravity wave drag)

Regional climate is determined by the interaction of forcings and circulations that occur at the planetary, regional, and local spatial scales



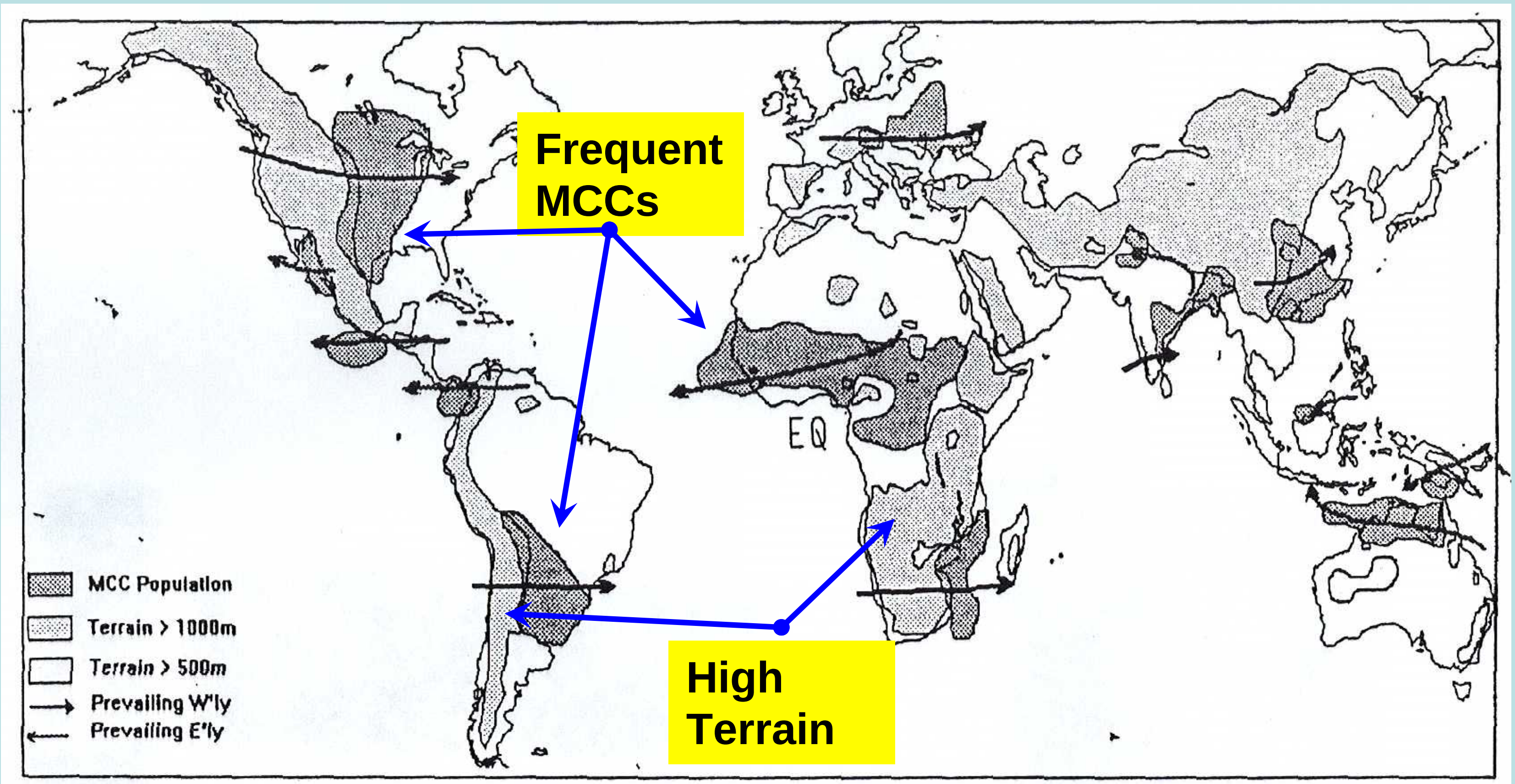
Important aspects of water cycle must be predicted at the regional scale for societal use

GCM Simulated Precipitation and Snowpack



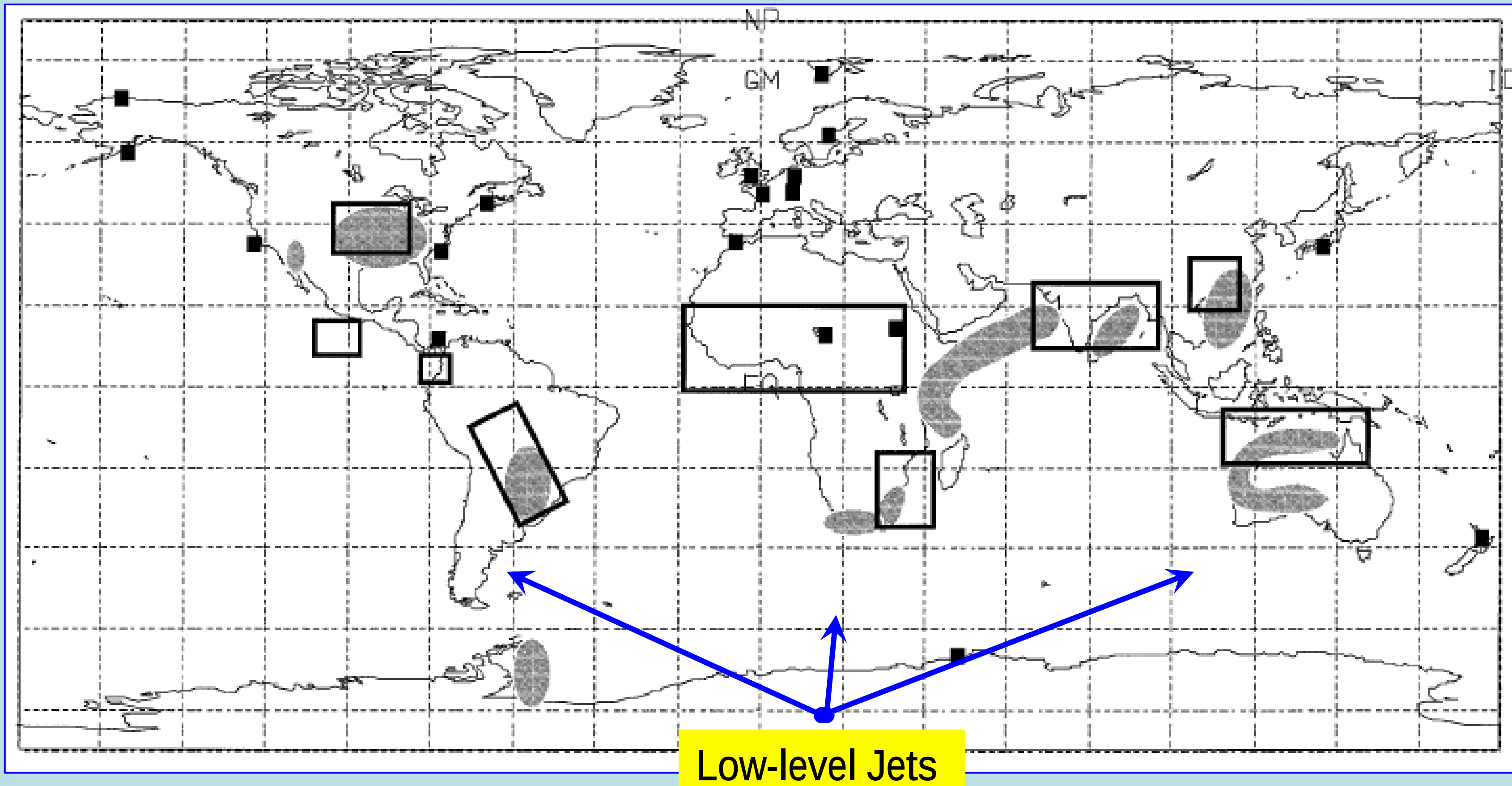
Ghan et al. (2003)

Mesoscale Climate Factors



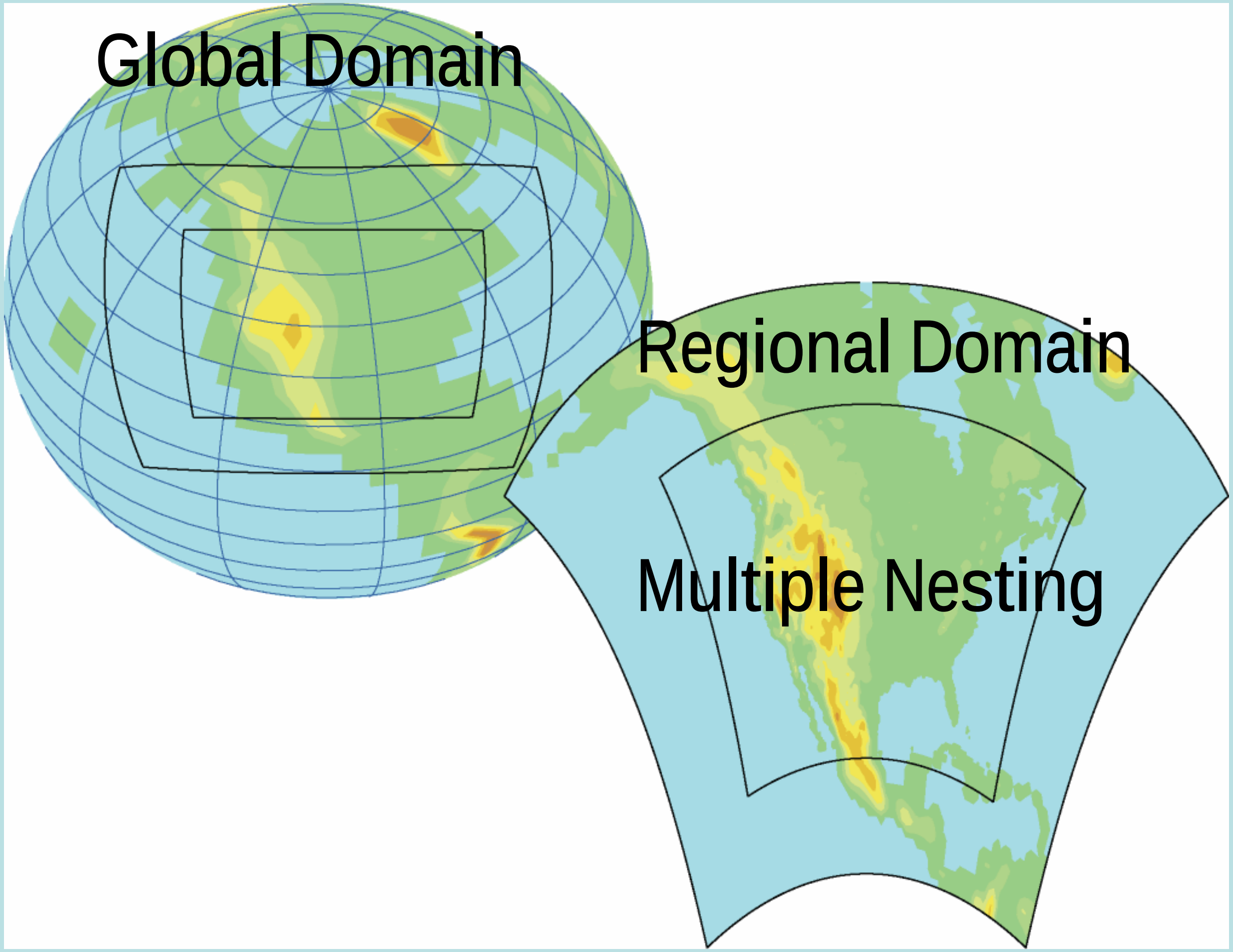
Laing & Fritsch (1997)

Mesoscale Climate Factors



Stensrud (1996)

Downscaling by Regional Climate Modeling



History and Current Status

- First Regional Climate Model -- RCM (Dickinson and Giorgi 1989) was developed based on PSU/NCAR MM4 to address downscaling needs
- Today there are more than 30 regional climate modeling groups worldwide (US ~ 15; Europe ~ 10; Asia/Australia/Canada ~ 5 - 10)
- Most RCMs were developed based on mesoscale weather forecasting models
- More active research is related to climate change (regional climate change scenarios and impact assessment)
- Intercomparison projects: PIRCS, ARCMIP, RMIP, PRUDENCE, NARCCAP, ENSEMBLE

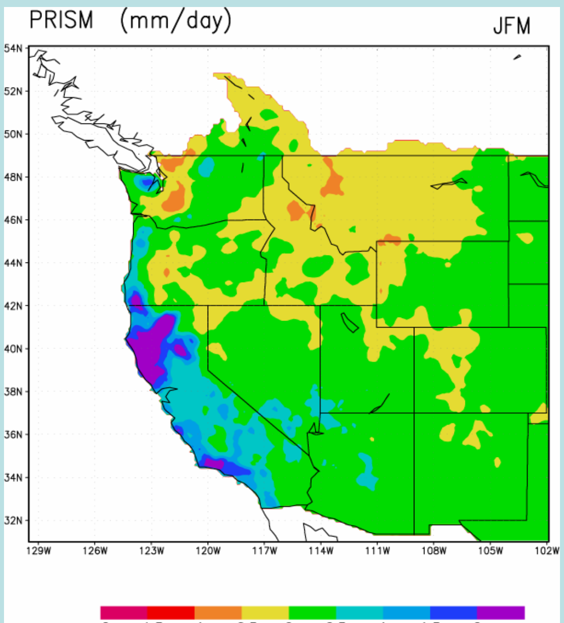
History and Current Status

- Alternative approaches: variable resolution GCM and high resolution AGCM
- The NSF/DOE sponsored RCM workshop in 2001 (Leung et al. 2003 BAMS) concluded that all downscaling approaches are valid and future development should proceed along parallel paths
- In 2001, WCRP WGNE appointed a working group led by Laprise to examine the validity of regional climate modeling
- Big-Brother experiments confirmed the downscaling ability of RCM
- A WCRP-sponsored workshop was held in 2004 (Lund, Sweden) to discuss modeling issues

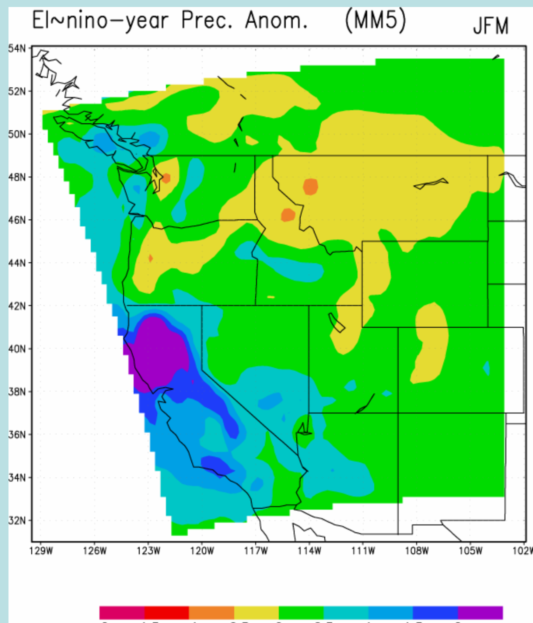
El Nino Precipitation Anomaly

RCM simulation of 1980-2000 driven by NCEP reanalysis
Anomaly calculated based on 6 El Nino cases minus 20 year mean

