CWRF Advances for NCEP Operational Use

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Brief NCEP

Acknowledgement

Collaborators

ISWS, NOAA/ARL, NCAR/MMM

Supercomputing Support

NOAA/ESRL, DOE/NERSC,
NCSA/UIUC, NCAR, NASA

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DOE, USDA/UVB, NSF, NASA

CWRF http://cwrf.umd.edu

Outline

- Why will RCM R&D continue?
- What is CWRF relative performance?
- How does CWRF solve challenges?
  - Scale/regime dependence
  - Physics configuration
  - Optimized physics ensemble
  - System uncertainty
- How much skill does CWRF enhance?
  - Weather forecast
  - Seasonal-Interannual climate prediction
  - Climate change and impacts national assessment
- What can CWRF advance NCEP operation?
  - Improved fine-scale weather/climate forecasts
  - Improved physics schemes for operational models

Q: Skeptical

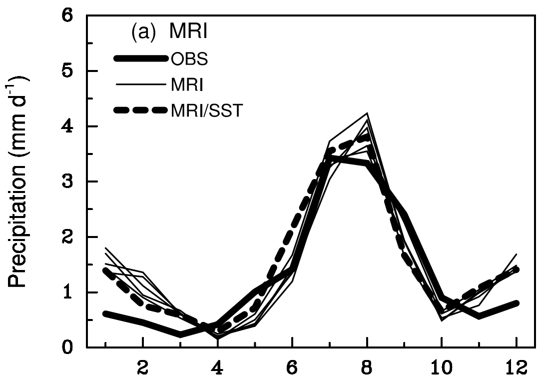
Supercomputing resource is sufficient for global model simulations at ultra-high resolution (~10 km)

Will the regional modeling effort be still worthy ?

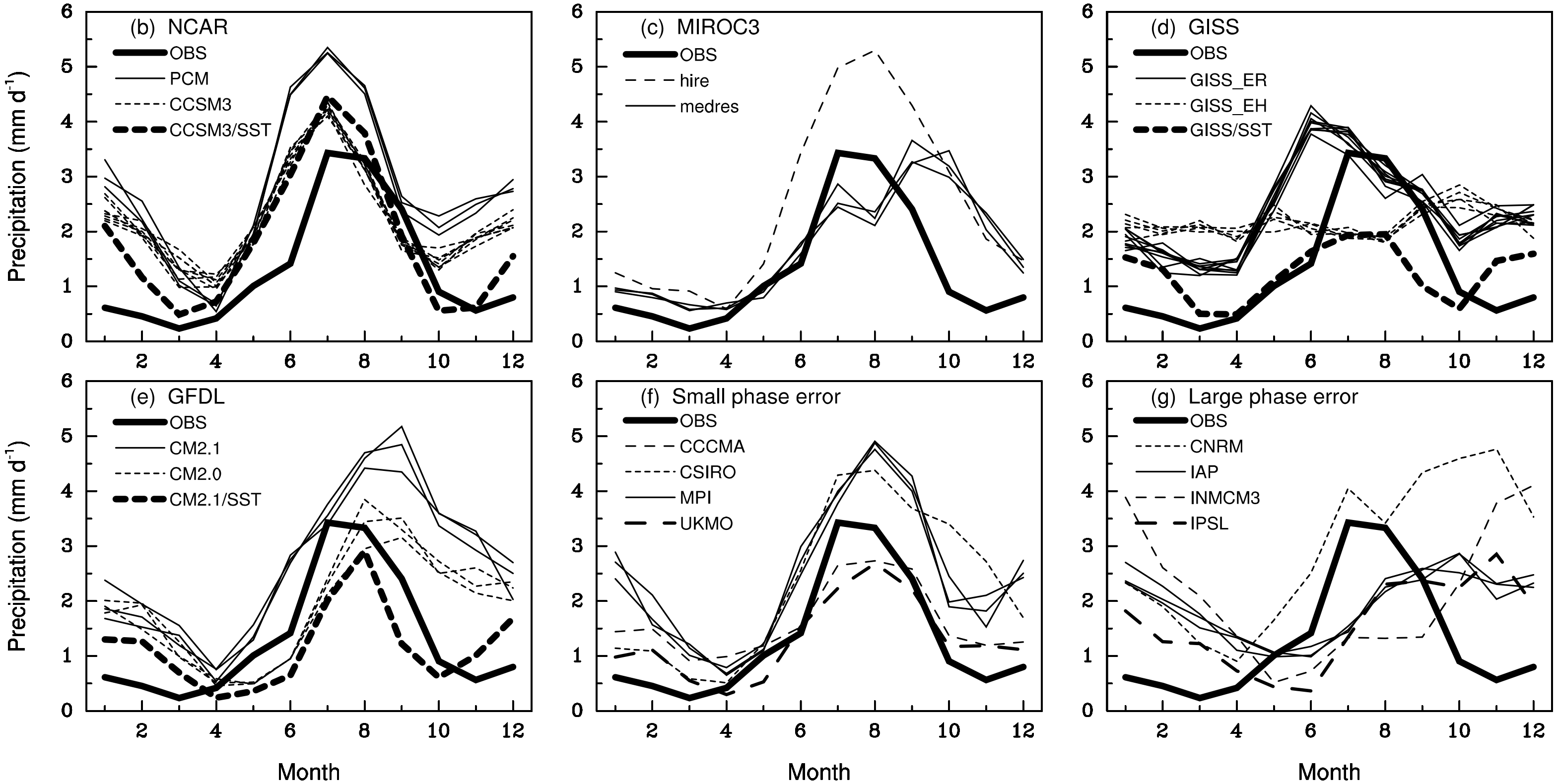
A: Absolutely!

- Physics enhancement—Necessary
  - Prolonged research & development
- System complexity—Ever increasing
  - Interdisciplinary model coupling
- Terrestrial characterization—More difficult
  - Comprehensive soil & canopy properties
- Impact study—Unlimited
  - Very specific of the application region
- RCM resolution—Further higher

Resolution Increase Does Not Solve All Problems



Only MRI with a medium resolution captures the observed NAM rainfall annual cycle. CCSM3 with higher resolution and updated physics reduces PCM amplitude error by half. MIROC3 finer resolution improves the phase but worsens the magnitude .



Liang, X.-Z., J. Zhu, K.E. Kunkel, M. Ting, and J.X.L. Wang, 2008: Do CGCMs simulate the North American monsoon precipitation seasonal-interannual variability? *J. Climate*, **21**, 4424-4448.

Physics Improvement is Critical

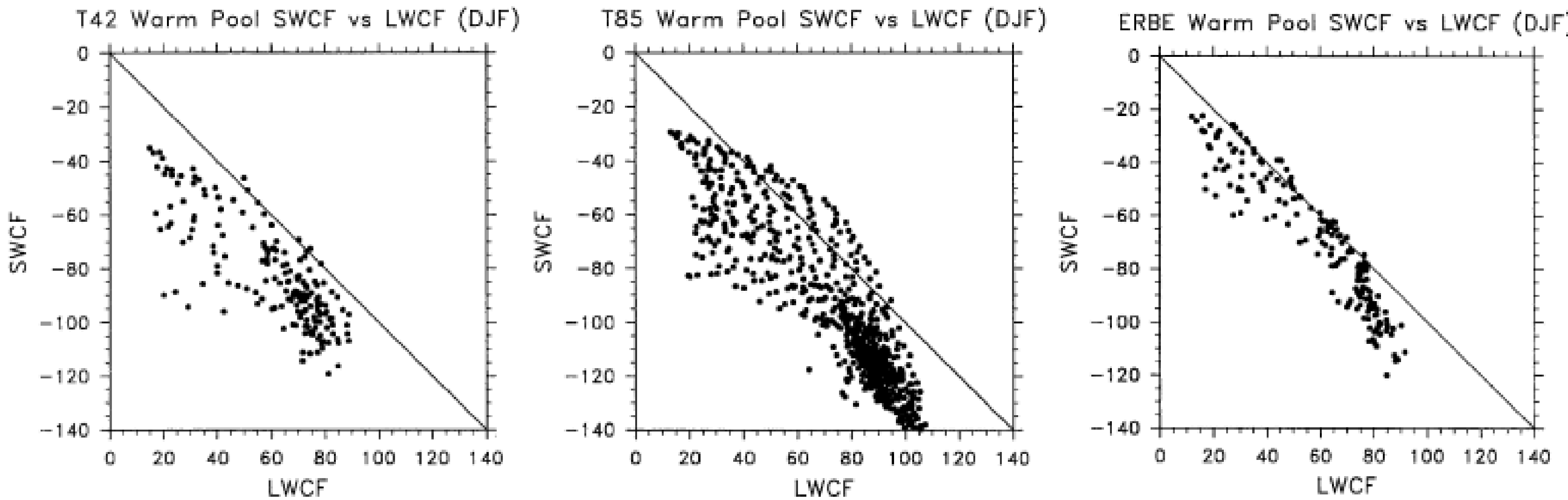
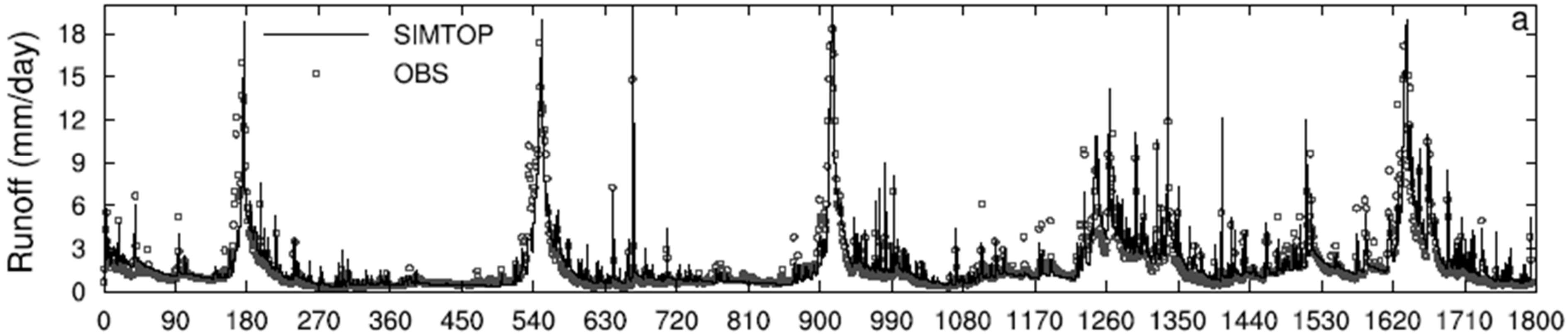
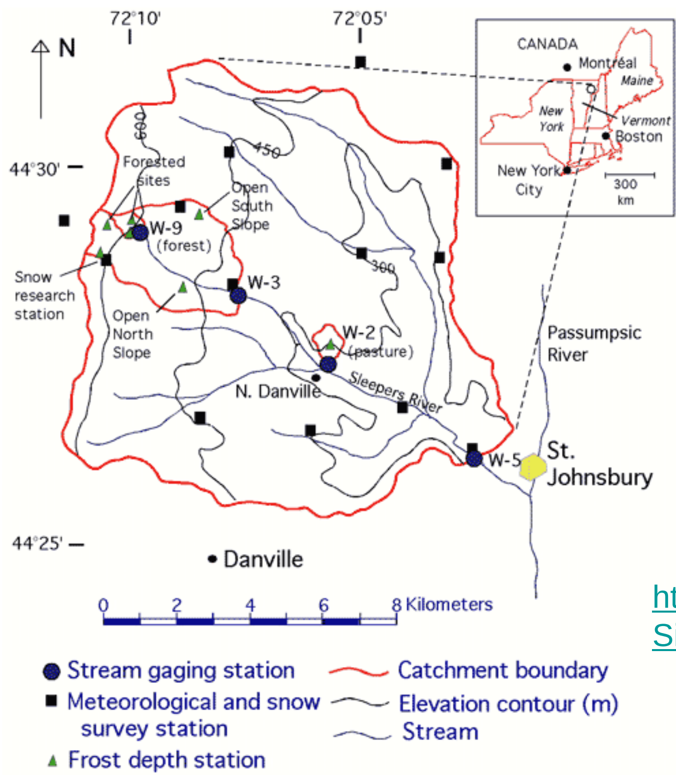


Fig. 3. Scatterplots showing shortwave vs longwave cloud forcing in the tropical west Pacific warm pool region for (left) the T42 CAM3, (middle) the T85 CAM3, and (right) ERBE.

CAM3 T42 closely simulates ERBE's strong linear correlation between SWCF and LWCF, but T85 exhibits a nonlinear correlation with a much greater range. This unrealistic cloud scheme in T85 will require additional research at the process level to better understand and improve.

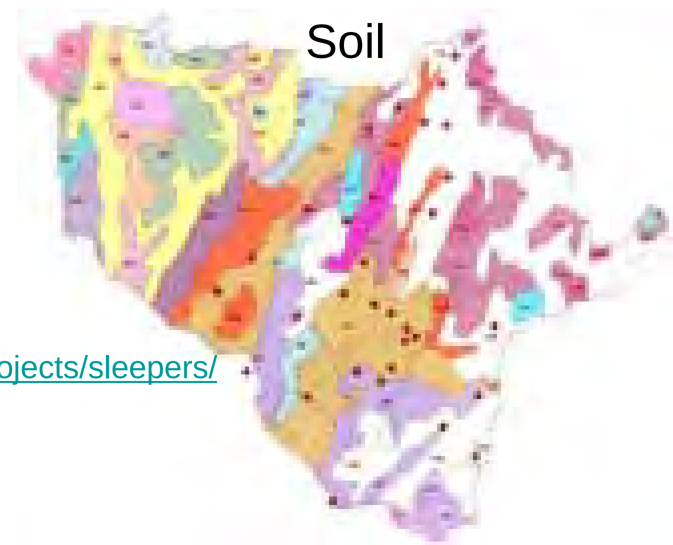
Hack, J.J., J.M. Caron, G. Danabasoglu, K.W. Oleson, C. Bitz, and J.E. Truesdale, 2006: CCSM–CAM3 climate simulation sensitivity to changes in horizontal resolution. *J. Climate*, **19**, 2267–2289.