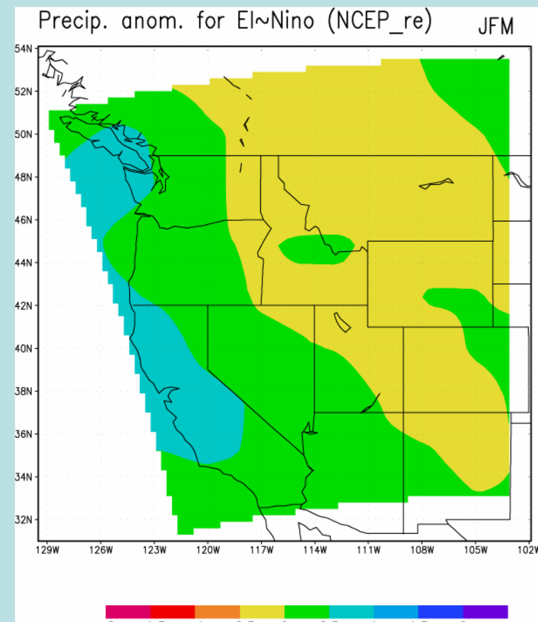
Observation



RCM Simulation

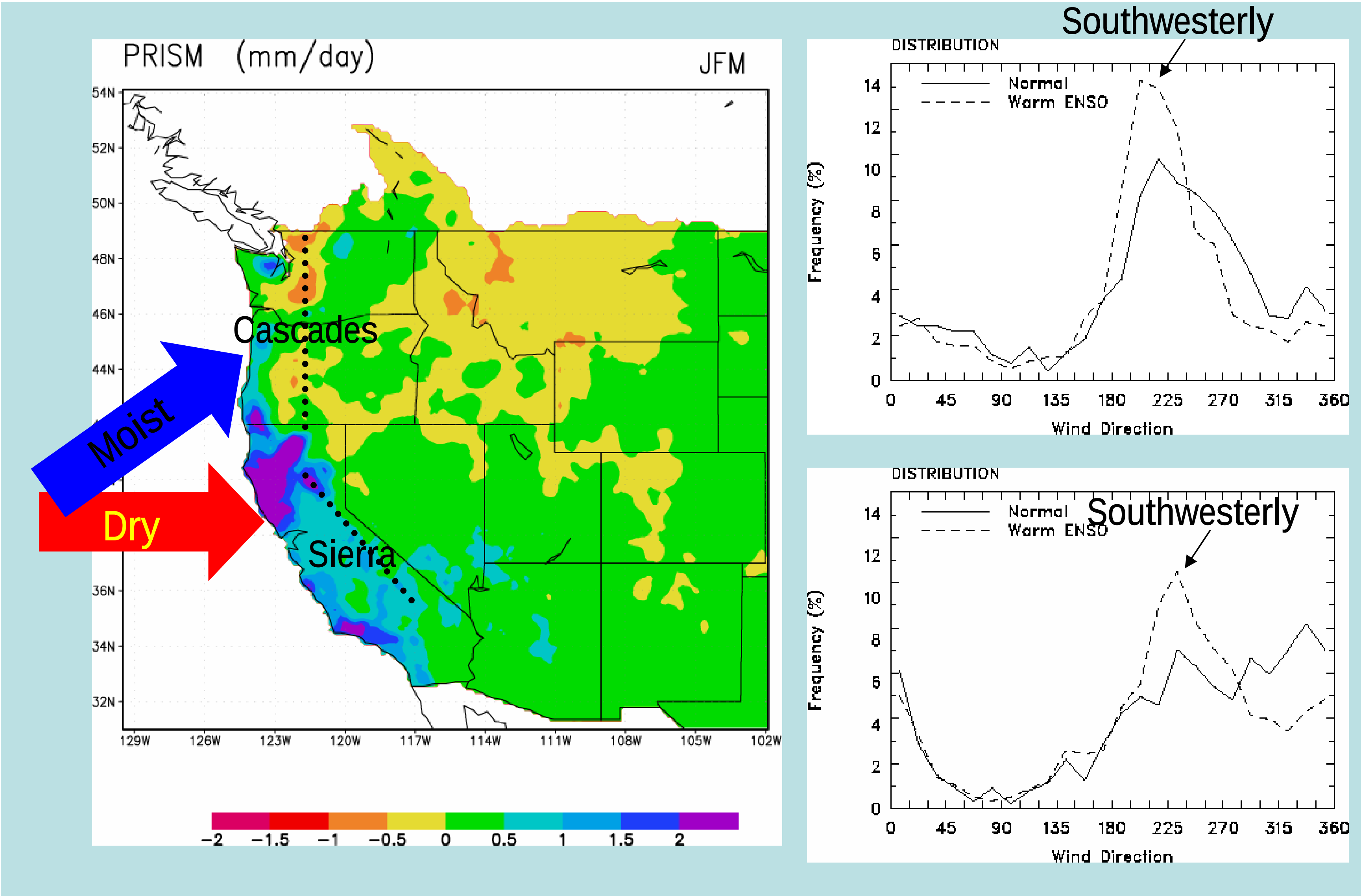


NCEP Reanalysis

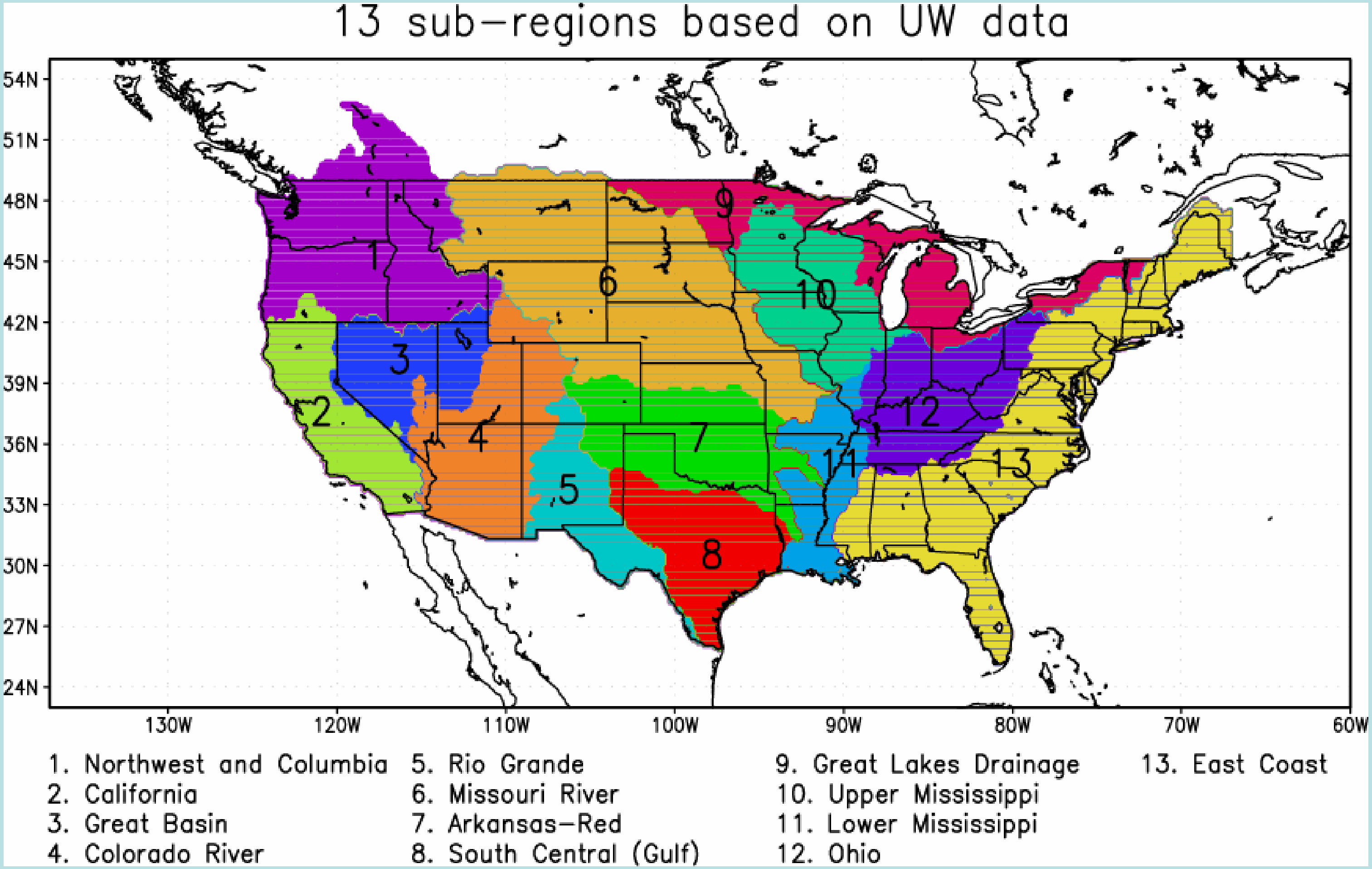


Leung et al. 2003 JC

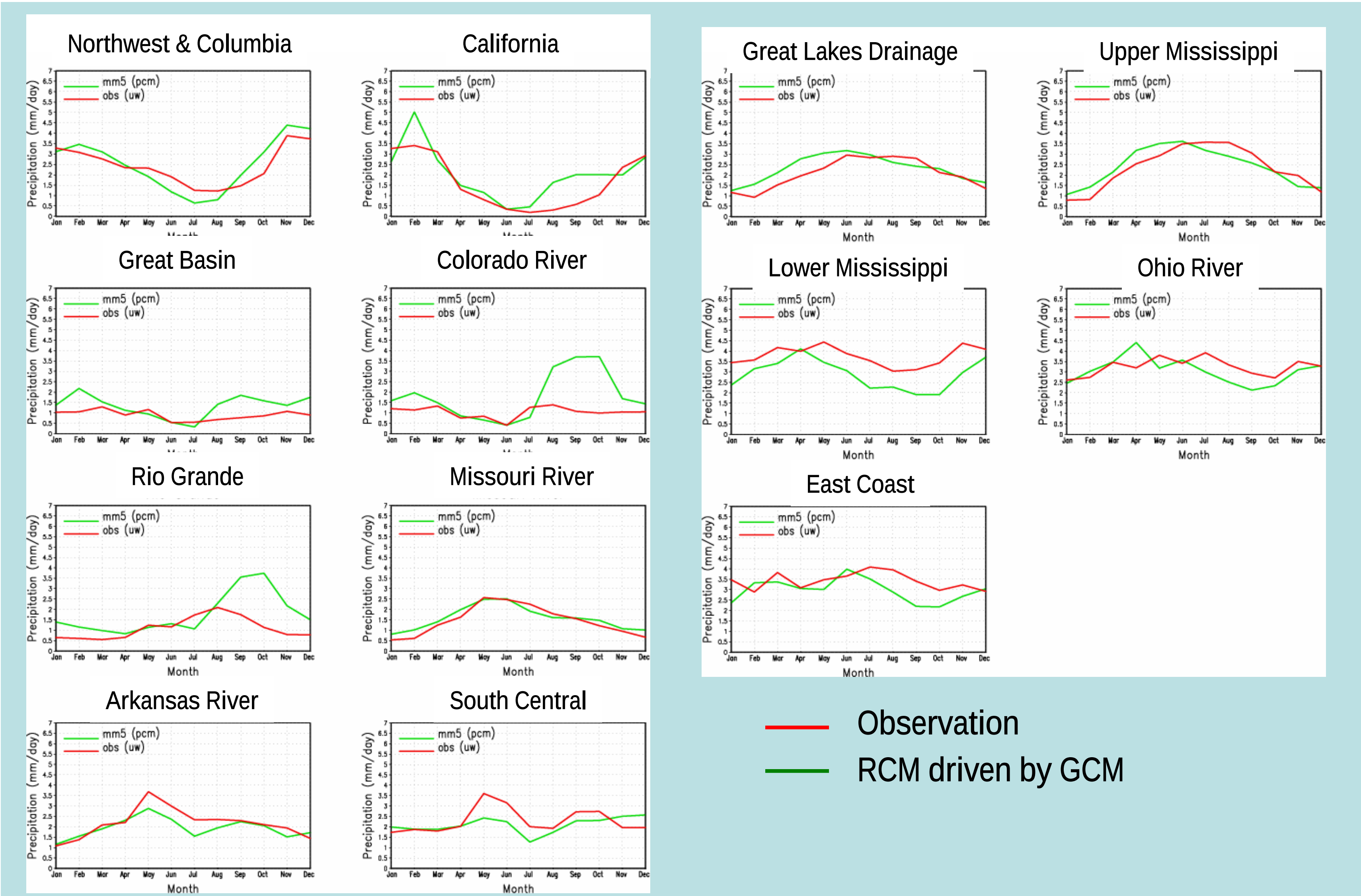
Need to predict changes in circulation and represent orographic effects



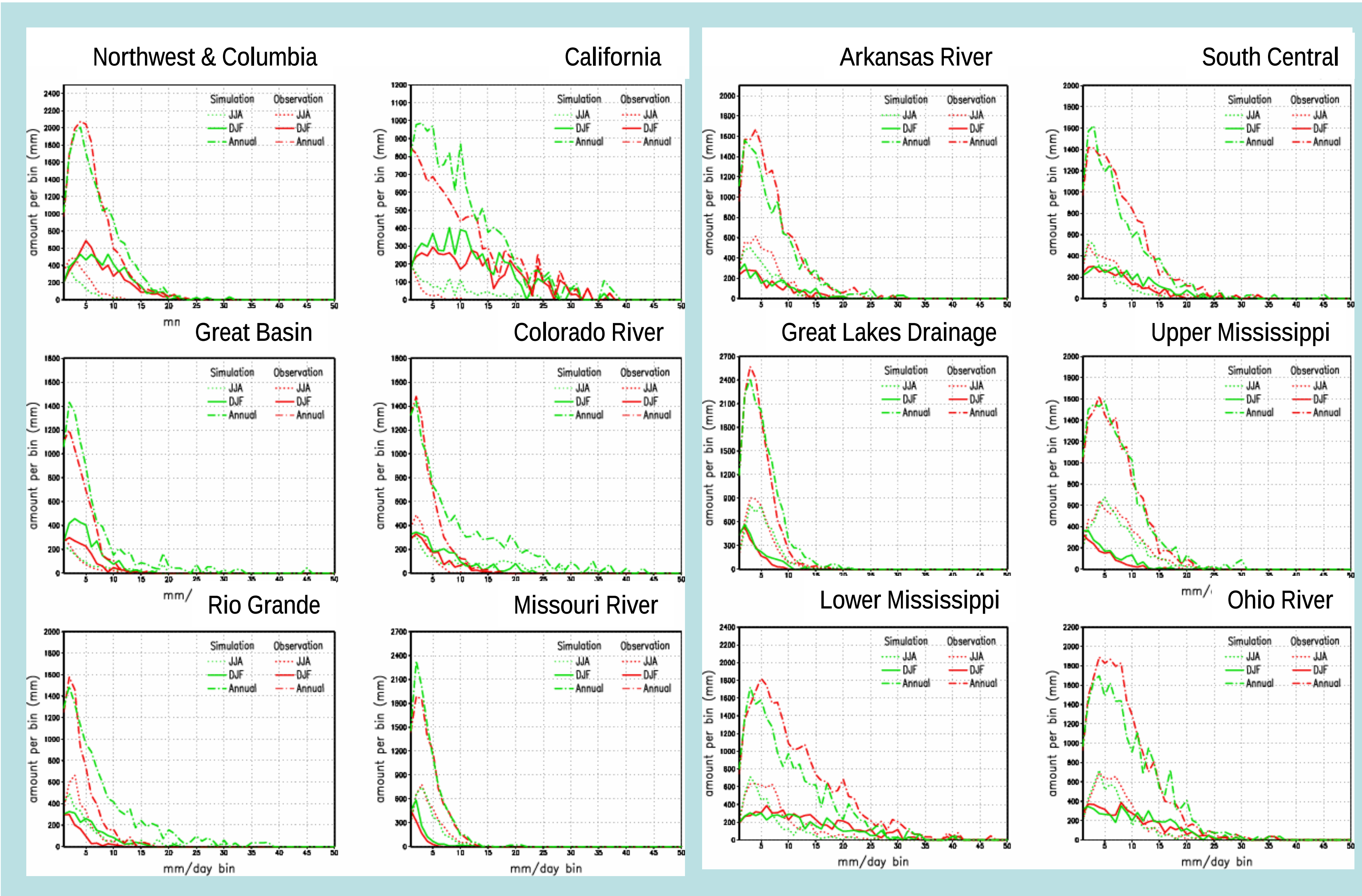
How Well Can We Simulate Regional Precipitation?