Subcatchment W-3 (8.4 km^2) of the Sleepers River watershed (111 km^2), located in the highlands of Vermont, USA.

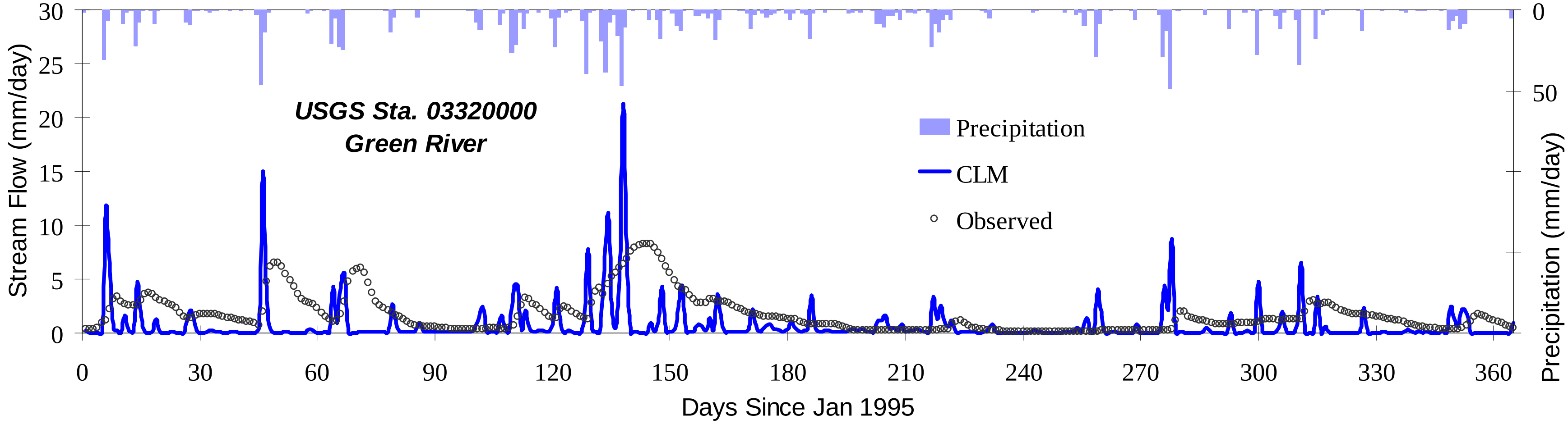
Soil

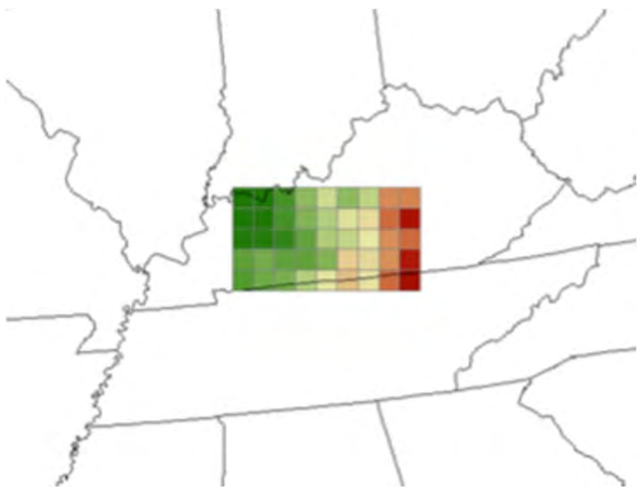


http://nh.water.usgs.gov/projects/sleepers/Site_Description.html

Niu, G.-Y., Z.-L. Yang, R.E. Dickinson, and L. E. Gulden, 2005: A simple TOPMODEL-based runoff parameterization (SIMTOP) for use in global climate models. *J. Geophys. Res.*, **110**, D21106, doi:10.1029/2005JD006111.

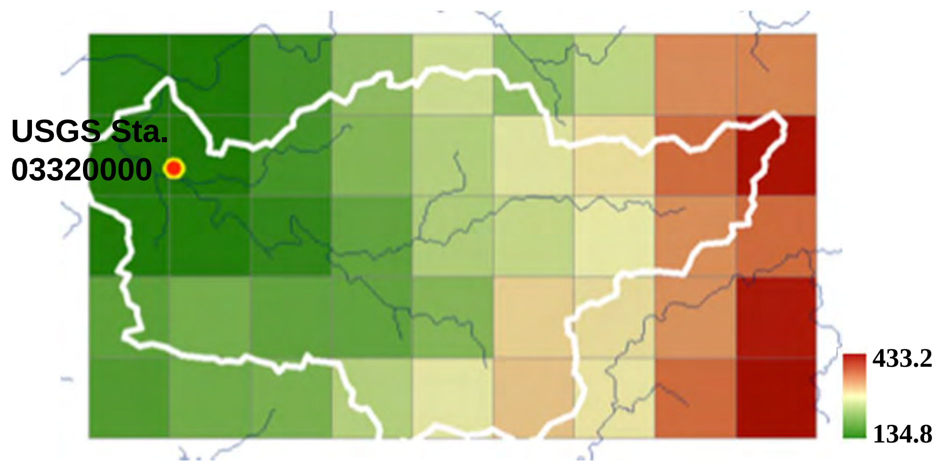
CLM Runoff Problem for CWRF 30-km





Study domain (15,623km^2)

Kentucky, USA



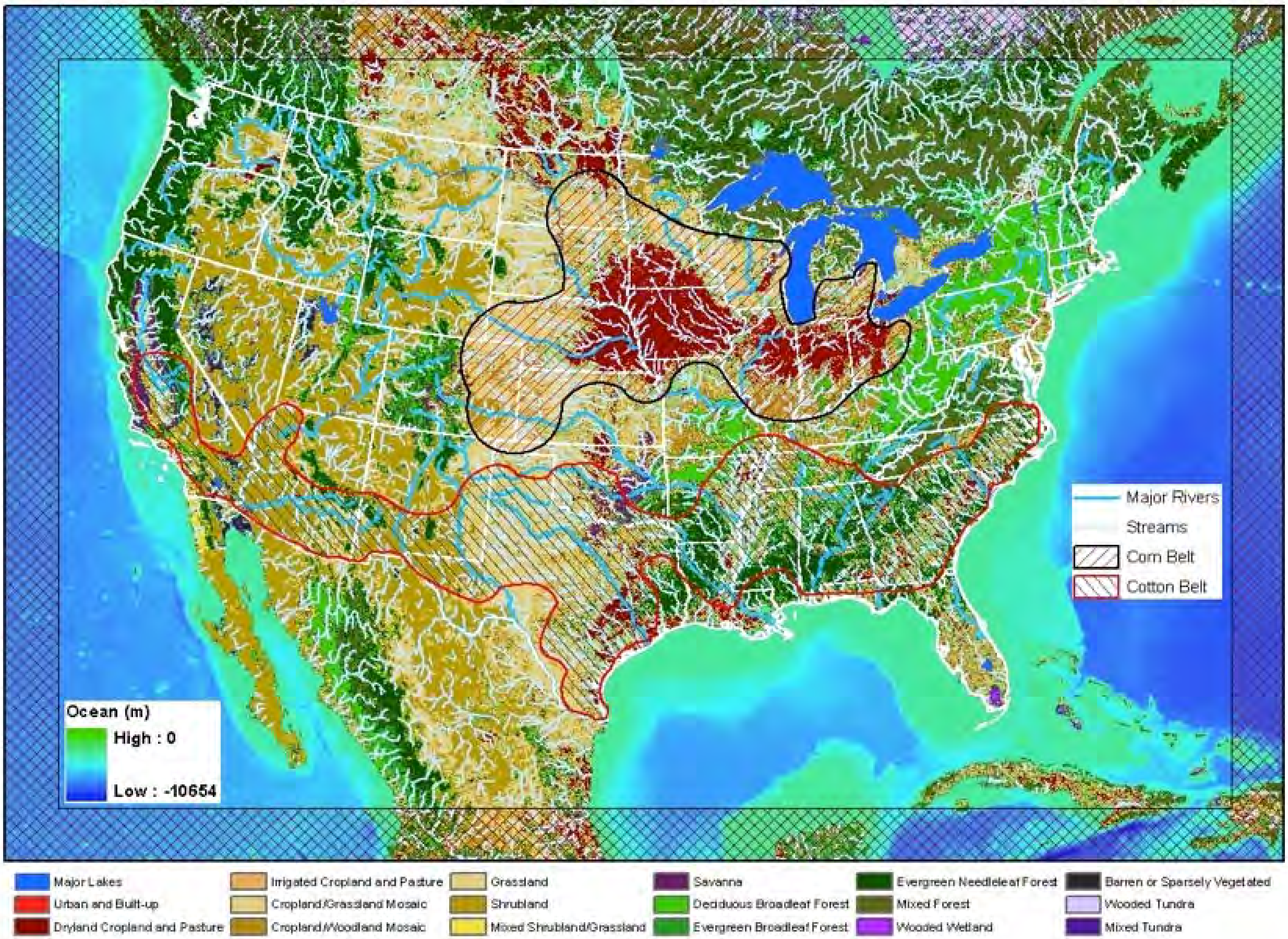
Green River Basin (white) overlaid with the HYDRO1K stream network (blue) and 30-km DEM (green-brown) on the 9×5 CWRF grids.

CWRF

Surface Boundary Conditions

Liang, X.-Z., H. Choi, K.E. Kunkel, Y. Dai, E. Joseph, J.X.L. Wang, and P. Kumar, 2005: Development of the regional climate-weather research and forecasting model (CWRF): Surface boundary conditions. *Illinois State Water Survey Scientific Report*, ISWS SR 2005-01, 32 pp.
http://www.sws.uiuc.edu/pubs/pubdetail.asp?CallNumber=ISWS+SR+2005%2D01

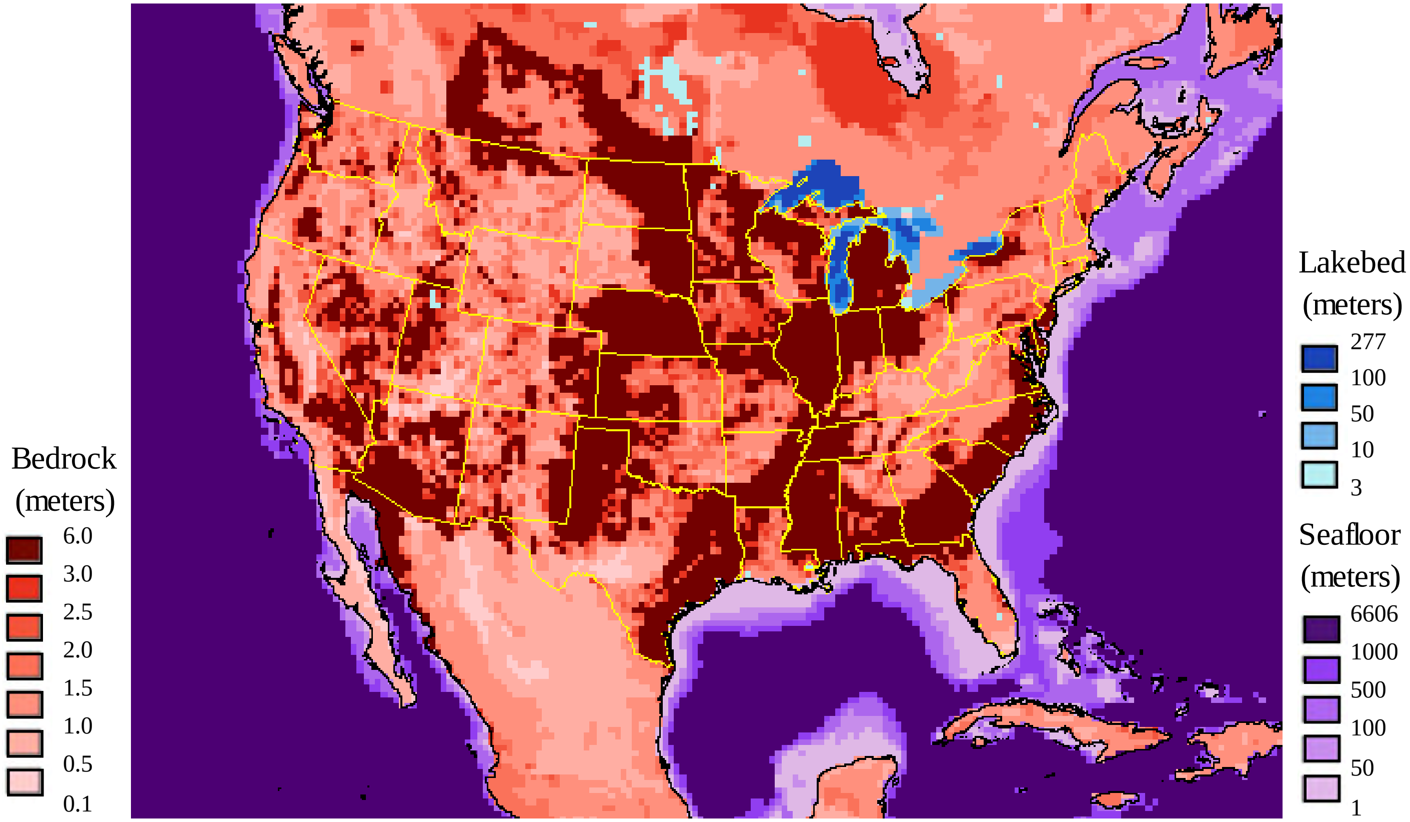
Liang, X.-Z., H. Choi, K.E. Kunkel, Y. Dai, E. Joseph, J.X.L. Wang, and P. Kumar, 2005: Surface boundary conditions for mesoscale regional climate models. *Earth Interactions*, **9**, 1-28.



Major Rivers
Streams
Corn Belt
Cotton Belt
Ocean (m)
High : 0
Low : -10654
Major Lakes
Urban and Built-up
Dryland Cropland and Pasture
Irrigated Cropland and Pasture
Cropland/Grassland Mosaic
Cropland/Woodland Mosaic
Grassland
Shrubland
Mixed Shrubland/Grassland
Savanna
Deciduous Broadleaf Forest
Evergreen Broadleaf Forest
Evergreen Needleleaf Forest
Mixed Forest
Wooded Wetland
Barren or Sparsely Vegetated
Wooded Tundra
Mixed Tundra

Demand for Terrestrial Characterization

Bedrock, Lakebed or Seafloor Depth (DBED)



Many key local characteristics are not available and difficult/expensive to measure. Their accurate specification, however, is the base to realize any gain from resolution increase and physics improvement.

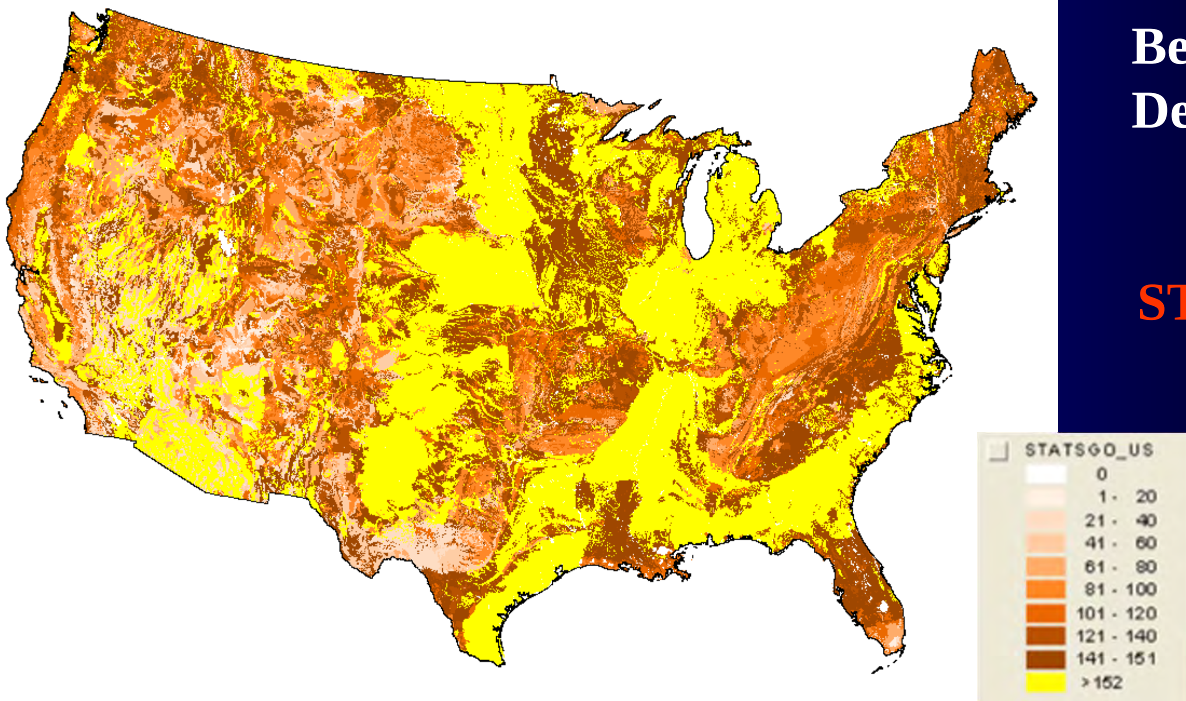
Liang, X.-Z., H. Choi, K.E. Kunkel, Y. Dai, E. Joseph, J.X.L. Wang, and P. Kumar, 2005: Surface boundary conditions for mesoscale regional climate models. *Earth Interactions*, **9**, 1-28.

Problems

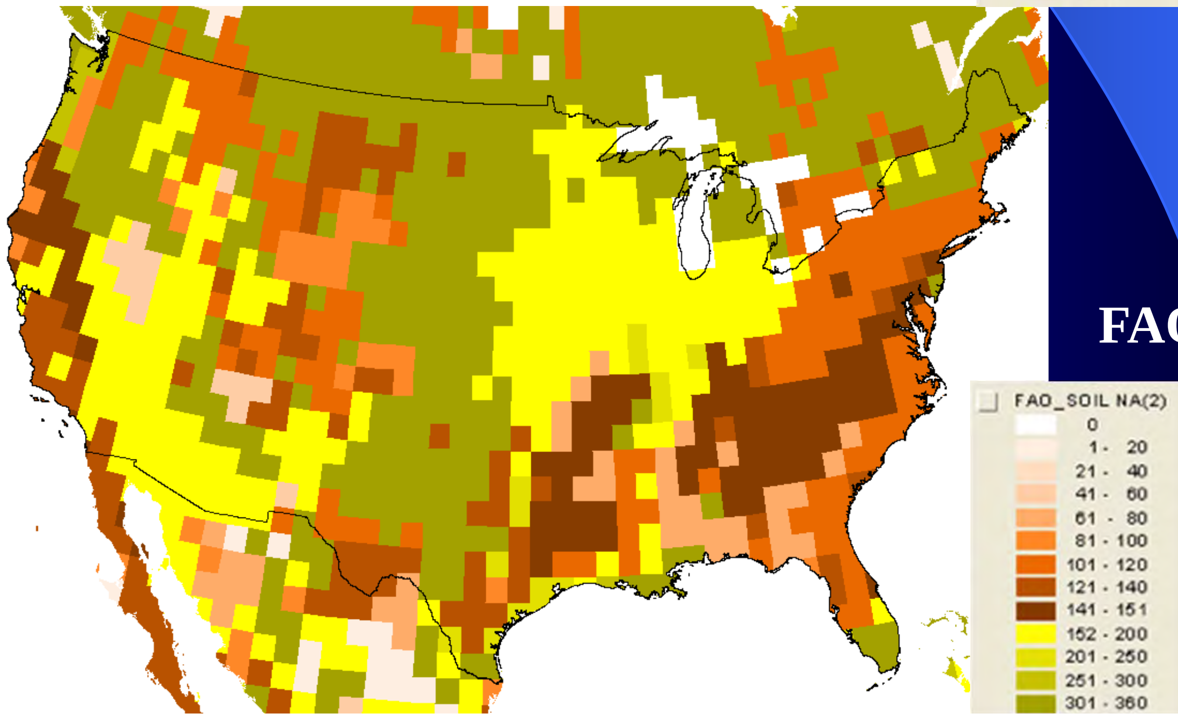
Soil Property

Bedrock Depth (cm)

STATSGO US



FAO SOIL

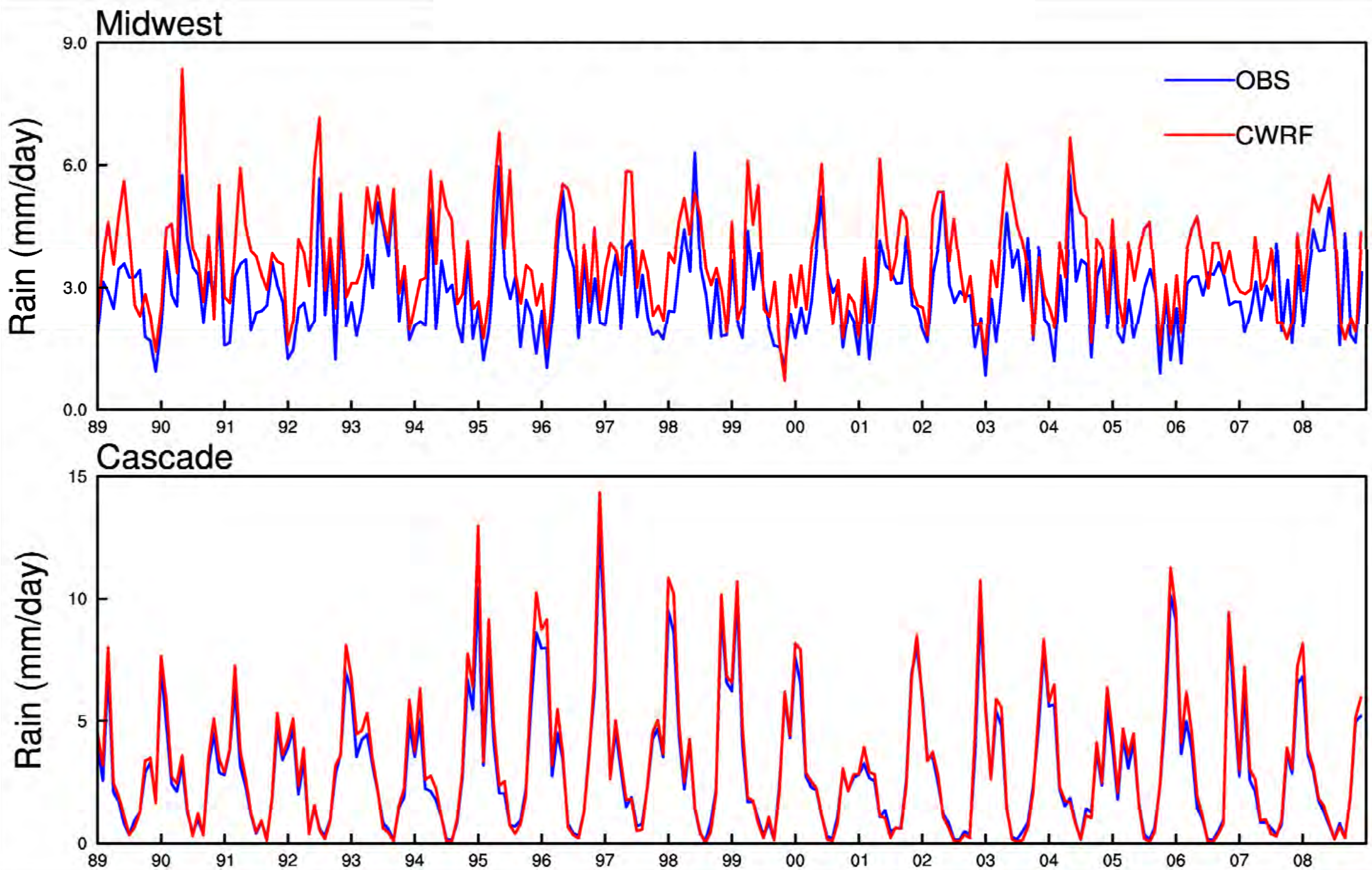


RCM Refinements

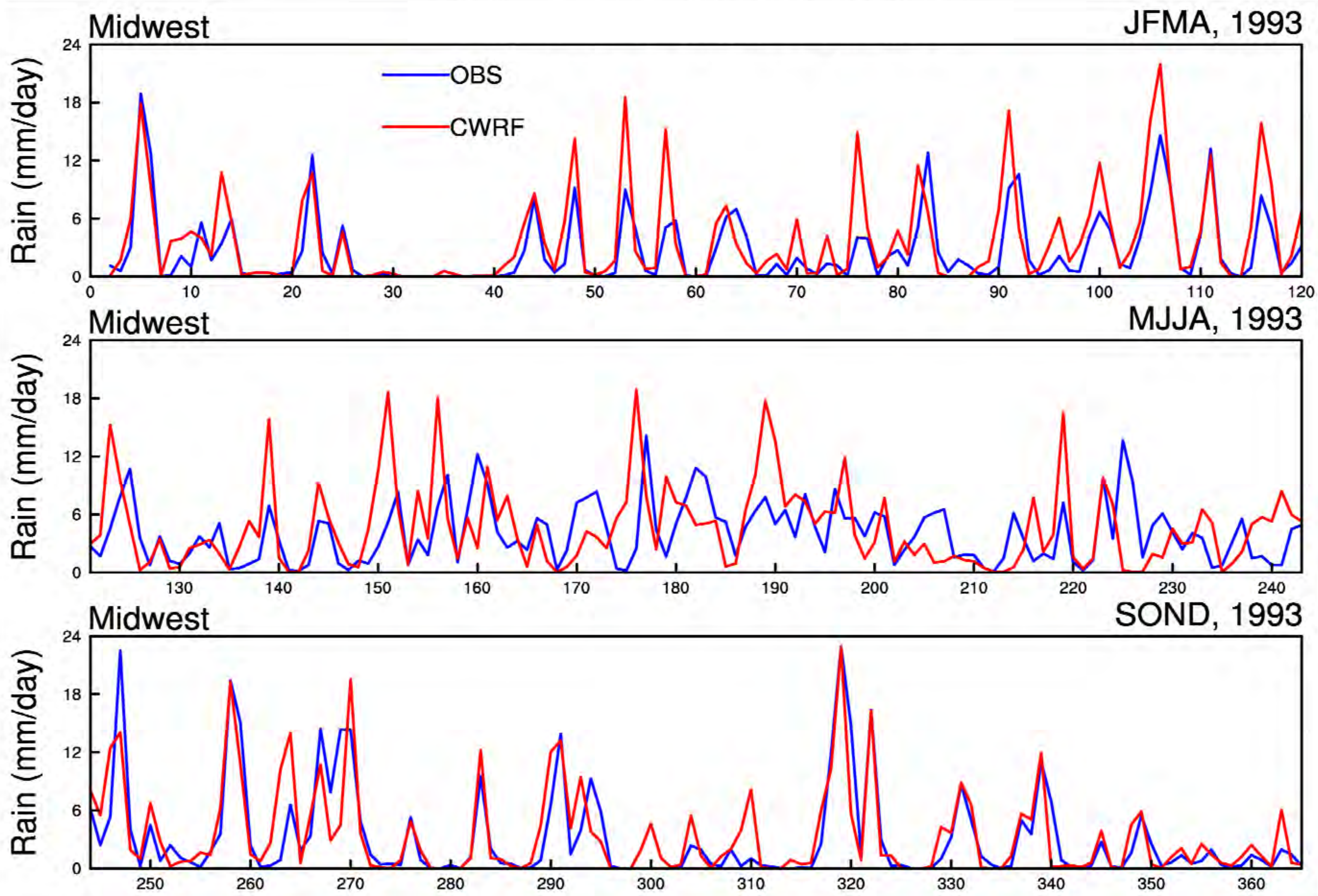
Improves GCM Predictions at Regional-Local Scales