Seasonal Cycle of Precipitation

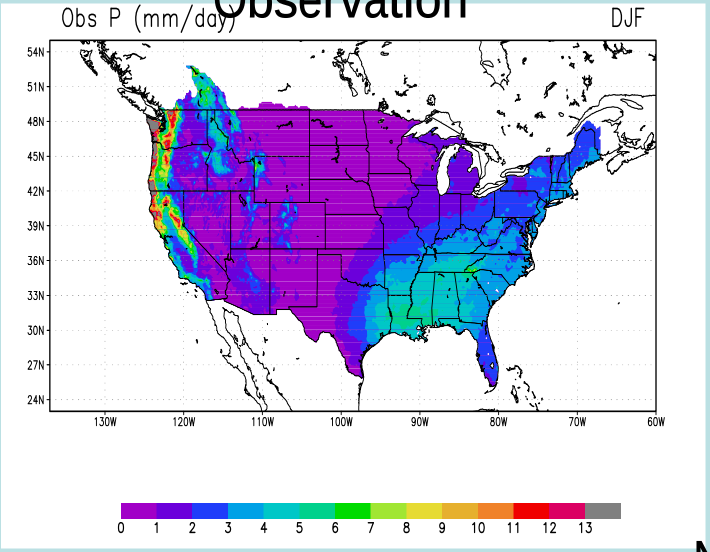


Distribution of Rain Rates

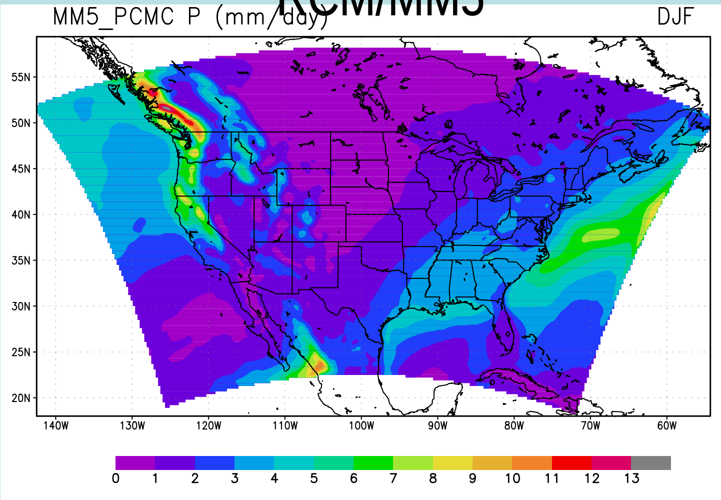


Cold Season Mean Precipitation (DJF)

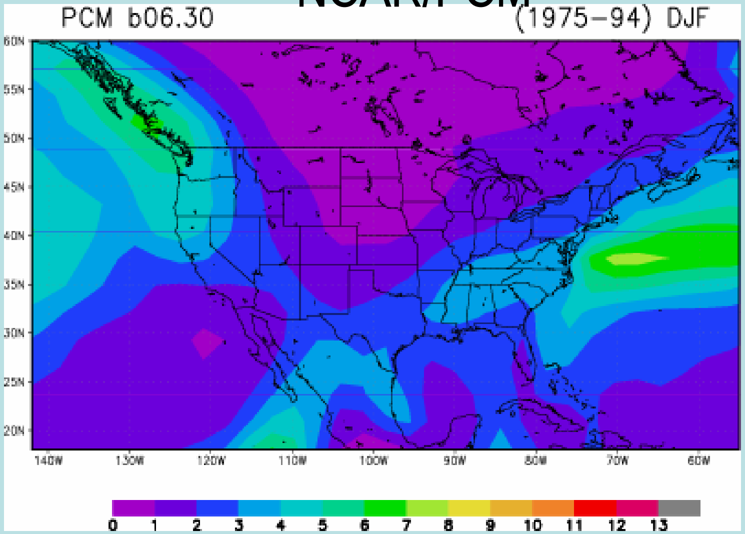
Observation



RCM/MM5

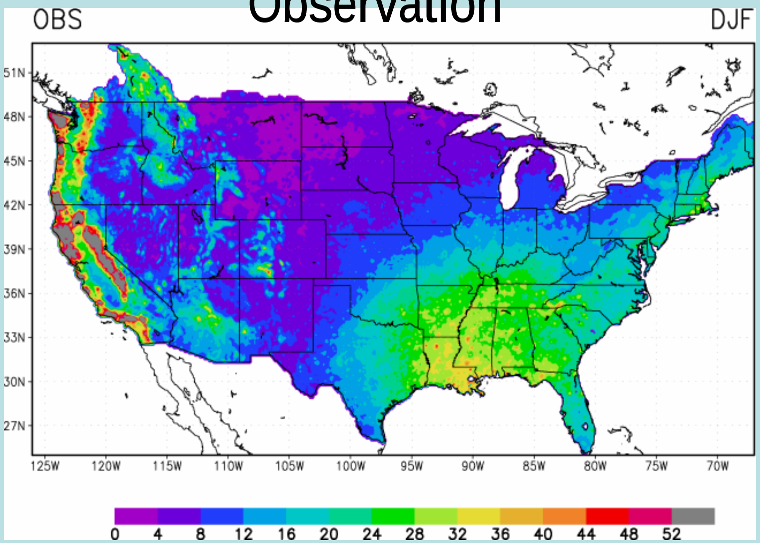


NCAR/PCM

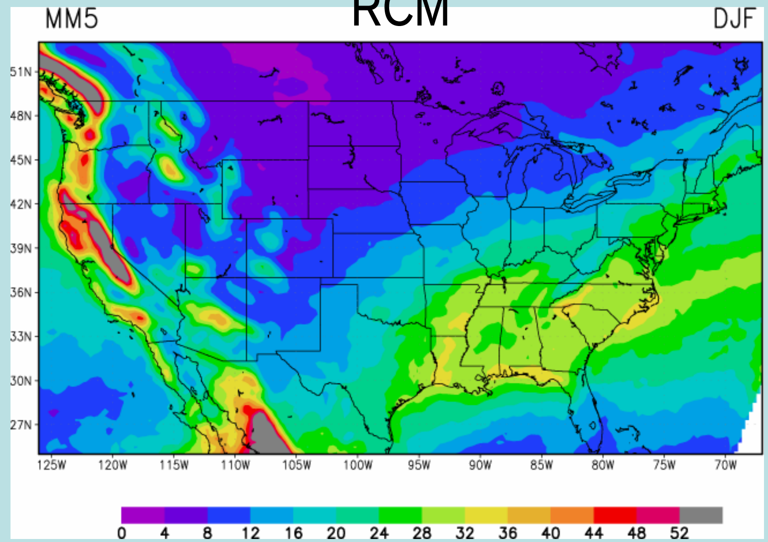


95th Percentile Extreme Precipitation (DJF)

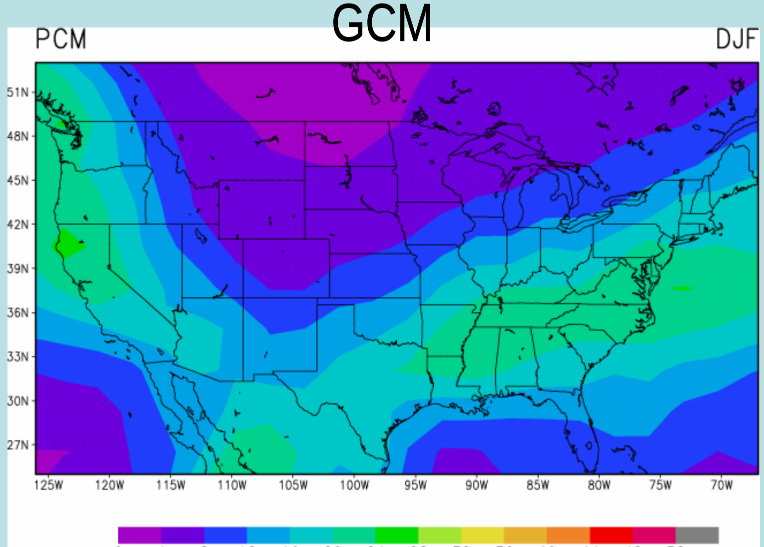
Observation



RCM



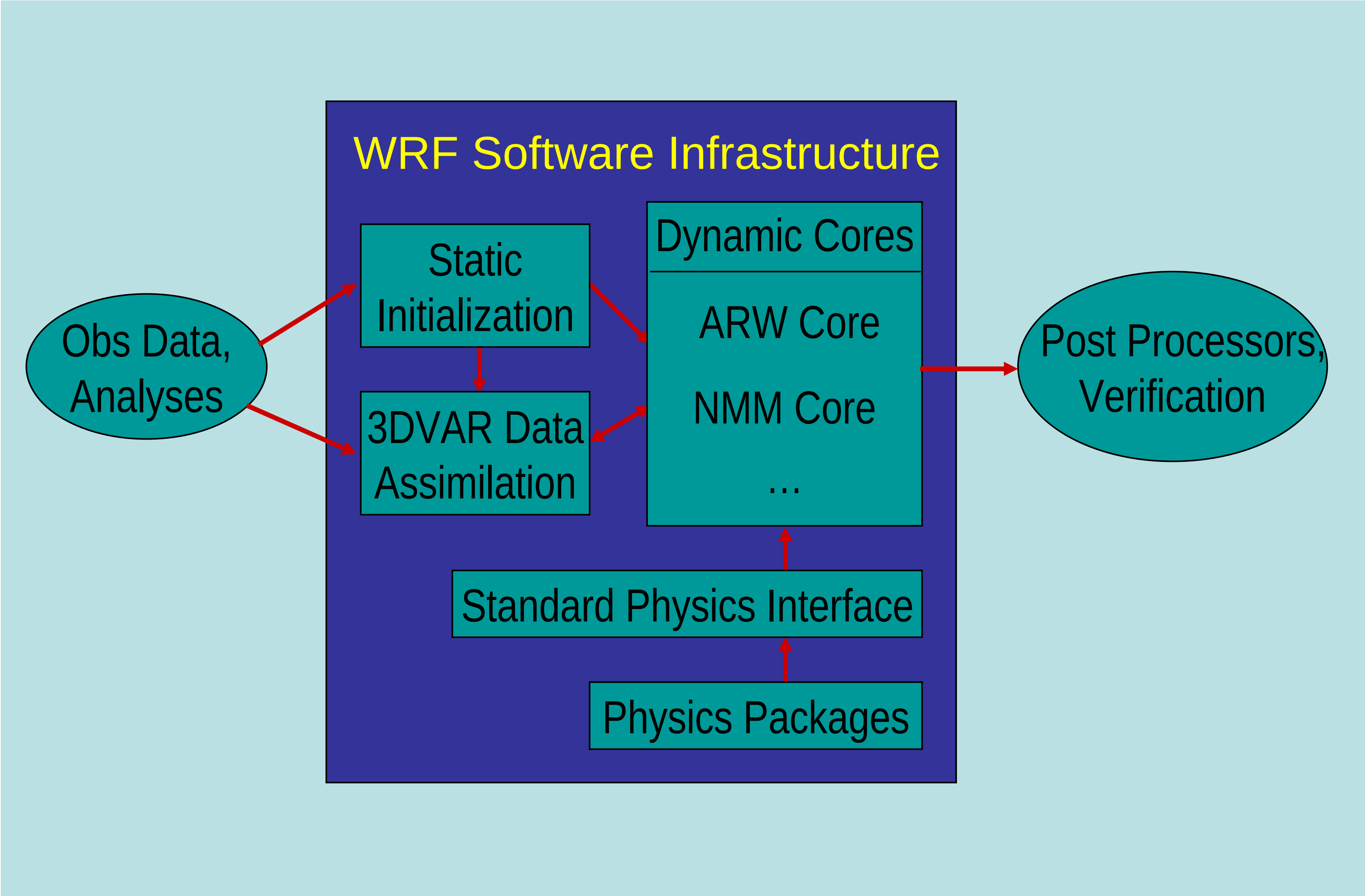
GCM



RCM Development Using WRF

- Since 2003, NCAR has supported a project to develop regional climate modeling capability with the Weather Research and Forecasting (WRF) model
- WRF is a next generation mesoscale model: it uses high-order numerical techniques that maintain accuracy and stability and is applicable to any scale of atmospheric simulation
- The WRF physics suite encompasses options that have been tested for grid scales from tens of meters to tens of kilometers
- Preprocessors can handle data from global/regional analysis and GCMs (using a converter from MM5 to WRF)
- Future physics development is only going to WRF, and new capabilities are planned for regional earth system modeling

WRF Modeling System



WRF Dynamical Core

- Mass Coordinate Core
  - Terrain-following hydrostatic pressure vertical coordinate
  - Arakawa C-grid
  - 3rd order Runge-Kutta split-explicit time differencing, 5th or 6th order differencing for advection
  - Conserves mass, momentum, dry entropy, and scalars using flux form prognostic equations
- NMM Core
  - Terrain-following hybrid sigma vertical coordinate
  - Arakawa E-grid
  - Explicit Adams-Bashforth time differencing
  - Conserves kinetic energy, enstrophy and momentum using 2nd order finite differencing

WRF Physics Options

– Microphysics:	Kessler-type (no-ice),Reisner, Lin et al. (graupel included), WSM3/5/6, Ferrier
– Cumulus Convection:	New Kain-Fritsch, Grell Ensemble, Betts-Miller-Janjic
– Shortwave Radiation:	Dudhia (MM5), Goddard, GFDL, CAM*
– Longwave Radiation:	RRTM, GFDL, CAM*
– Turbulence:	Prognostic TKE, Smagorinsky, constant diffusion
– PBL:	MRF, MYJ, YSU
– Surface Layer:	Similarity theory, MYJ
– Land-Surface:	5-layer soil model, RUC LSM Noah unified LSM, CLM*

* RCM effort

WRF Development Teams

<table>
<tr><th>Numerics and Software
(J. Klemp)</th><th>Data Assimilation
(C. Bishop)</th><th>Analysis and Validation
(K. Droegemeier)</th><th>Community Involvement
(W. Kuo)</th><th>Operational Implementation
(G. DiMego)</th></tr>
<tr><td rowspan="3">Dynamic Model Numerics
(W. Skamarock)</td><td rowspan="2">Standard Initialization
(W. Wang)</td><td rowspan="2">Analysis and Visualization
(M. Stoelinga)</td><td>Workshops, Distribution, and Support
(J. Dudhia)</td><td rowspan="2">Data Handling and Archive
(G. DiMego)</td></tr>
<tr><td rowspan="2">Model Physics
(J. Brown)</td></tr>
<tr><td rowspan="3">3-D Var
(J. Derber)</td><td rowspan="3">Model Testing and Verification
(C. Davis)</td><td rowspan="2">Operational Requirements
(G. DiMego)</td></tr>
<tr><td rowspan="4">Software Architecture, Standards, and Implementation
(J. Michalakes)</td><td>Atmospheric Chemistry
(G. Grell)</td></tr>
<tr><td rowspan="2">Land Surface Models
(J. Wegiel)</td><td rowspan="3">Operational Forecaster Training
(T. Spangler)</td></tr>
<tr><td rowspan="2">Advanced Techniques
(D. Barker)</td><td rowspan="2">Ensemble Forecasting
(D. Stensrud)</td></tr>
<tr><td>Regional Climate Modeling
(R. Leung)</td></tr>
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Overall Approach

- Same source for all applications: weather and forecasting research, climate process studies, upscaling, and downscaling
- Compatible physics with CCSM: radiative transfer (CAM3 radiation), land surface processes (CLM3)
- Extensible to regional earth system modeling: regional ocean, sea ice, land (river transport, dynamic vegetation, lake, groundwater), aerosol-chemistry, biogeochemistry
- Two-way coupling with CCSM to address upscaling issues

Project Tasks

- Establish validity of WRF for regional climate modeling using mostly existing capability (WRF and MM5 have very similar physics parameterizations)
- Comparison of WRF and MM5 simulations
- Examine effects of higher model resolution (via nesting)
- Implement CCSM physics (radiation and CLM)
- Demonstrate downscaling of global climate simulations
- Address model development needs for upscaling research

Model Configuration

- Sea surface temperature, vegetation fraction, and albedo are updated every 6 hours
- Linear-exponential function for relaxation used in 10 layers of buffer zone
- Same physics parameterizations for all domains