http://cwrf.umd.edu CWRF

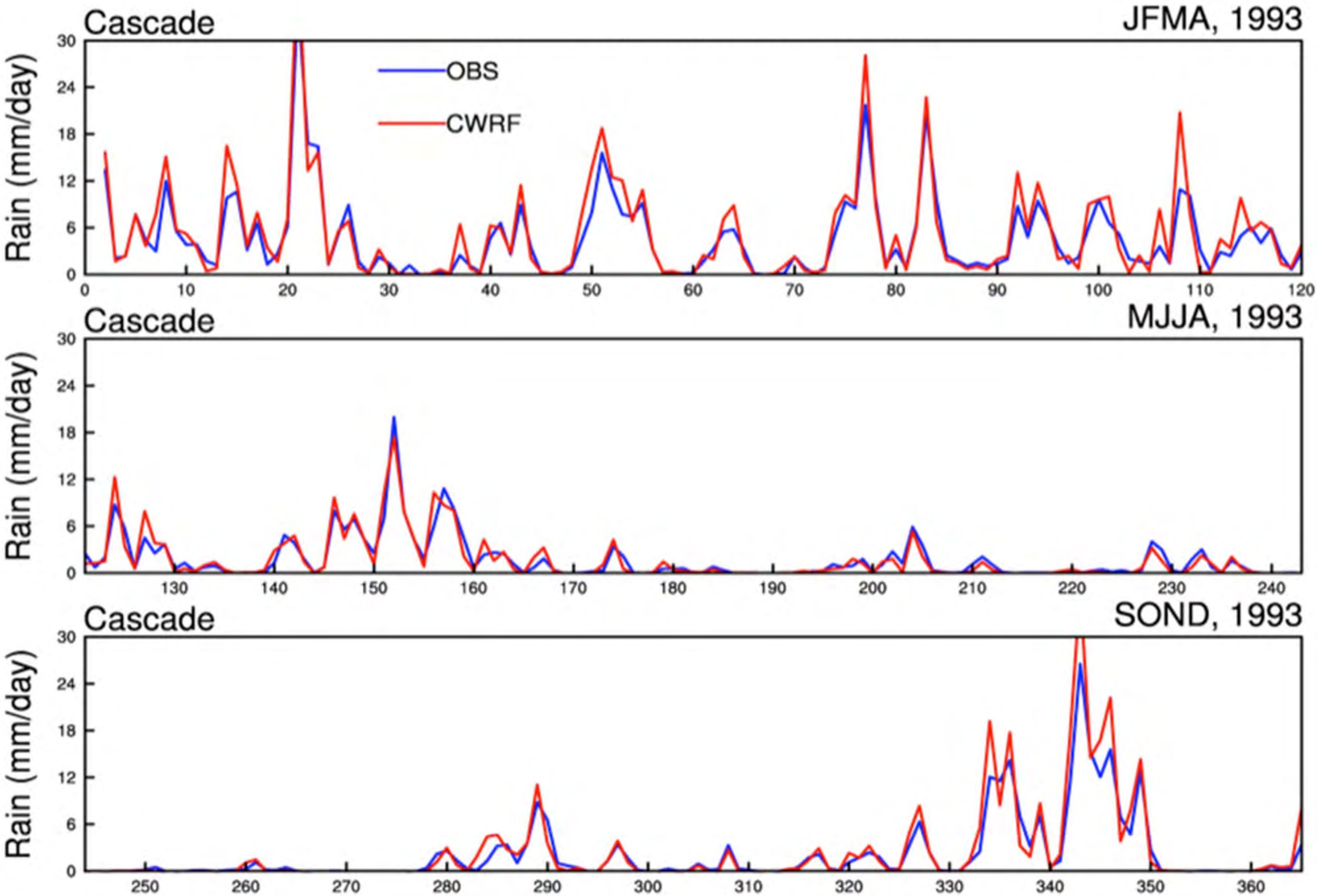
Monthly


Midwest
9.0
6.0
3.0
0.0
Rain (mm/day)
OBS
CWRF
89 90 91 92 93 94 95 96 97 98 99 00 01 02 03 04 05 06 07 08
Cascade
15
10
5
0
Rain (mm/day)
89 90 91 92 93 94 95 96 97 98 99 00 01 02 03 04 05 06 07 08

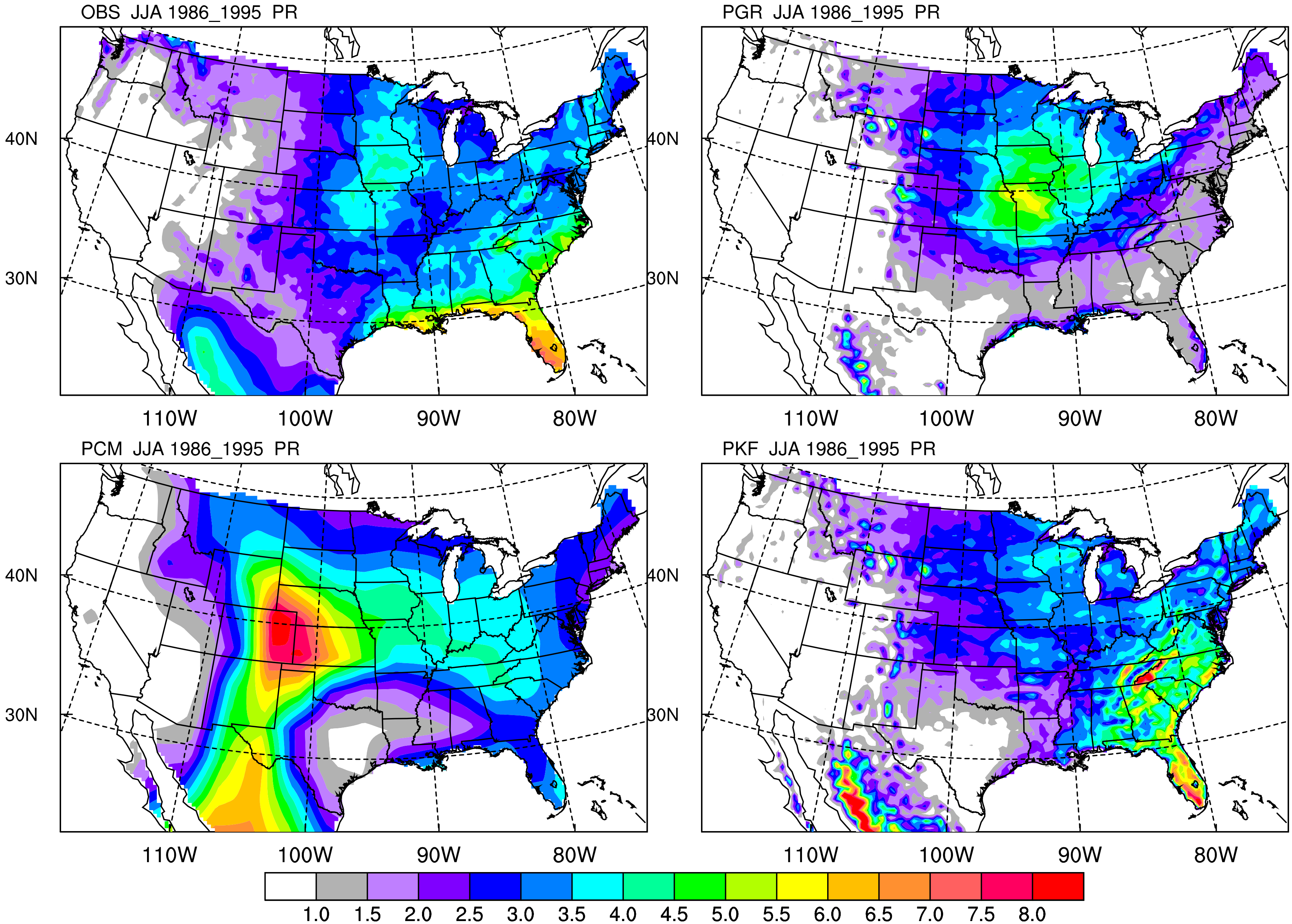
Daily


Midwest
JFMA, 1993
OBS
CWRF
Rain (mm/day)
Midwest
MJJA, 1993
Rain (mm/day)
Midwest
SOND, 1993
Rain (mm/day)

Daily

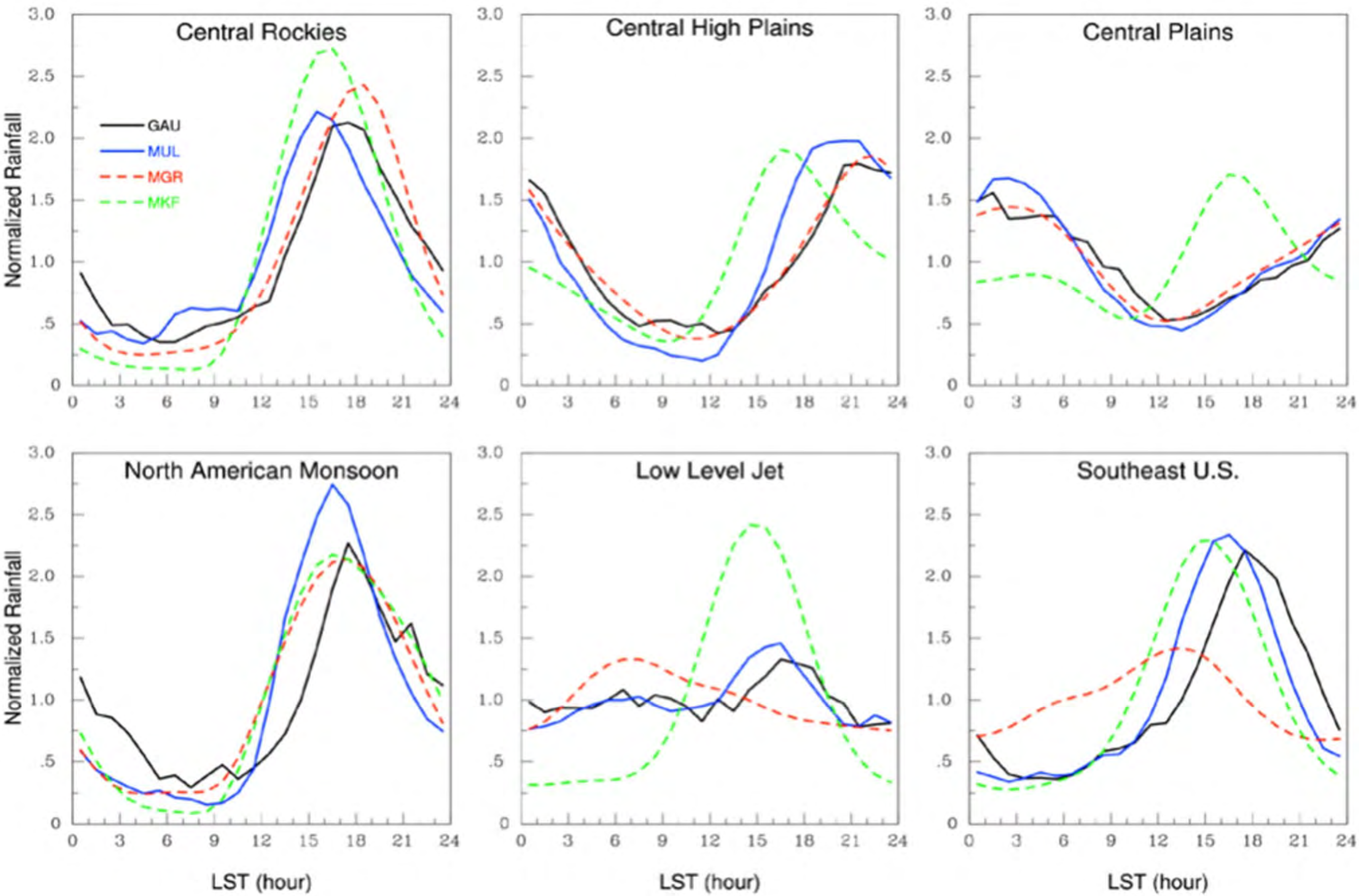

Cascade
JFMA, 1993
OBS
CWRF
Rain (mm/day)
Cascade
MJJA, 1993
Rain (mm/day)
Cascade
SOND, 1993
Rain (mm/day)

Much More Than That…

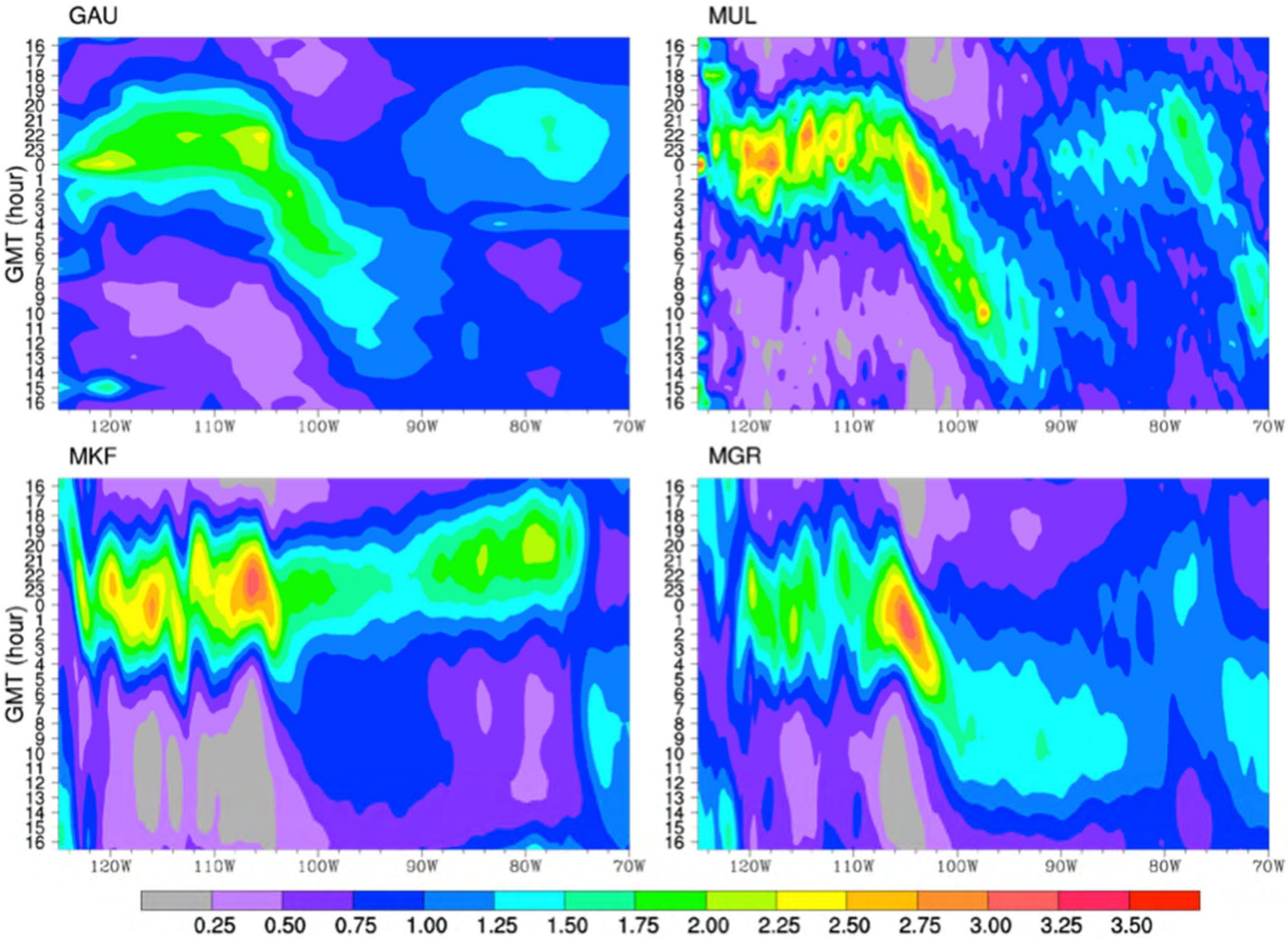


Adopt from Liang et al. (2006, JGR).

RCM Can Resolves Diurnal Cycle

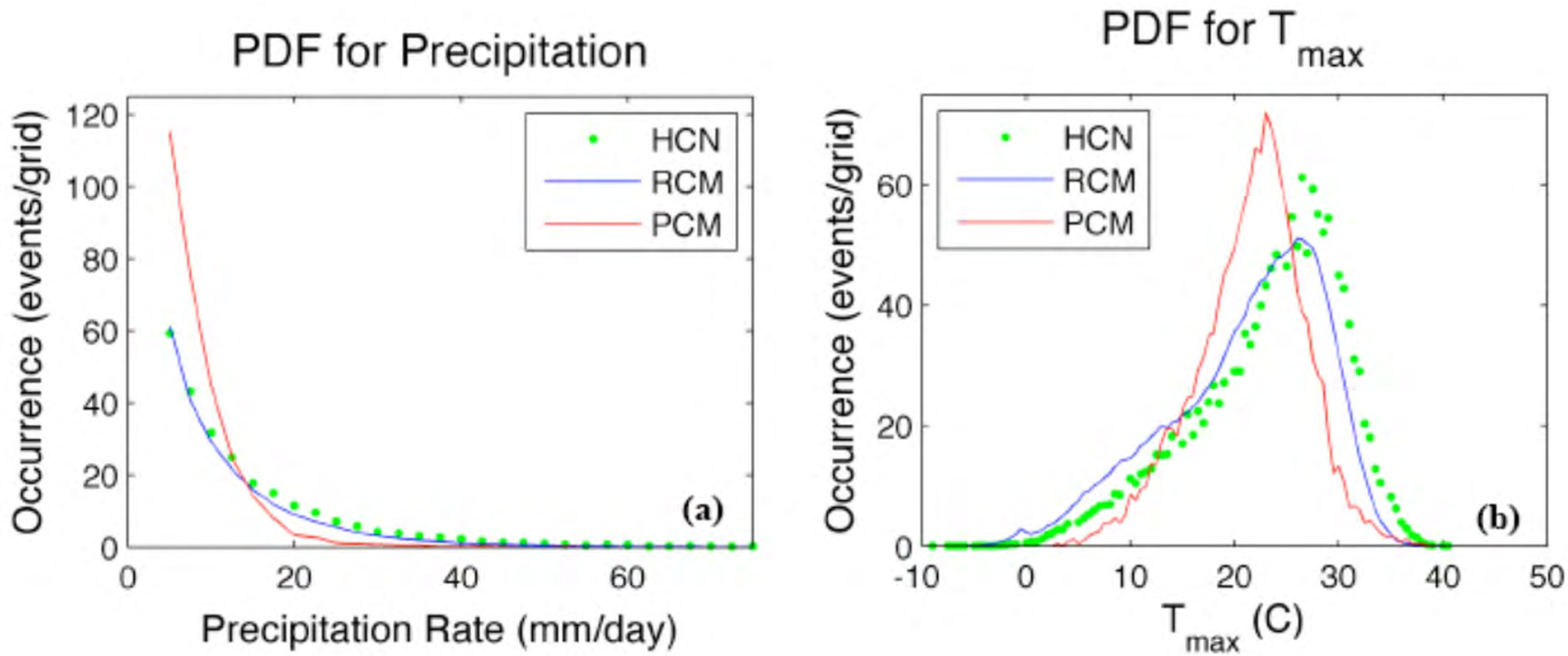


Mean diurnal evolution (relative to LST) of the normalized rainfall averaged over 6 key regions: (a) the central Rockies, (b) central high Plains, (c) high Plains, (d) North American monsoon, (e) low level jet, and (f) southeast U.S. *Adopt from Liang et al. (2004, GRL).*



Hovmöller diagram (GMT hour versus 0.25° longitude bin) of normalized rainfall diurnal variations averaged between 38-42° N for (a) GAU, (b) MUL, (c) MKF, and (d) MGR. *Adopt from Liang et al. (2004, GRL).*