  - Noah land surface model

  - Kain-Fritsch/Grell-Devenyi convection scheme

  - Ferrier microphysics

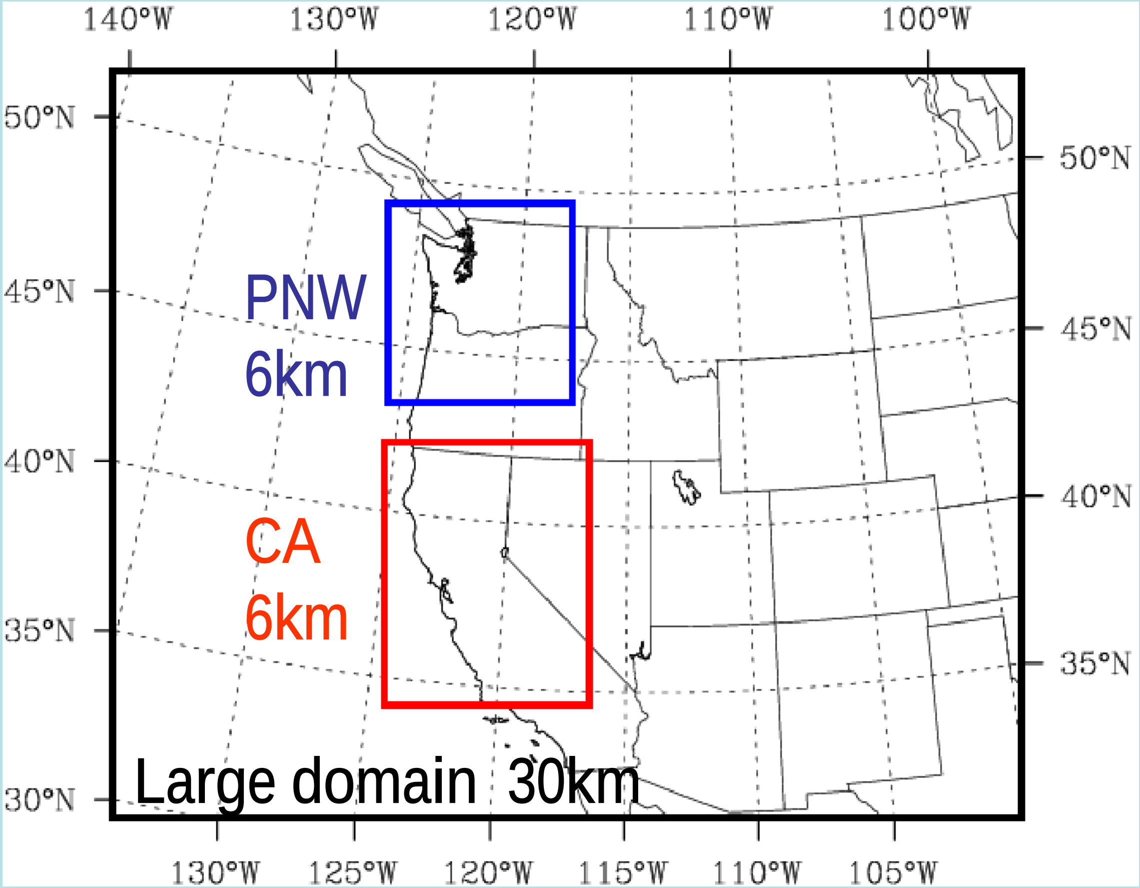
  - RRTM and Dudhia shortwave radiation

  - Mellor-Yamada-Janjic TKE scheme

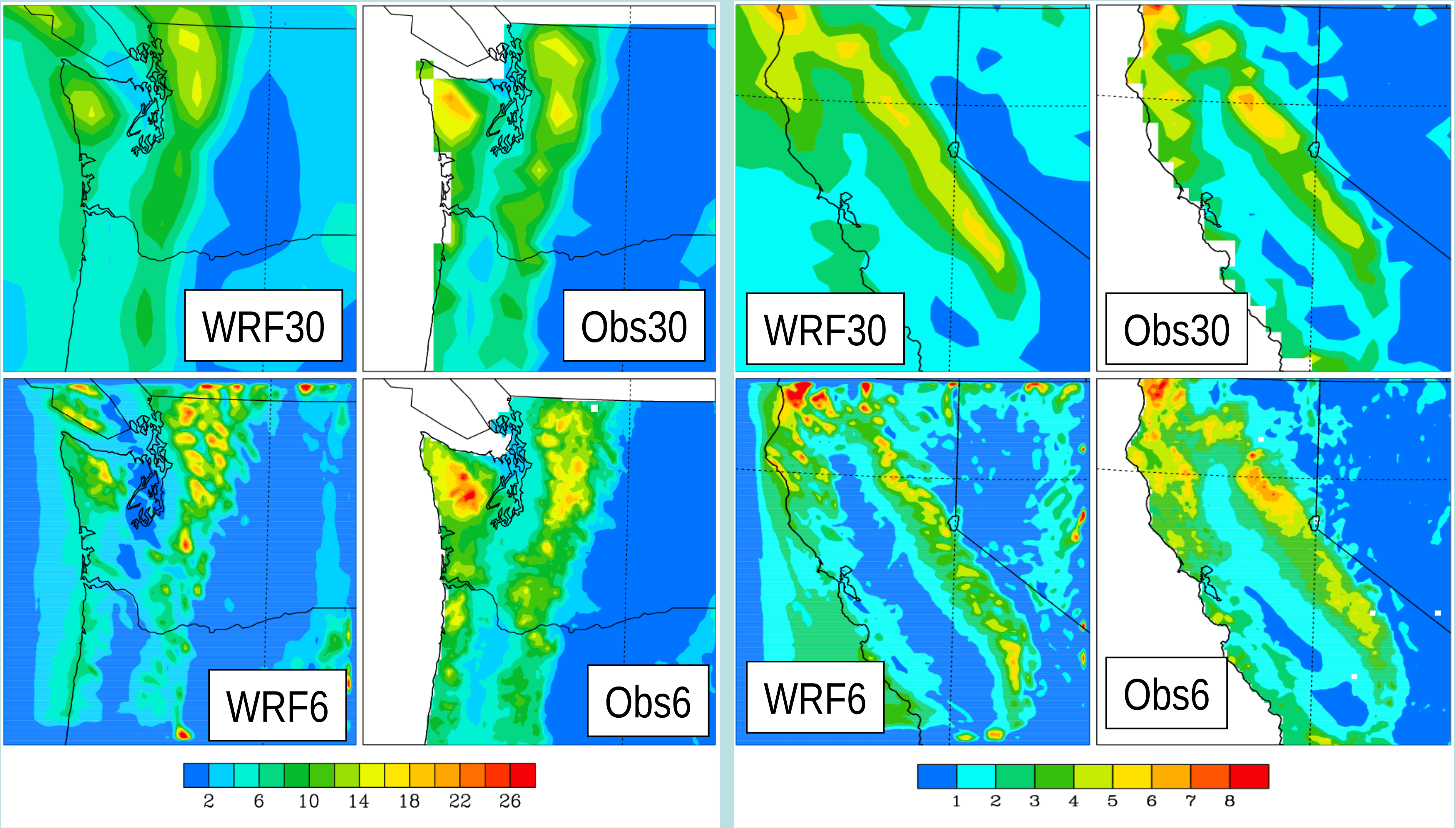
Cold Season Orographic Precipitation

Simulation of Cold Season Orographic Precipitation

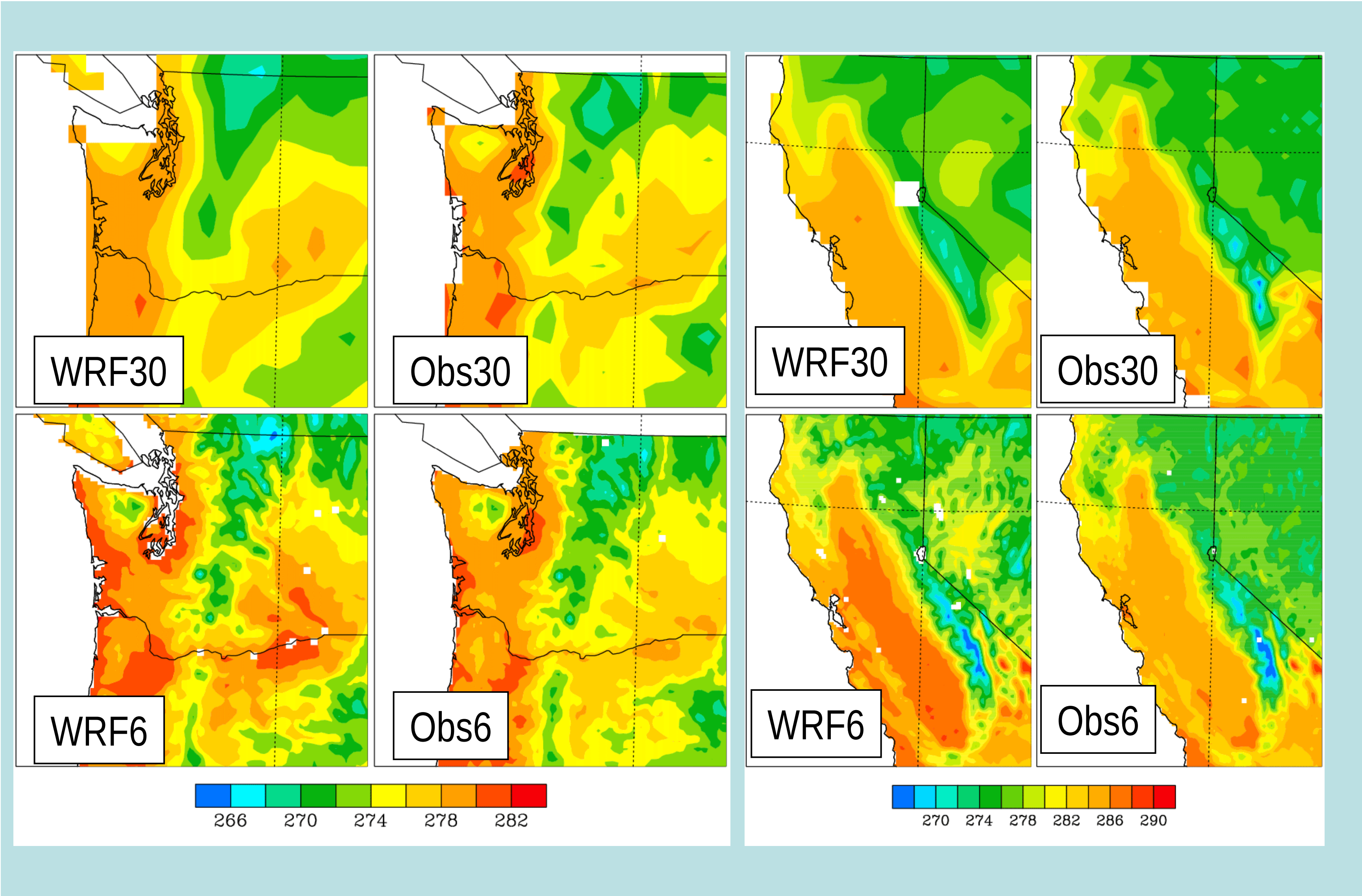
- Large domain at 30 km resolution (WRF30) driven by NCEP/NCAR reanalysis
- One-way nesting applied to two nested domains at 6 km resolution (WRF6)
- Simulation period: 10/1/1990 – 3/31/1991



Mean Precipitation (mm/day)

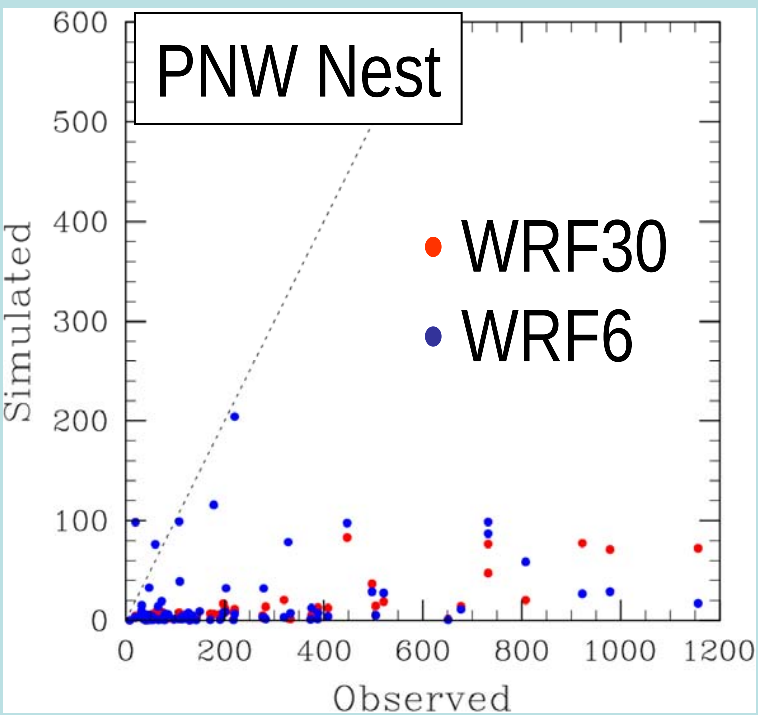


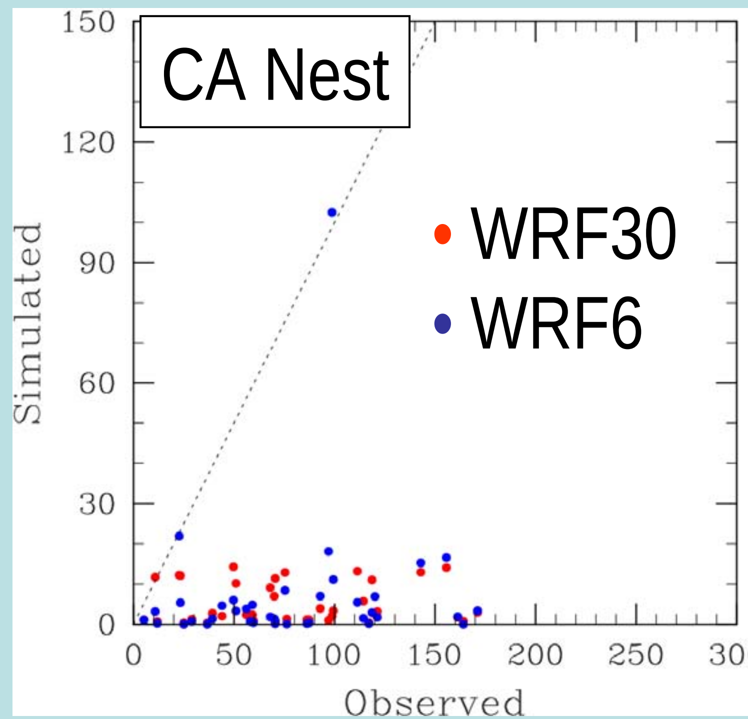
Mean Surface Temperature (C)



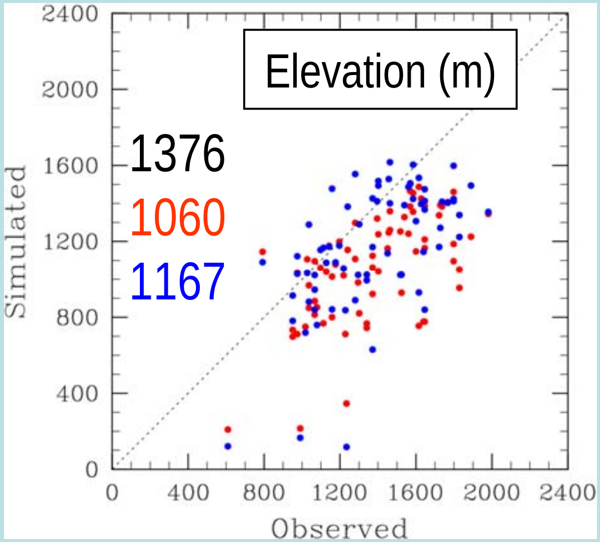
Mean Snowpack

- Comparison of snowpack at snotel sites
- Snowpack is severely under-predicted at both resolutions





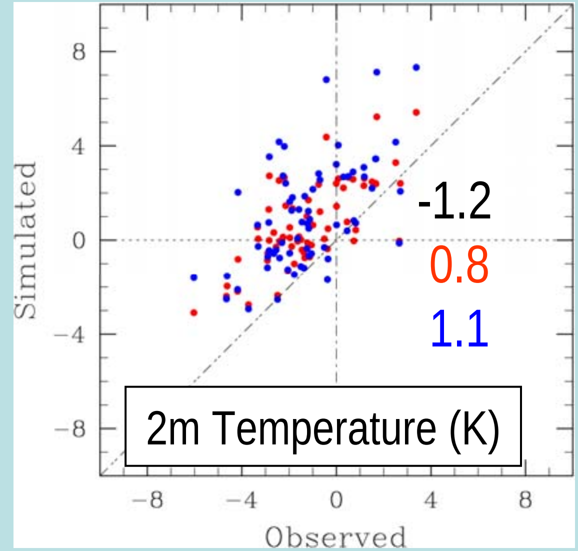
Why snowpack simulation is so poor?

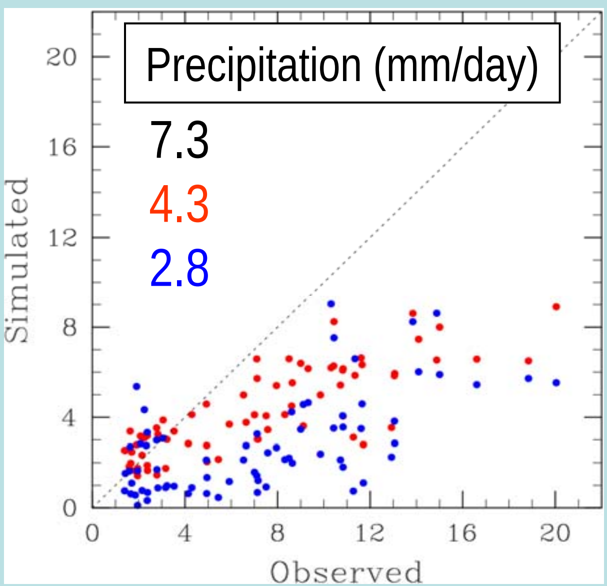


← Low Bias

• WRF30
• WRF6

Warm Bias →





← Dry Bias

(Similar biases using WSM 6-class microphysics)

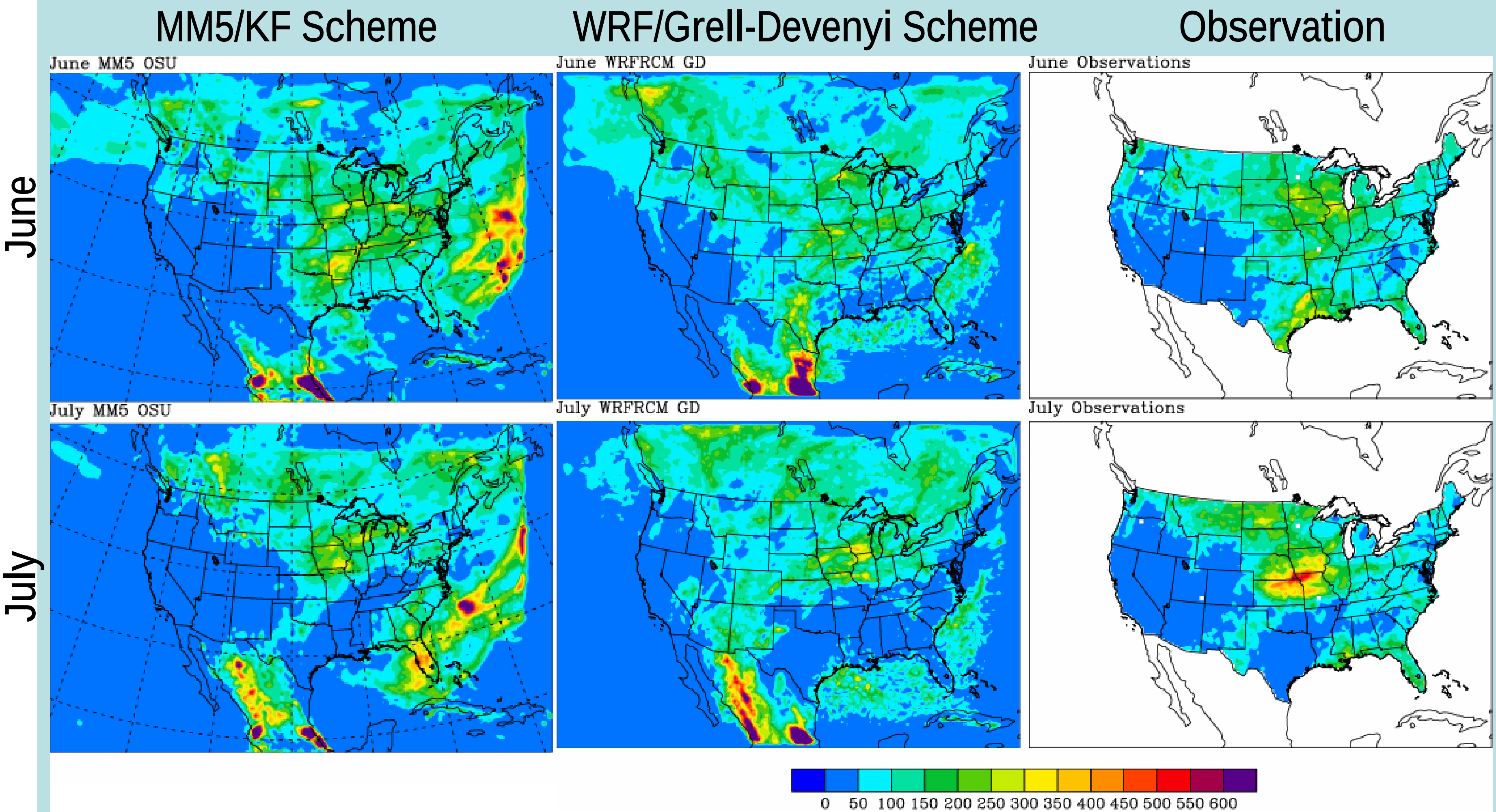
- Dependent on land surface model
- Good snowpack simulation requires accurate surface temperature prediction near the snowline

Does higher resolution improves climate simulation in mountainous regions?

- Realistic finer scale precipitation and surface temperature structure
- Improved orographic shadowing effect
- Increased warm bias over the basins
- Substantial increase in snowpack over the highest terrain only
- Results not sensitive to cloud microphysics parameterizations
- In contrast to MM5, regional mean precipitation decreases as spatial resolution increases (numerics differences?)

Simulation of the 1993 Flood Case

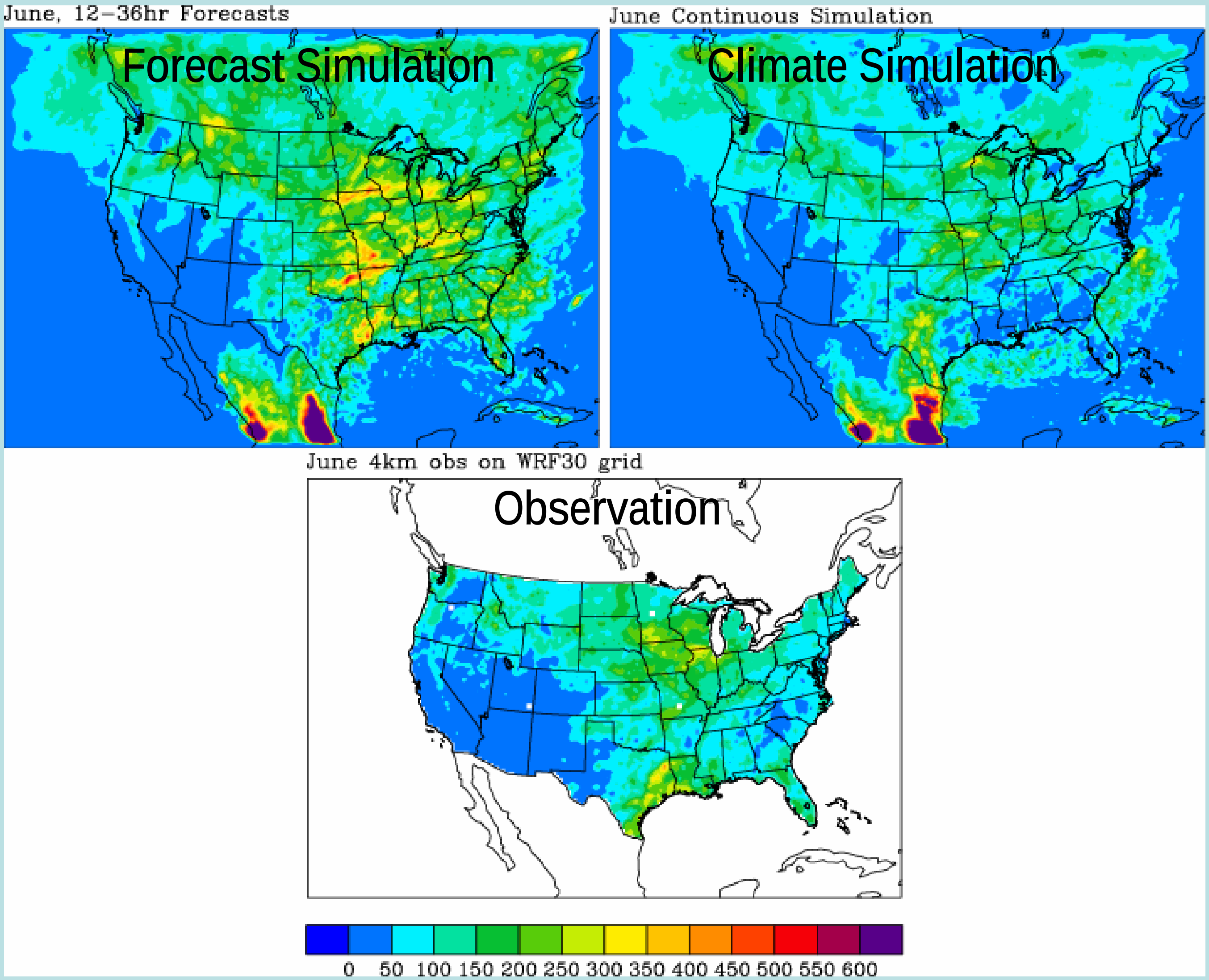
Observed/Simulated Rainfall in 1993



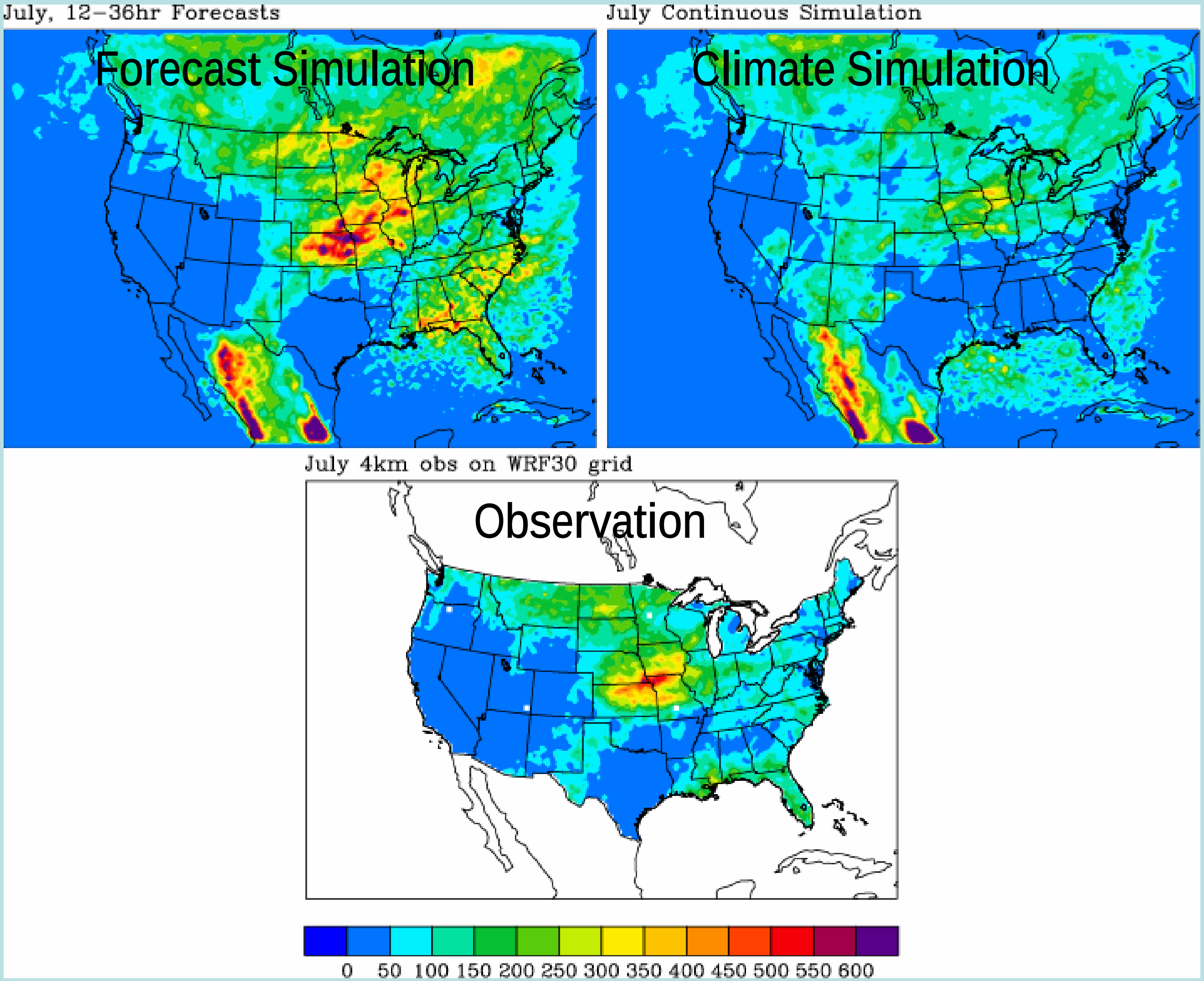
Forecast Experiment

- Forecast runs were initialized at 12 UTC each day and ran for 36 hours
- Results from 12 – 36 hours were analyzed
- Use same physics as in climate run
- Another set of forecast runs performed using initial soil moisture and temperature from climate run