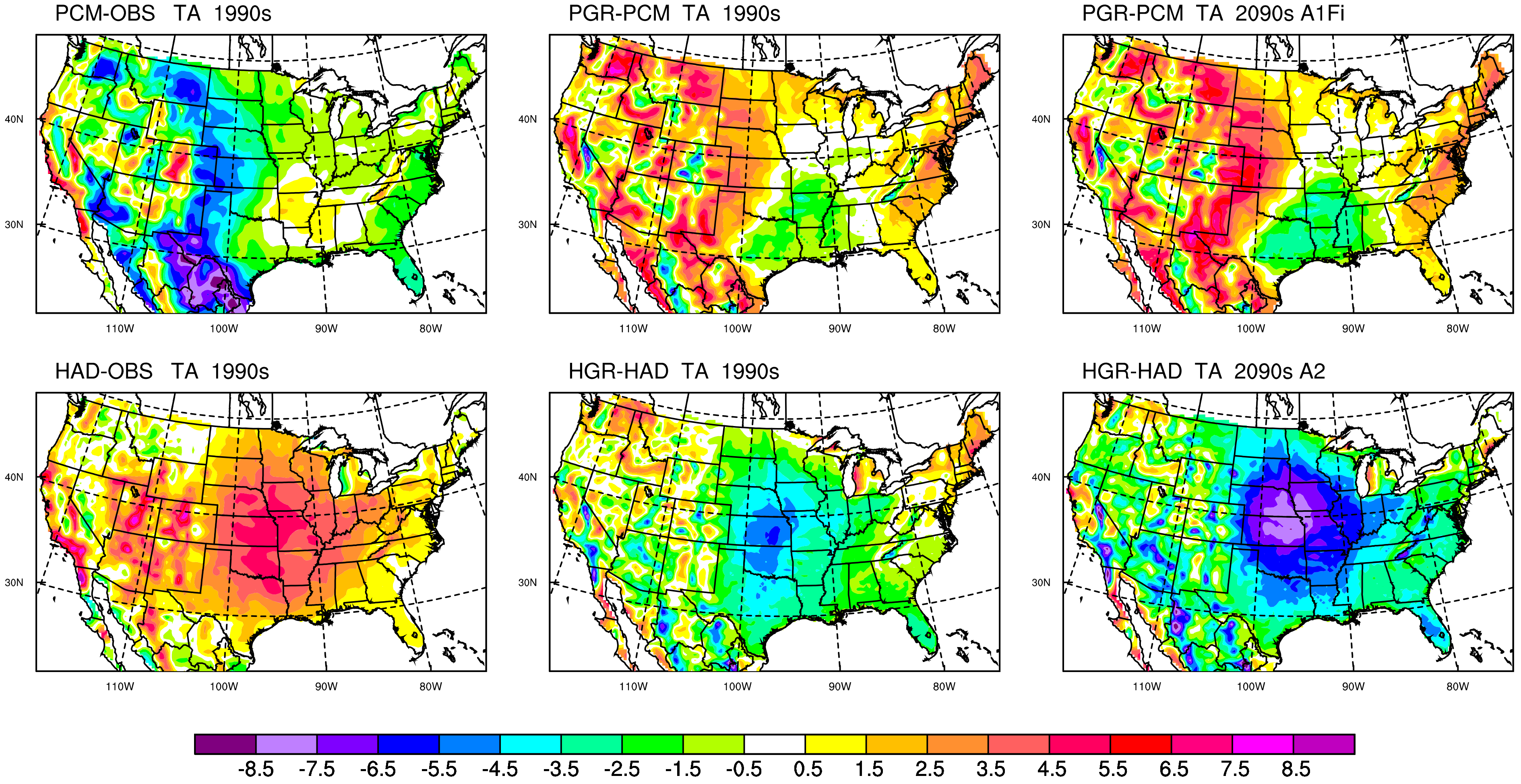
RCM Better Resolves Extremes



Northeast U.S. Assessment

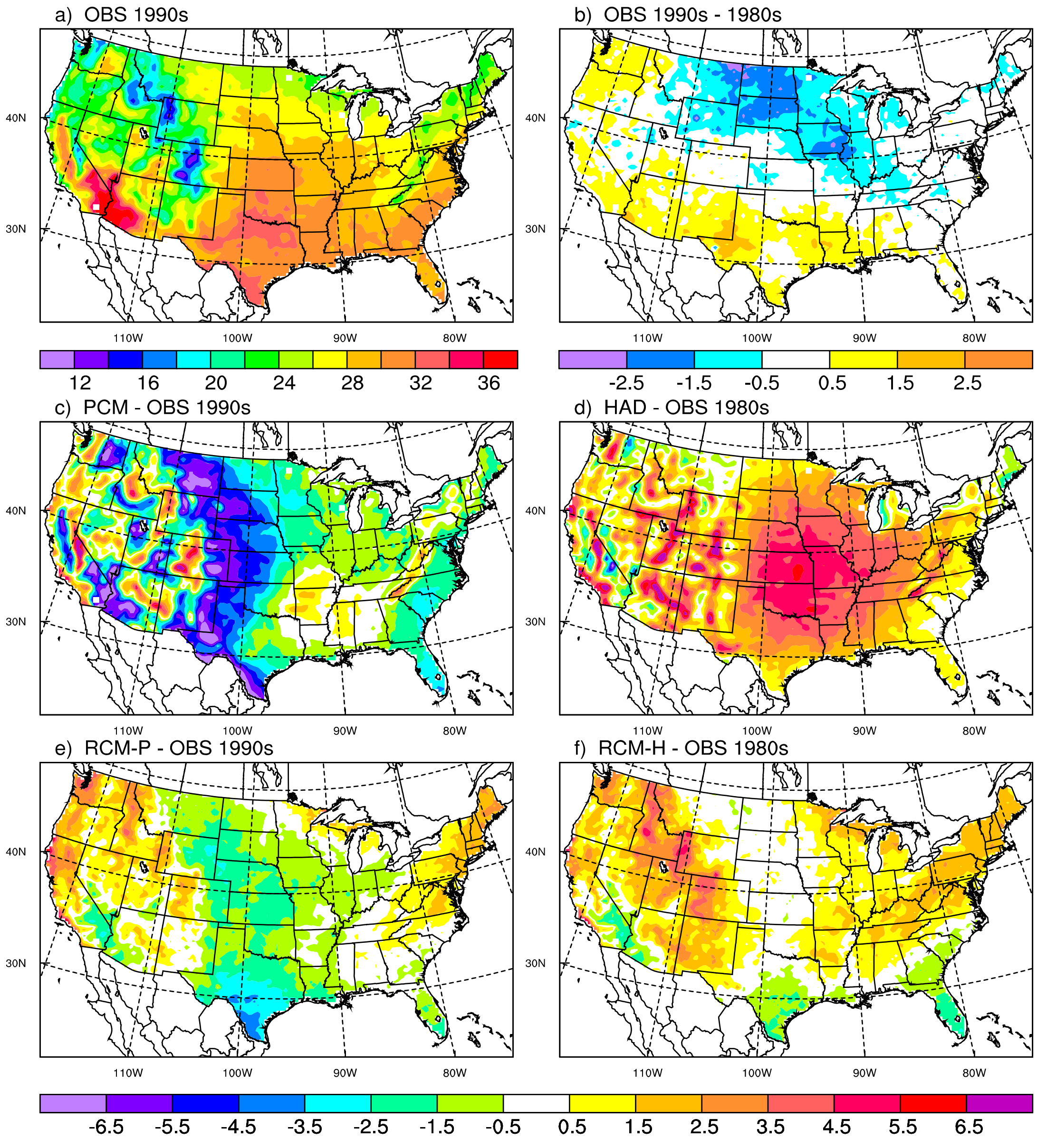
Anderson, B.T., K. Hayhoe, and X.-Z. Liang, 2009: Anthropogenic-induced changes in the 21st Century summertime hydroclimatology of the Northeastern US., *Climate Change*, doi.10.1007/s10584-009-9673-3.

Propagation of GCM Present Climate Biases into Future Change Projections: Temperature



Adopt from Liang et al. (2008, GRL).

RCM Refinement Improves Heat Wave Prediction

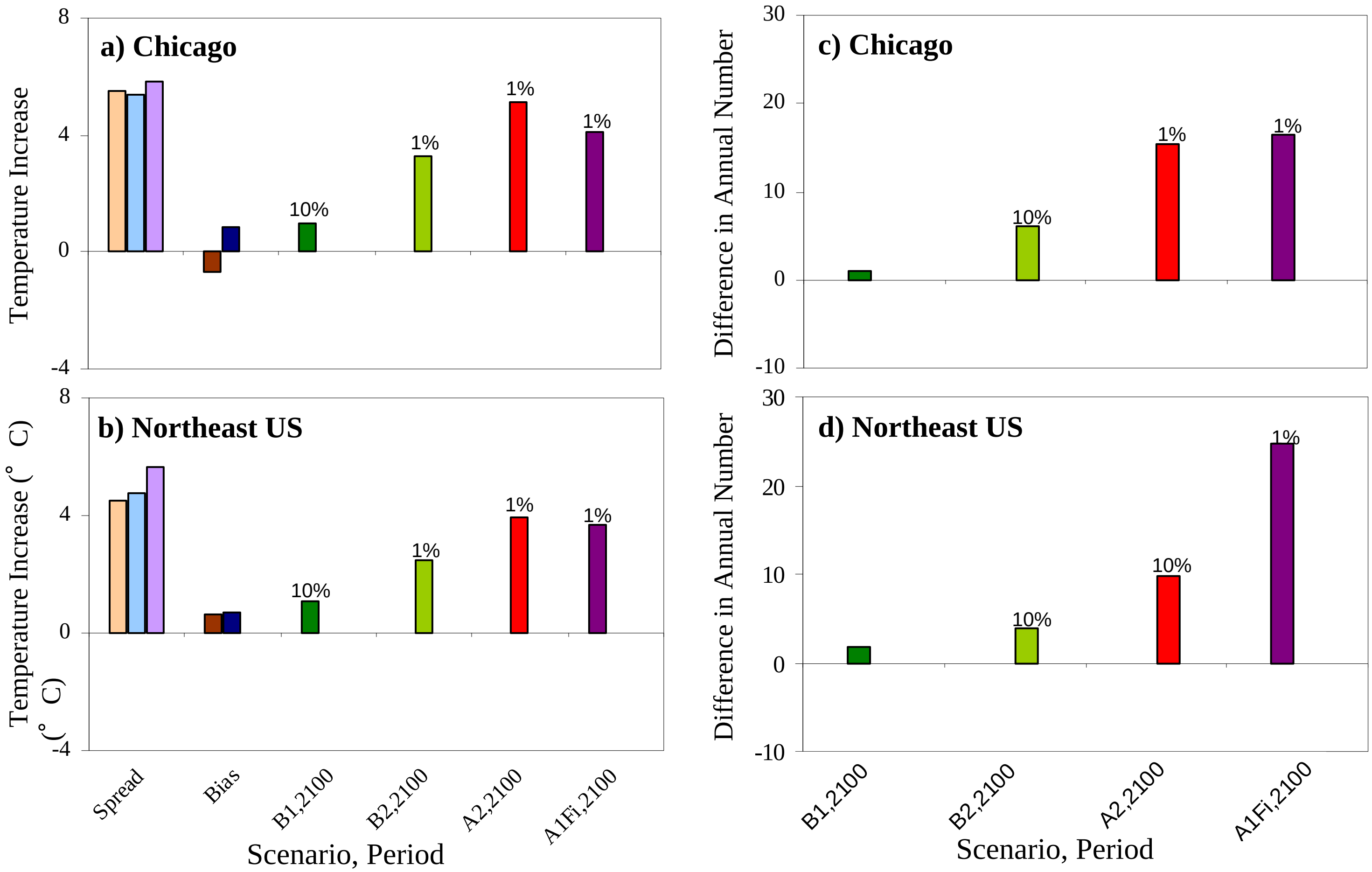


- Shown are the 97.5 percentile summer temperature threshold (° C) for heat waves observed in 1990s (a) and trends from 1980s (b), as well as model biases as simulated by PCM (c) and HAD (d), and refined by RCM from PCM (e) and HAD (f).

- Although the signs of the major biases are opposite between HAD and PCM, the RCM produces values much closer to observed in both cases, reducing the overall average biases by a factor of 2 to 3. This bias reduction results from the more complete physics and higher resolution of the RCM.

- See details in Kunkel, K.E., X.-Z. Liang, and J. Zhu, 2010: Regional climate model projections and uncertainties of U.S. summer heat waves. *J. Climate*, **23**, 4447-4458.

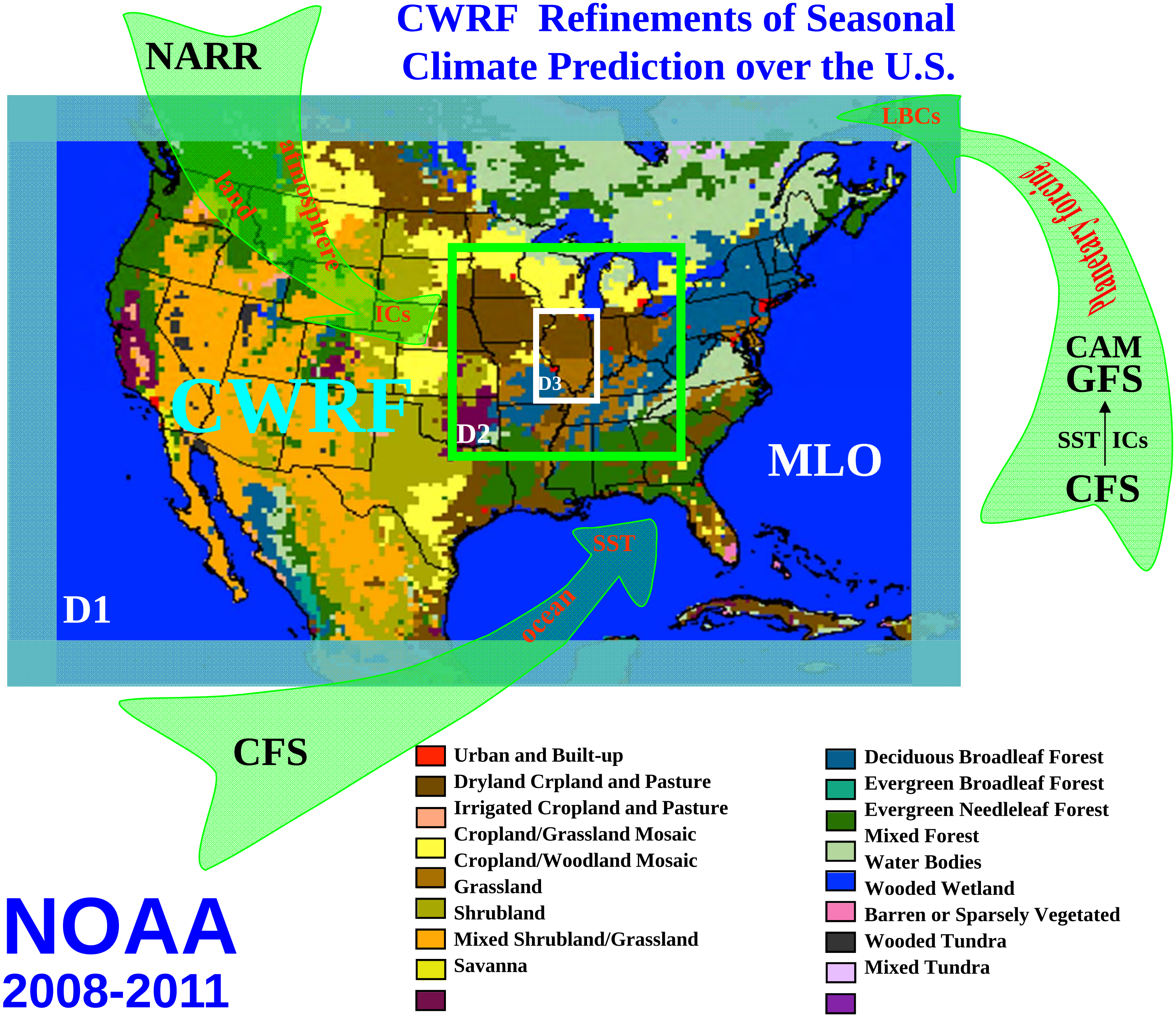
Projected U.S. Heat Wave Changes



Projections of changes in the average annual 3-day heat wave temperature (° C) for a) Chicago and b) Northeast US and of the annual average number of heat wave days for c) Chicago and d) Northeast US. The two sets of bars on the far left side of a) and b) compare the present-day annual 3-day heat wave temperature spread (from its own summer mean temperature as simulated and observed); and model biases (from observations). The simulations are arranged from left to right in order of increasing greenhouse gas concentrations. The % number at the bar top depicts the corresponding statistical significance level.

Kunkel, K.E., X.-Z. Liang, and J. Zhu, 2010: Regional climate model projections and uncertainties of U.S. summer heat waves. *J. Climate*, **23**, 4447-4458.

CWRF Refinements of Seasonal Climate Prediction over the U.S.



NOAA
2008-2011

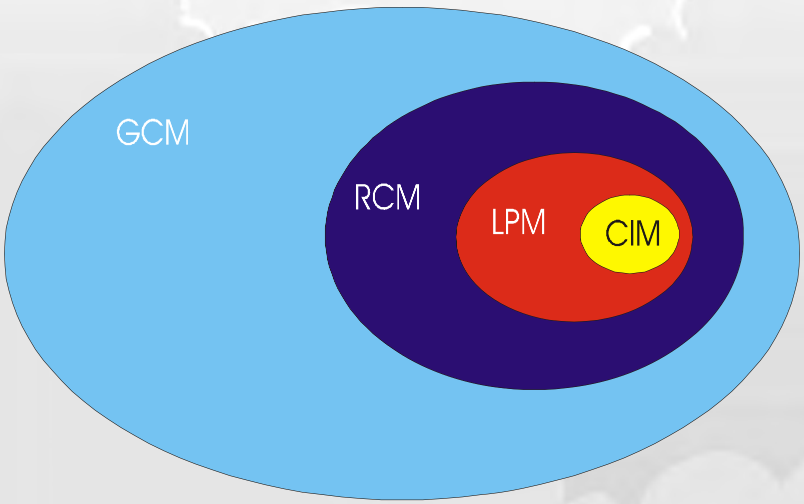
RCM Modeling is
Science + Due Diligence

- Do NOT take an RCM off the shelf (localization)
- Domain Design (integrating planetary forcing)
- Physics Configuration (regime & scale dependence)
- Verification or Evaluation (obs. data & added values)
- Ensemble Approach (prediction skill & uncertainty)

Doing details is the key to success!