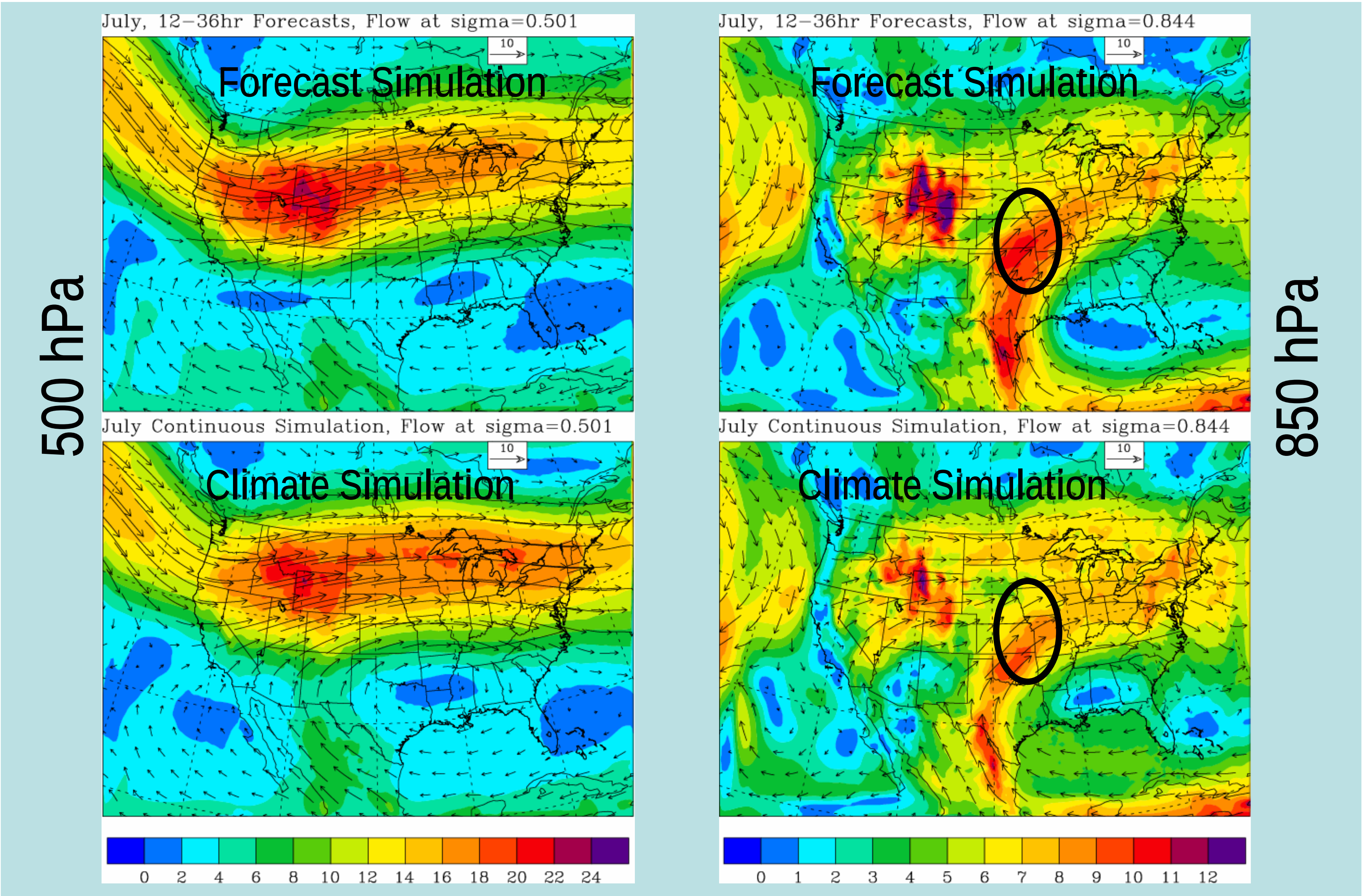
Monthly Precipitation (June)



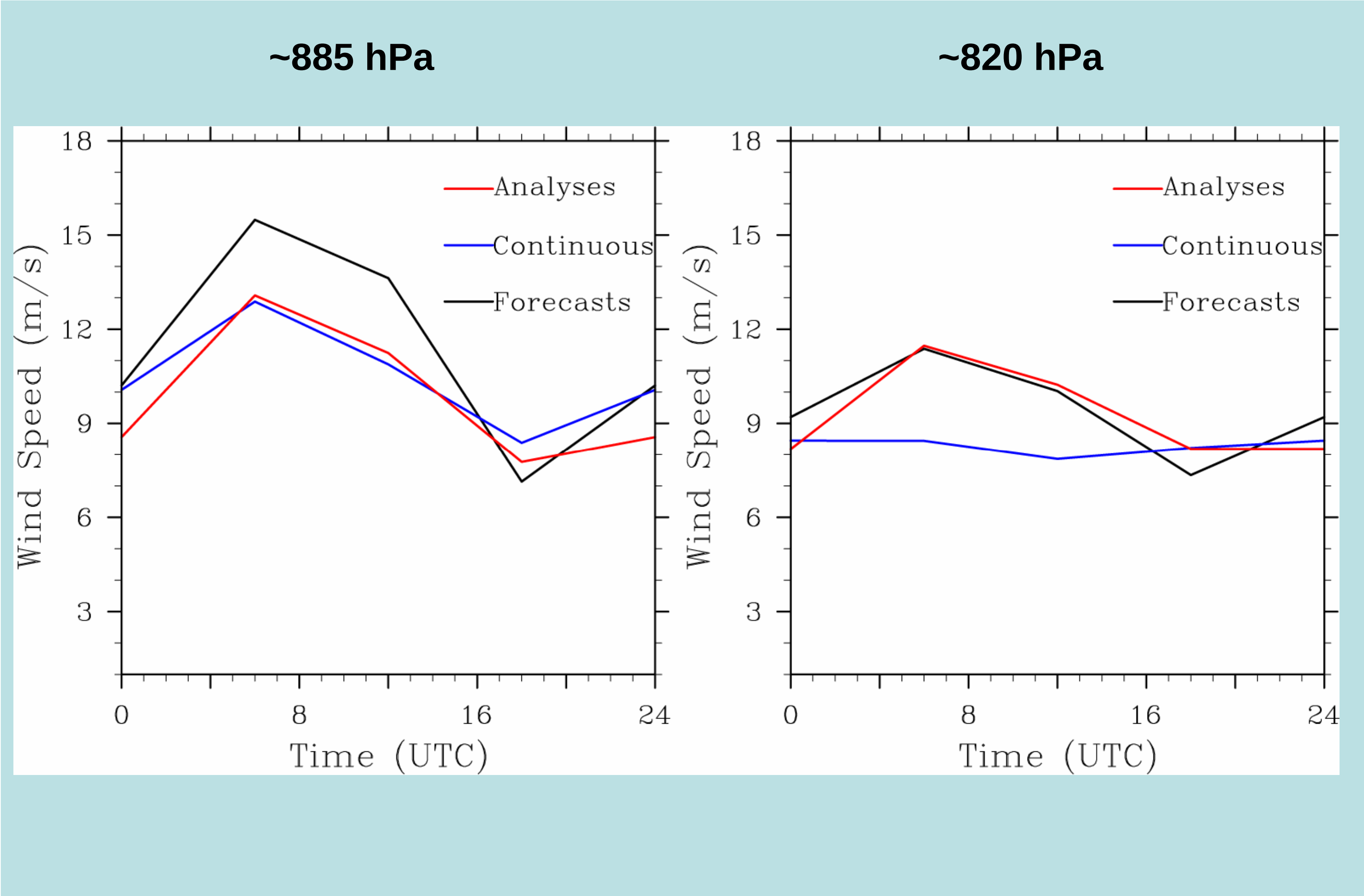
Monthly Precipitation (July)



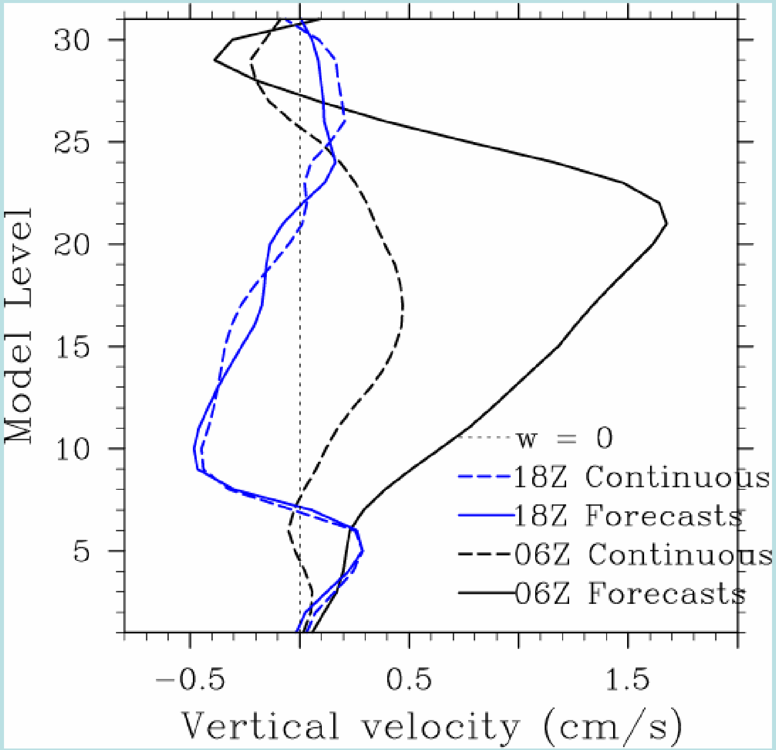
Monthly Winds (July)

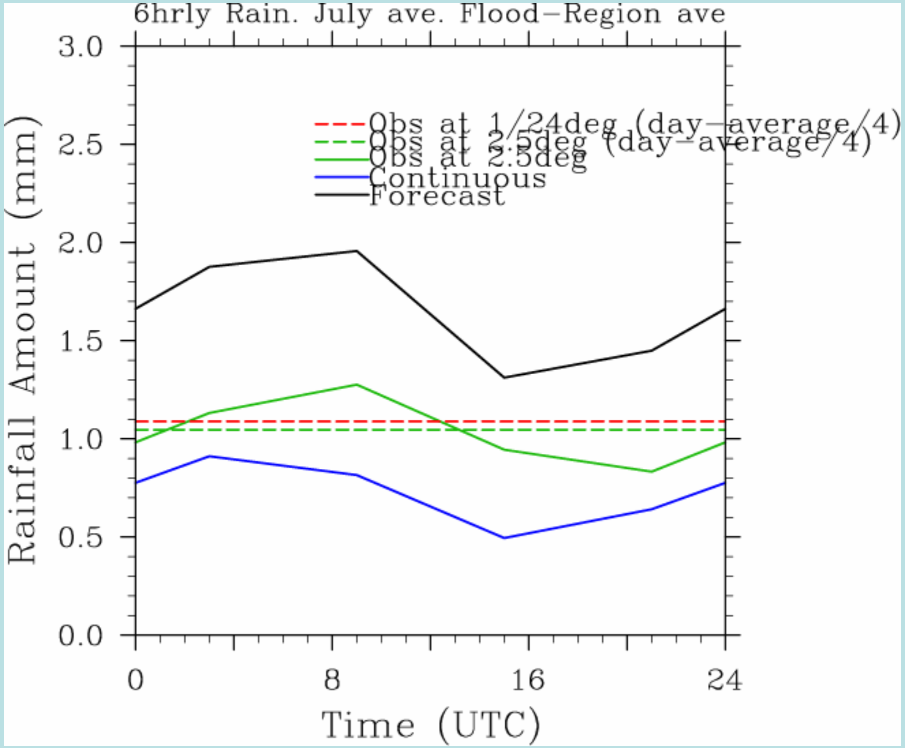


Diurnal Cycle of Winds (July)



Diurnal Cycle of Rainfall (July)





Sensitivity Simulations

Data	Convection	Land Model	Rainfall
WRF	GD	Noah LSM	97mm
WRF	BM	Noah LSM	97mm
WRF	KF	Noah LSM	80mm
WRF	GD	RUC LSM	91mm
MM5	KF	OSU LSM	95mm
WRF Fct	GD	Noah LSM	233mm
WRF Fct	GD	Noah LSM*	222mm
OBS(1/8^o)			165mm

Note: All simulations at 30 km resolution

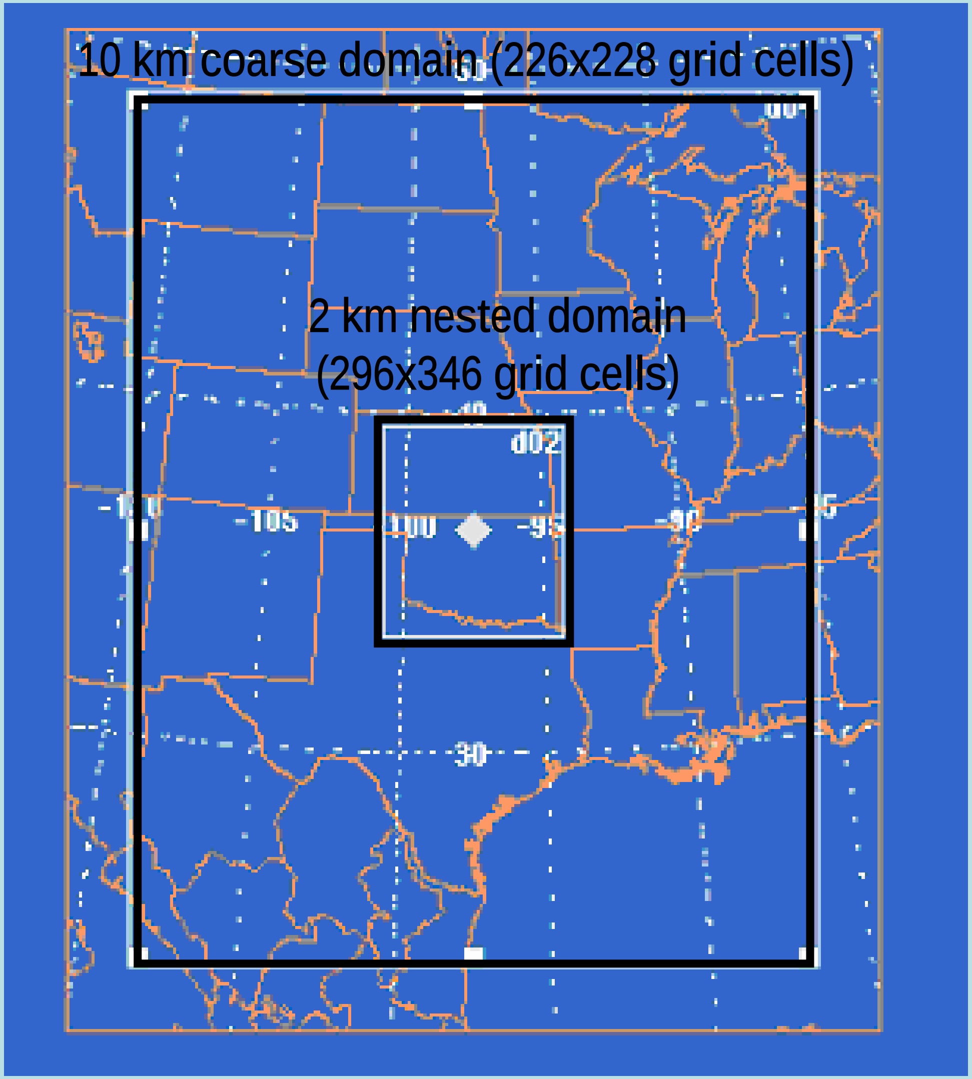
*Soil moisture based on climate runs

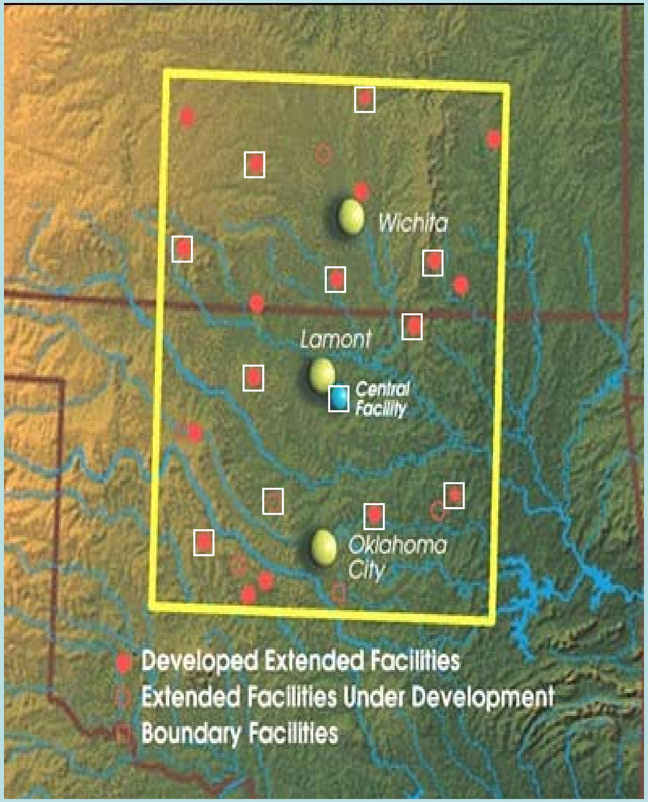
Summary

- All climate simulations (different convection schemes, land surface schemes, and initial land surface states) under-predict precipitation intensity in the central Great Plains during the 1993 flood
- Comparison of forecast and climate runs shows stronger and deeper nocturnal Low Level Jet (LLJ) and upper level flows in the forecast run
- Both climate and forecast runs correctly captured the nocturnal maxima in winds and rainfall
- Simulations were not too sensitive to convection schemes nor land surface initialization or parameterizations

Cloud Resolving Simulation

Evaluation of Cloud Resolving Simulation During IHOP 2002

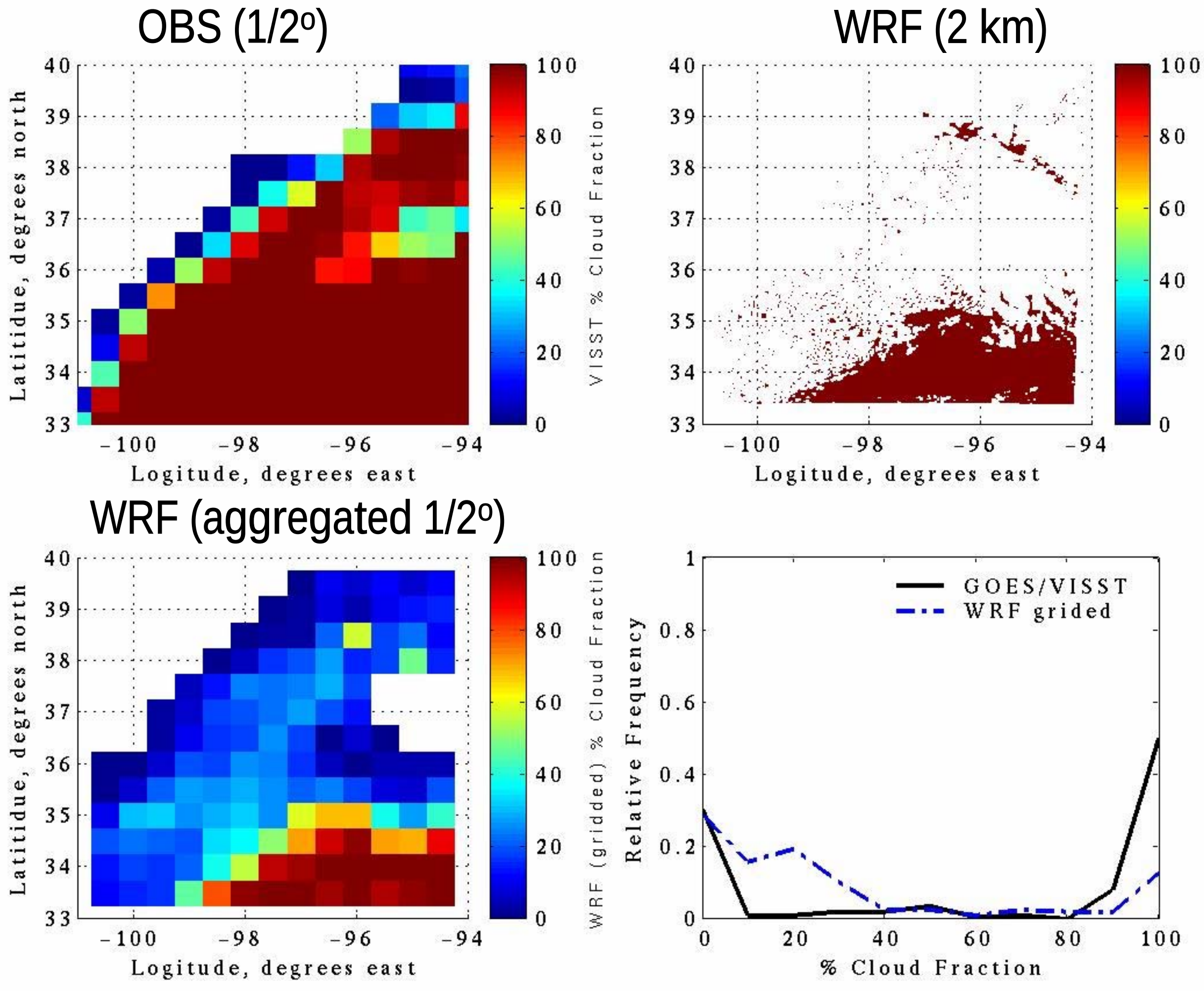




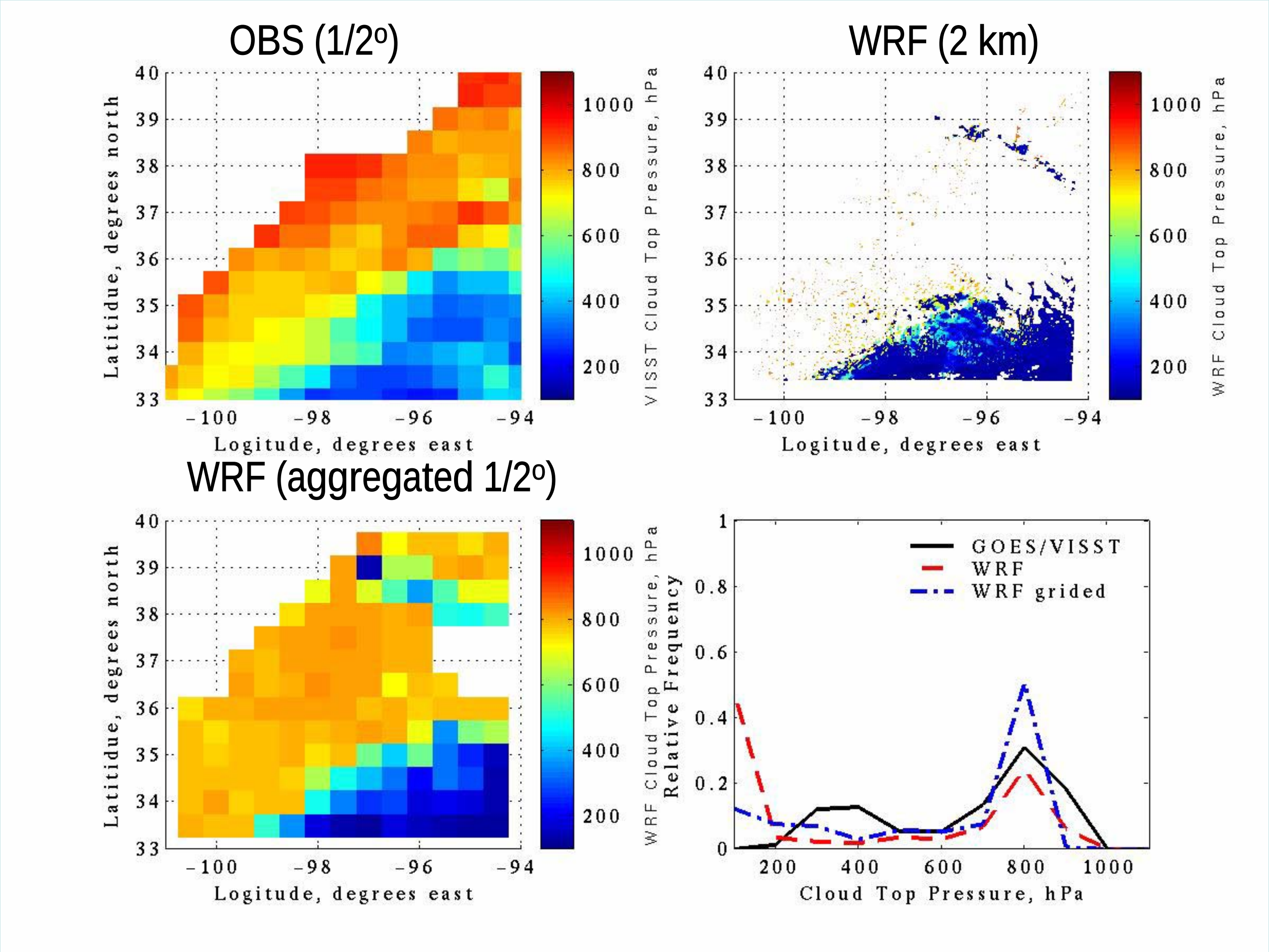
- ARM Extended Facilities
- EBBR Stations

Boundary conditions: North American Regional Reanalysis (32 km resolution)

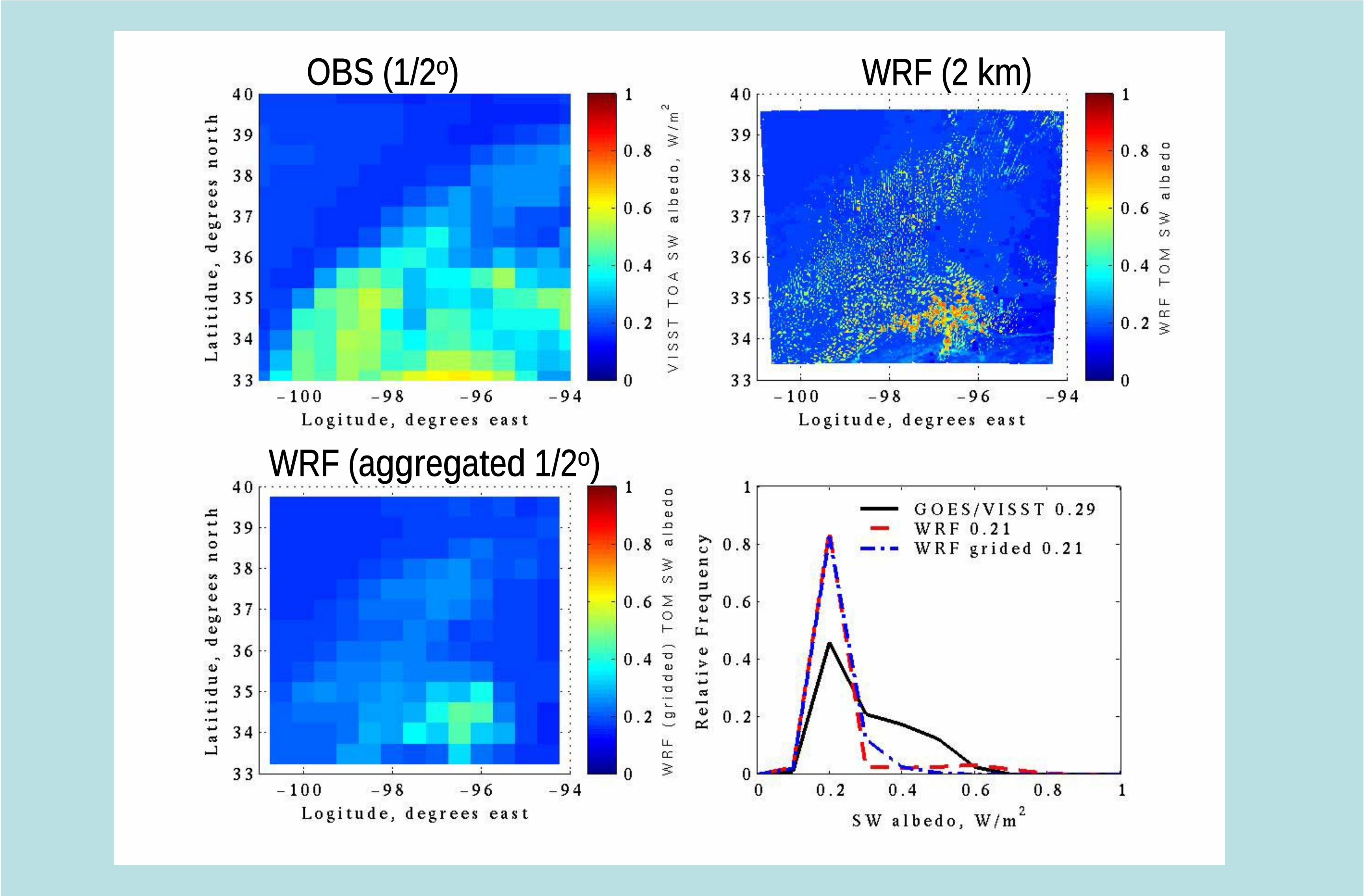
Cloud Fraction (6/30/2002 18Z)



Cloud Top Pressure (6/30/2002 18Z)

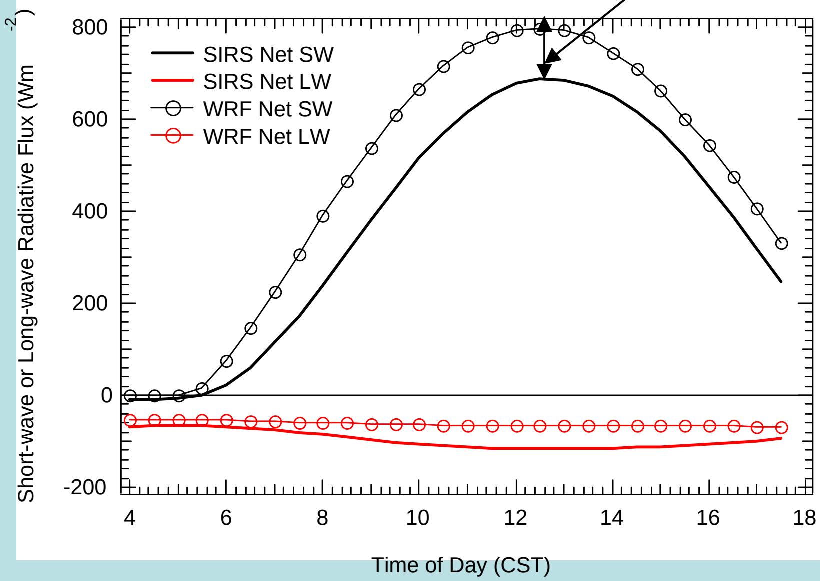


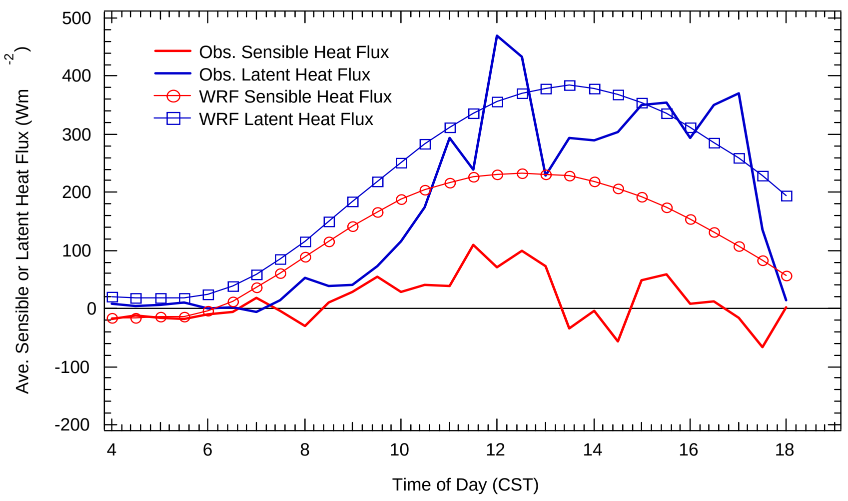
TOA SW Albedo (6/30/2002 18Z)



Comparison of Surface Fluxes

~180 W/m^2 difference





Summary

- The WRF clouds are less organized spatially compared to the ISCCP retrievals and generally not enough low clouds
- The WRF high (ice) clouds are optically too thin
- As a result, WRF SW albedo is too low (0.21 vs 0.26) and OLR is about 2 W/m^2 too high
- This leads to large bias in surface fluxes (LH and SH) of about 180 W/m^2 too high
- Running WRF as a cloud resolving model can be useful in diagnosing deficiency in physics parameterizations

Summary

- WRF has comparable features (treatment of boundary conditions, nesting, physics parameterizations) to MM5 that has been widely used in regional climate modeling
- WRF is better suited for high resolution and cloud resolving simulations than MM5
- WRF has comparable skill in simulating cold season orographic precipitation in the western U.S. and warm season precipitation in the central U.S.
- Physics parameterizations (radiation/land surface) compatible with CCSM has been implemented