Domain Design

Regional Climate Model
Buffer Zone Treatment



- **Planetary Circulation**
- **OBS Uncertainty**
- **GCM Bias**

Liang, X.-Z., K.E. Kunkel, and A.N. Samel, 2001: Development of a regional climate model for U.S. Midwest applications. Part 1: Sensitivity to buffer zone treatment. *J. Climate*, **14**, 4363-4378.

Liu, S., X.-Z. Liang, W. Gao, and H. Zhang, 2008: Climate-Weather Research and Forecasting Model (CWRF) Application in China: Domain Optimization. *Chinese J. Atmos. Sci.*, **32**, 457-468.

Ensemble Global Forecast System

⇒ICs, SSTs, LBCs

NCEP
ECMWF
……………
……………

OP DASs ⇒ICs

NOAA CFS
NASA GMAO
……………………
……………………
Bias corrections

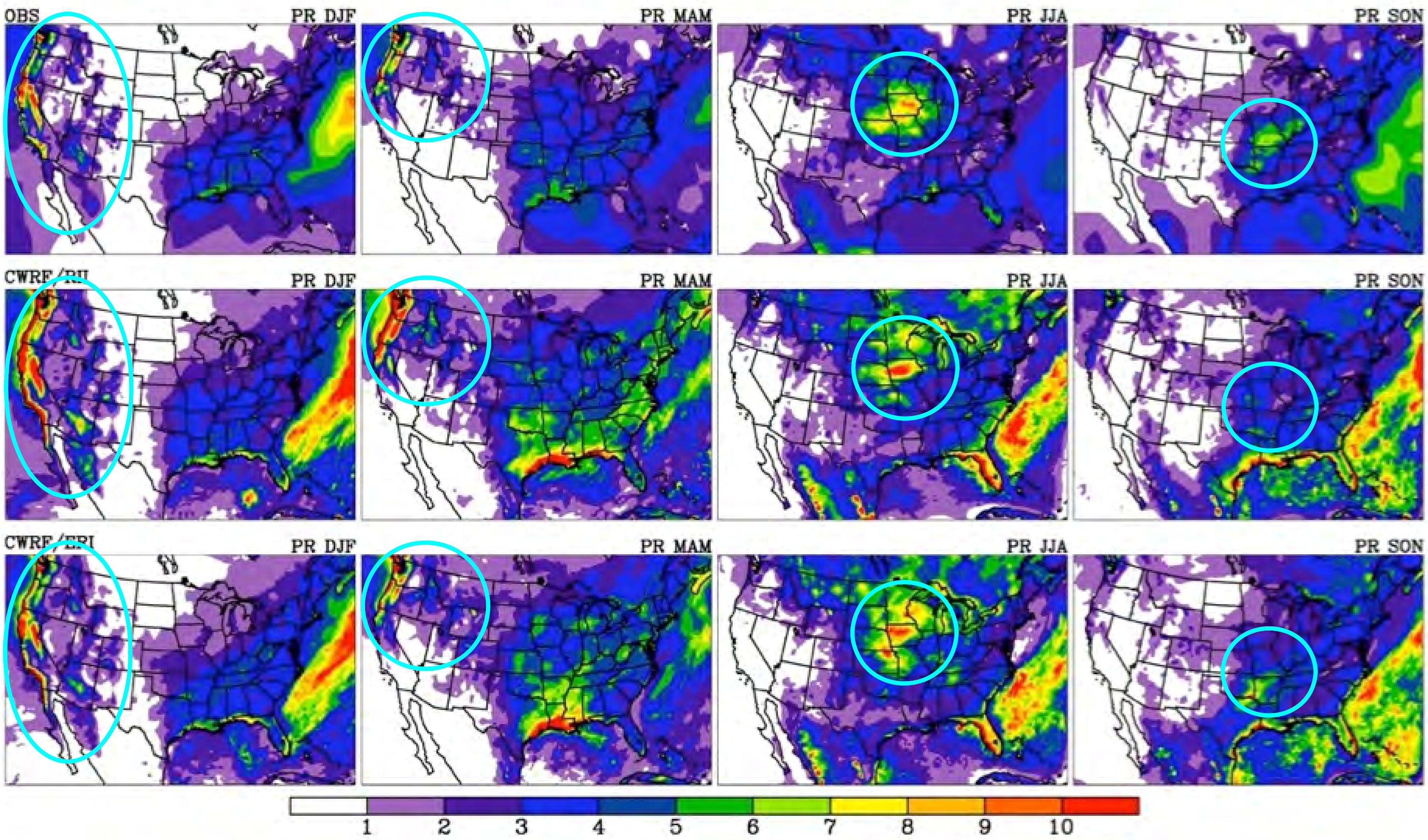
OP CGCMs ⇒SSTs

NOAA GFS
NCAR CAM
IRI ECHAM
……………………
……………………

AGCMs ⇒LBCs

NCEP/AMIP II vs ECMWF-Interim Reanalysis

(1993 summer record flood in the Midwest)



CWRF Performance

Relative to other RCMs

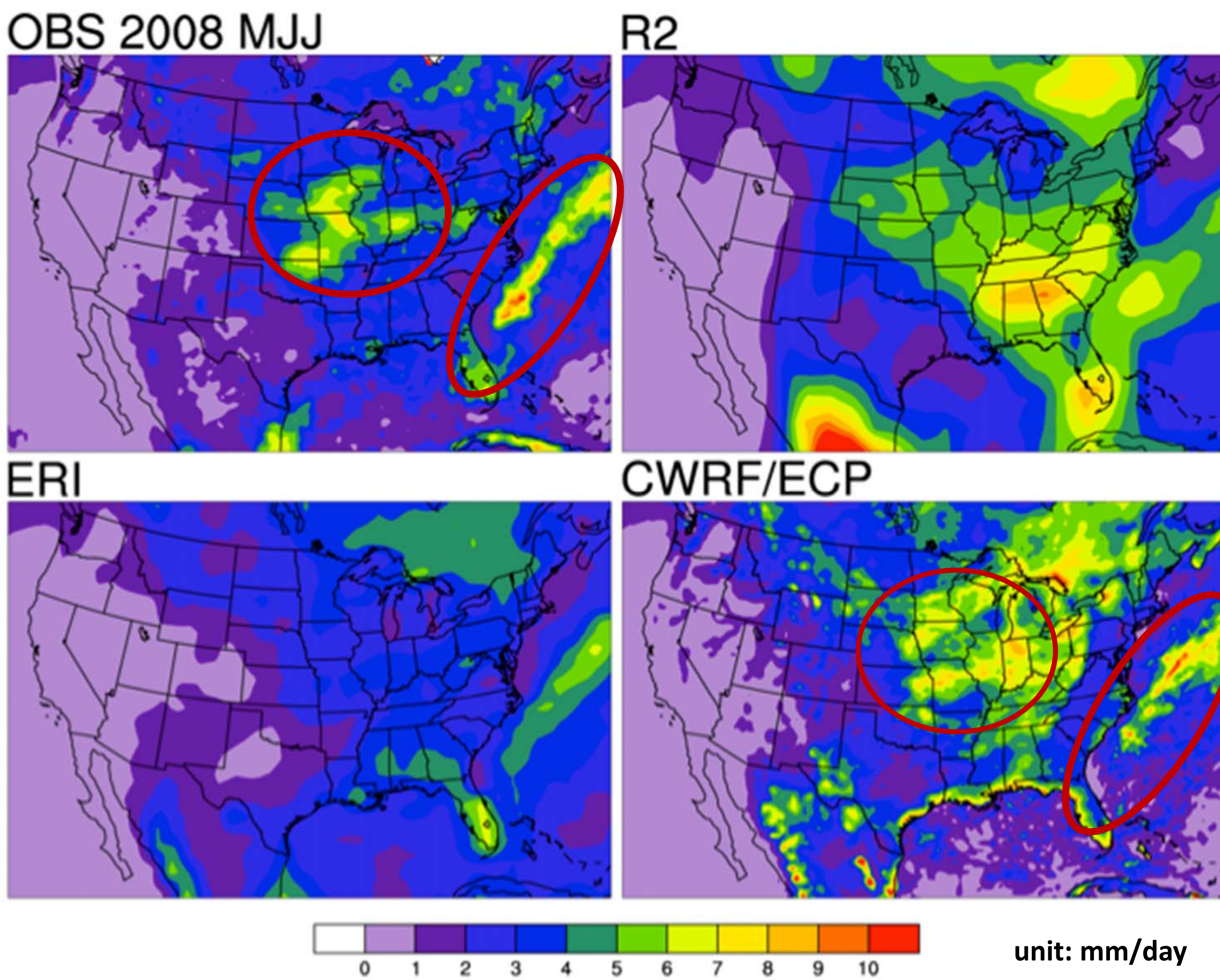
Ability to reproduce observations

- All driven by the same reanalysis
- Result comparison on
  - Seasonal variations
  - Interannual anomalies
  - Extreme events

Precipitation Prediction Improvement over the U.S. Land and East Coastal Ocean

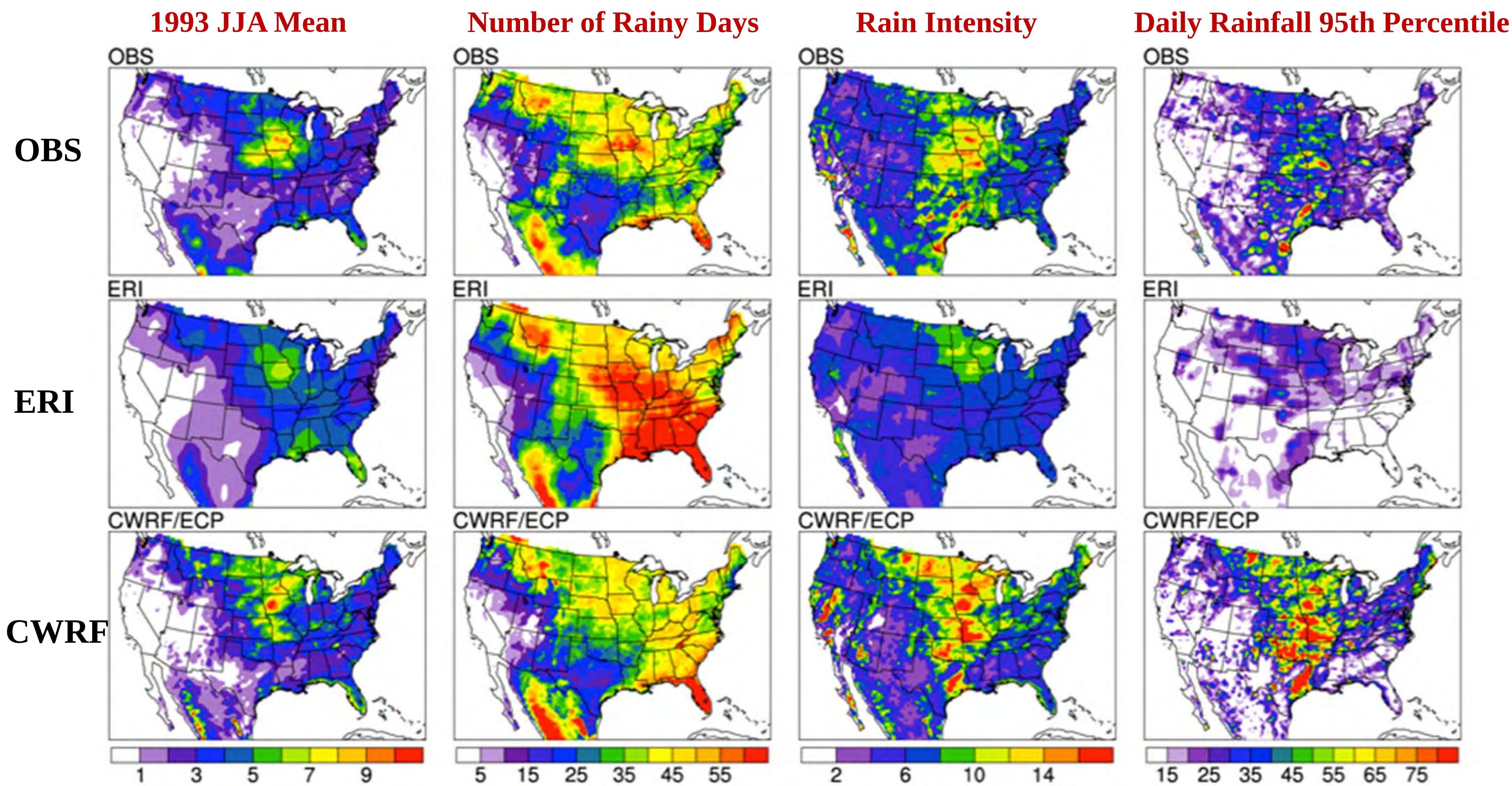
CWRF/ECP simulation compared to NCEP Reanalysis (R-2) & ERA Interim (ERI)

[2008 MJJ flood over U.S. Midwest & TRMM data over Ocean]