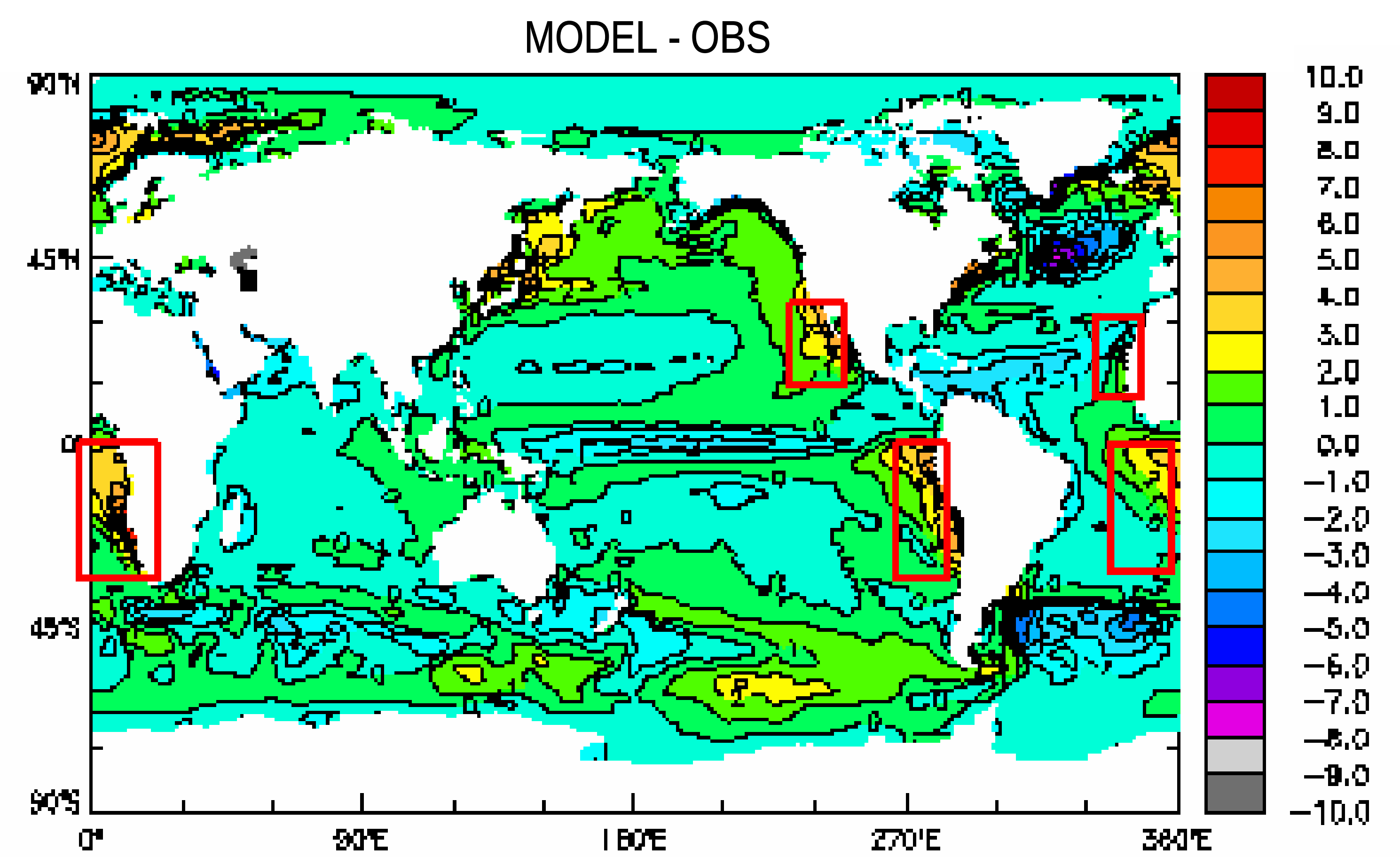
Summary

- The framework for WRF-CLM coupling may be extended to coupling with other models (e.g., ocean and sea ice)
- A preprocessor has been developed for downscaling application (one-way coupling with GCM)
- Need community involvement to further develop and test WRF for regional climate applications
- Need to prioritize model development based on science questions

Workshop on Research Needs and Directions of Regional Climate Modeling Using WRF and CCSM (March 22-23, 2005)

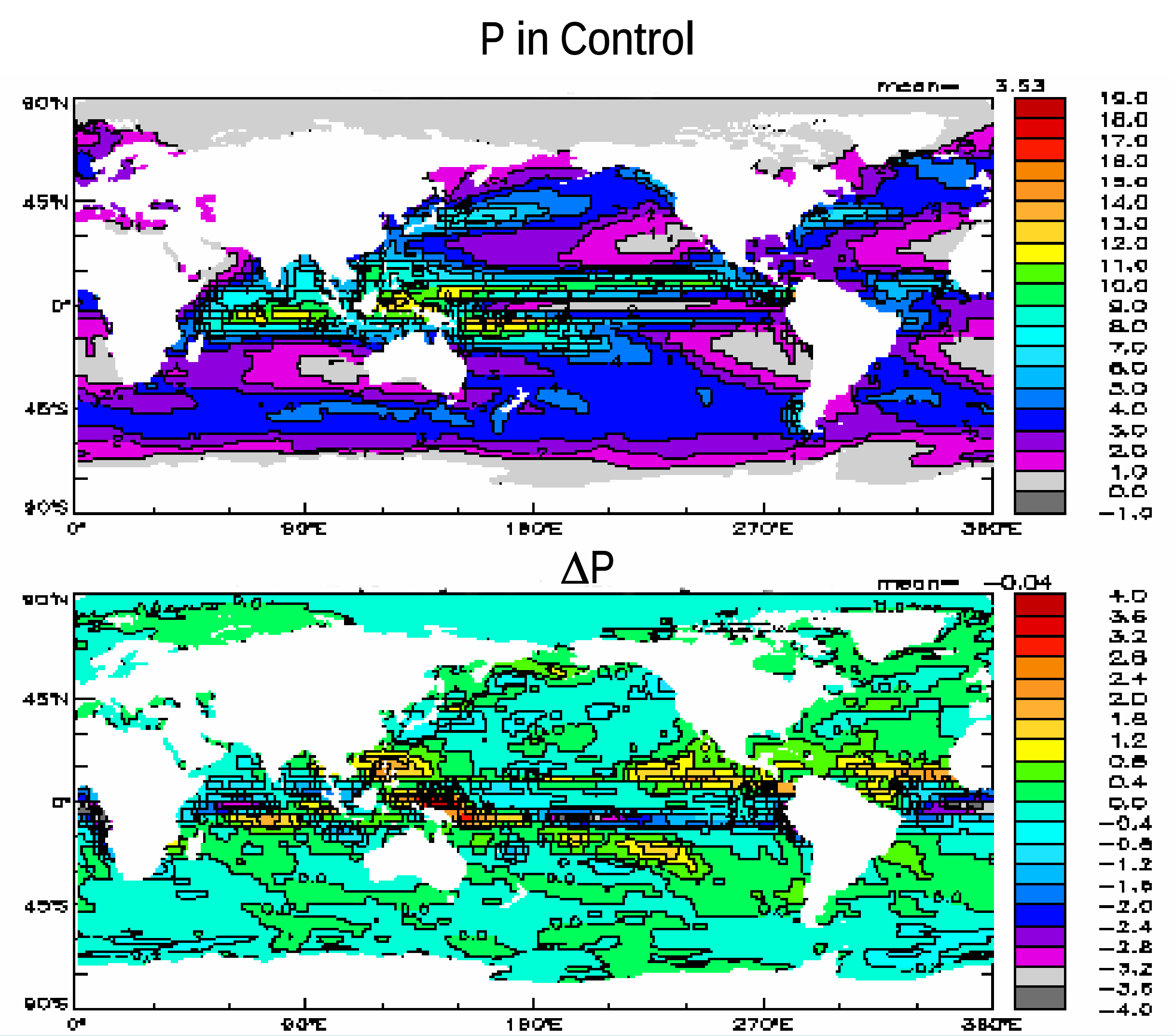
- Organizing committee: L. Ruby Leung, Bill Kuo, Joe Tribbia, Phil Merilees
- 60 US and international participants
- Define research needs for the development of a next generation community regional climate model based on WRF and CCSM
- Define upscaling and downscaling research that can be addressed by regional climate models
- Develop a plan of actions that would meet the research needs

CCSM2 SST Bias



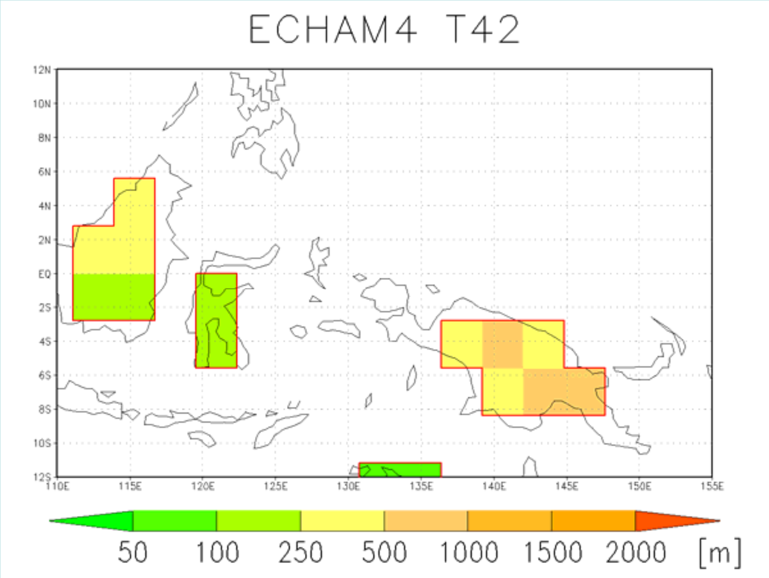
Large and Danabasoglu 2005

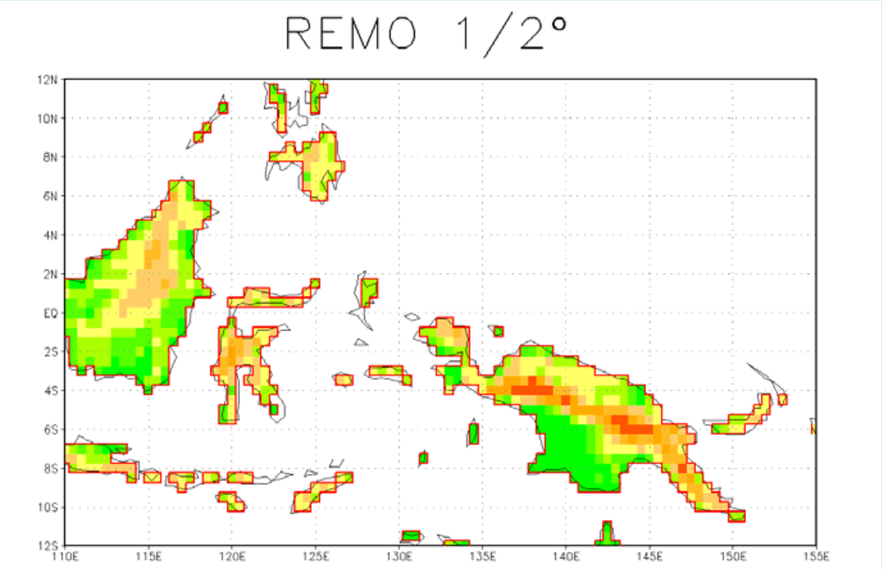
Large-Scale Effects of ΔSST < 0 off South America and South Africa



Two-Way Nested Domains

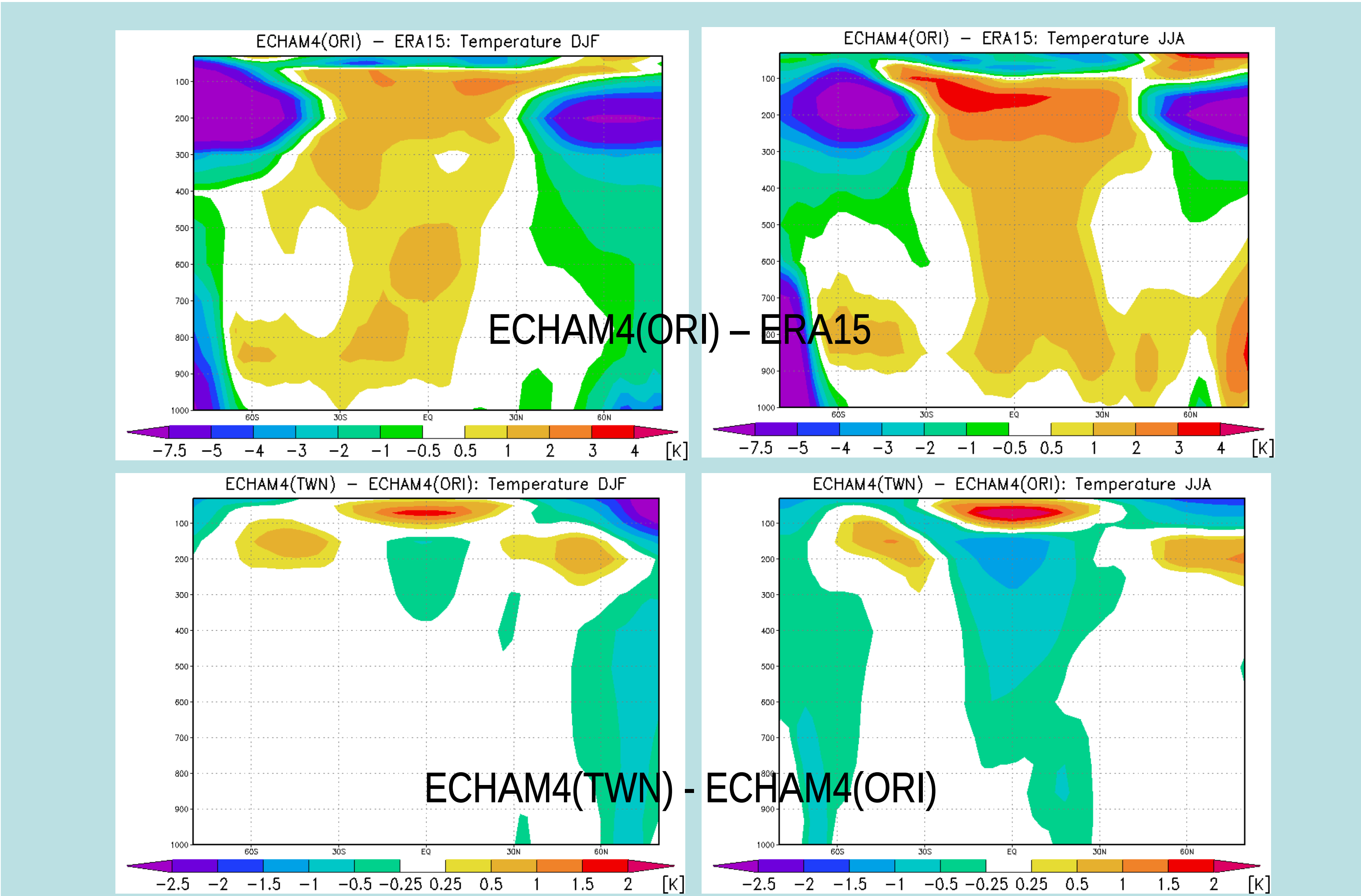
A 10-year simulation with two-way nesting over the Western Pacific regional "Warm Pool"





Lorenz and Jacob (2005)

Zonal Mean Temperature Difference



Recommendations/Future Directions

- Development of WRF towards a Regional Earth System Model – a comprehensive tool to address interdisciplinary science questions
- Exploit high resolution modeling capability of WRF - How to provide regional climate information for assessing societal impacts and managing resources; and examine how to efficiently capture scale interactions and their impacts?
- Develop two-way nesting capability in WRF and CCSM - How do local/regional processes affect the larger scale?

Proposed Modeling Framework

- WRF/ROMS (regional ocean modeling system) nested within CCSM with WRF interacting with ROMS and CAM, and ROMS interacting with WRF and POP (global ocean model)