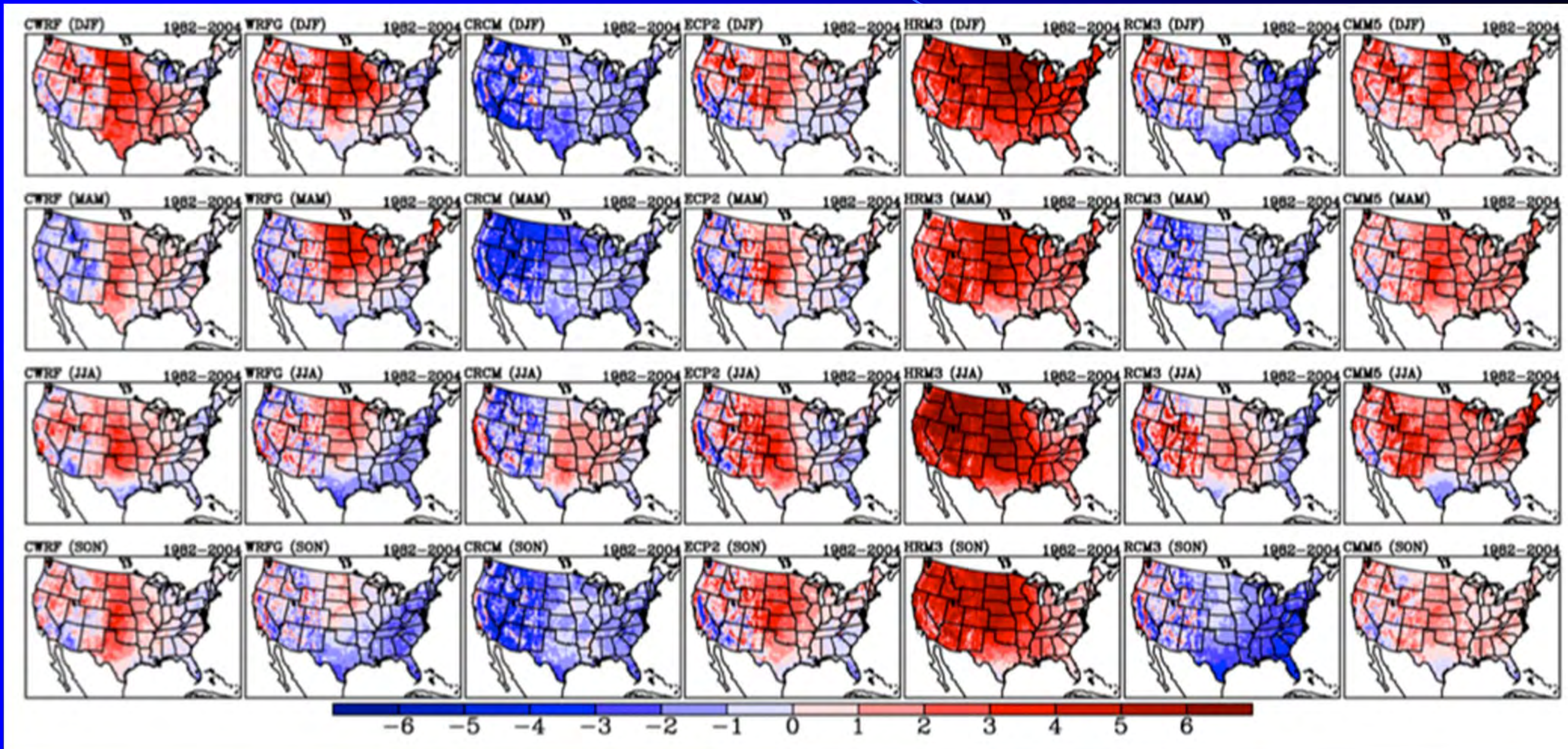
unit: mm/day

CWRF with ECP/W closure over the U.S. land



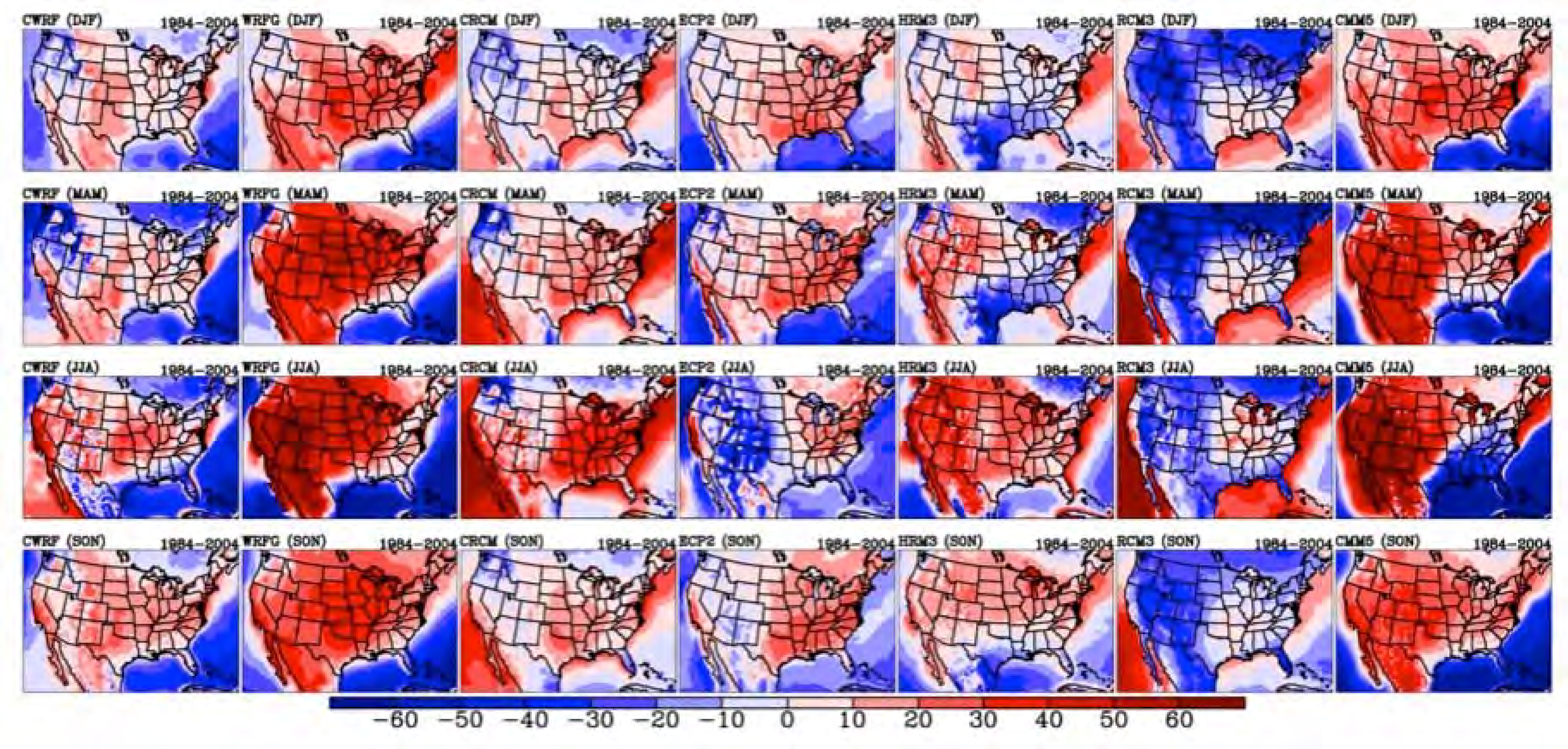
The reanalysis has already assimilated *local* observational data, while CWRF is driven by only LBCs. The CWRF skill will be enhanced if assimilating local data.

Surface Temperature Biases



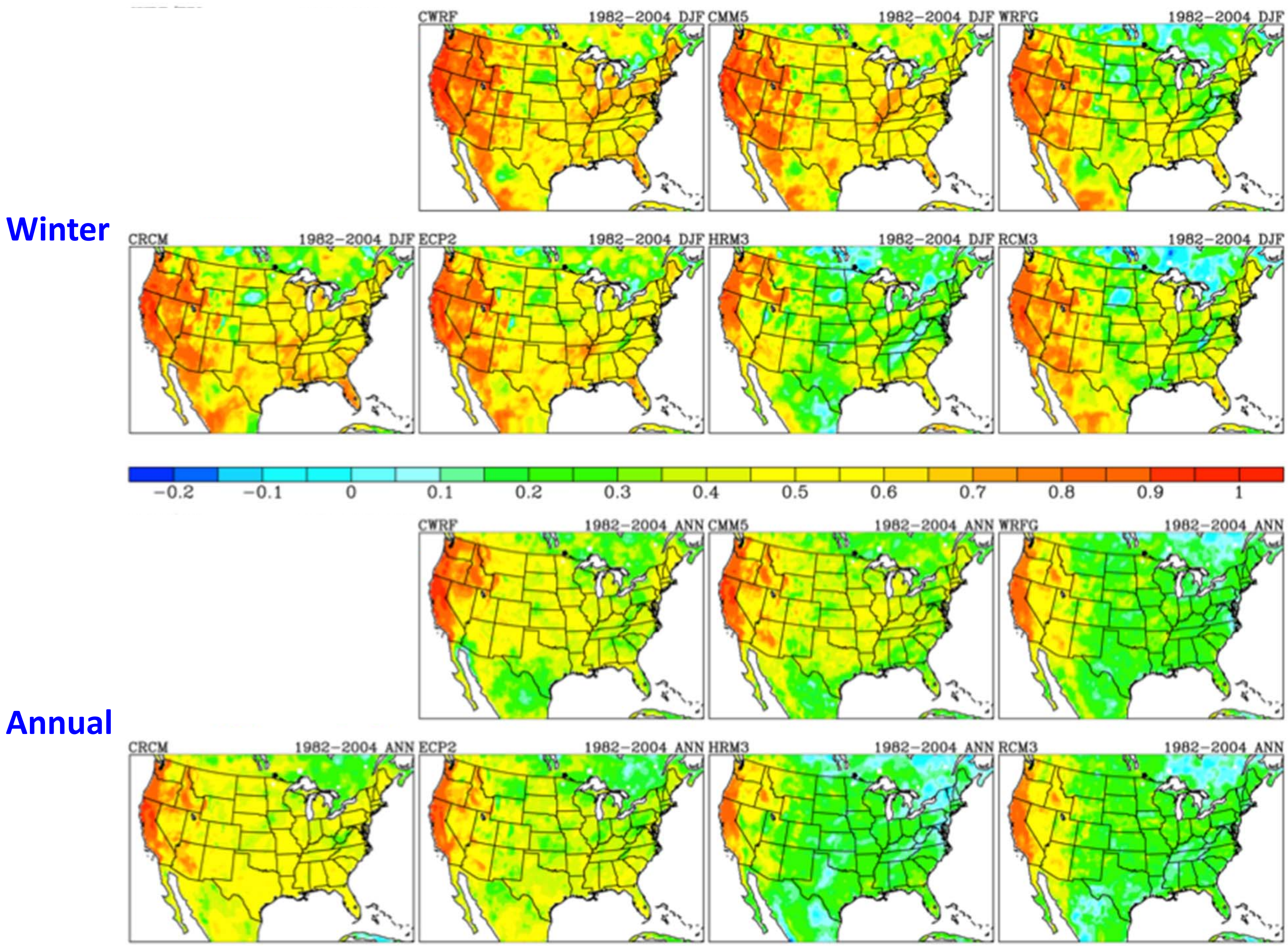
All driven by NCEP/DOE AMIP II Reanalysis

Surface SW_d Biases



All driven by NCEP/DOE AMIP II Reanalysis

Precipitation Anomaly Correlation with Observations



Why Do RCM Results Differ?

- Domain: U.S. + Adjacent for CWRF & CMM5, Extended North America for NARCCAP
- Resolution: 30 km for CWRF & CMM5, 50 km for all other NARCCAP RCMs
- Forcing: linear-exp relaxation in buffer zones of 14 (CWRF, CMM5), 10 (WRFG) grids linear relaxation in 4 grids (MM5I, HRM3) domain spectral nudging (ECP2, CRCM) NARCCAP IA correlations differ largely due to the strength of forcing integrated
- Physics: CWRF is much better than CMM5, being identical in all other settings Different dynamics may also contribute

Physics Representation

Evaluating Skill under Correct Forcing Conditions

From 2002 onward

CWRF Development History

Liang, X.-Z., K.E. Kunkel, R. Wilhelmson, J. Dudhia, and J.X.L. Wang, 2002: The WRF simulation of the 1993 central U.S. heavy rain: Sensitivity to cloud microphysics representation. In Proceedings of the 82nd AMS Annual Meeting: 16th Conference on Hydrology, Orland, FL, January 13-17, pp. 123-126.

Liang, X.-Z., J. Pan, K.E. Kunkel, J.X.L. Wang, E.C. Hunke, and W.H. Lipscomb, 2004: Coupling the CWRF with the CICE for Arctic climate applications. In *Proceedings of 5th WRF/14th MM5 User's Workshop*, Boulder, CO, June 22-25, pp. 215-220.

Liang, X.-Z., M. Xu, W. Gao, K.E. Kunkel, J. Slusser, Y. Dai, and Q. Min, 2004: New land surface albedo parameterization based on MODIS data: A preliminary result. In *Remote Sensing and Modeling of Ecosystems for Sustainability*. W. Gao and D. Shaw (Eds.), Vol. 5544, SPIE Press (Bellingham, WA) pp. 55-60.

Liang, X.-Z., H. Choi, K.E. Kunkel, Y. Dai, E. Joseph, J.X.L. Wang, and P. Kumar, 2005: Development of the regional climate-weather research and forecasting model (CWRF): Surface boundary conditions. *Illinois State Water Survey Scientific Research*, ISWS SR 2005-01, 32 pp. (http://www.sws.uiuc.edu/pubs/pubdetail.asp? CallNumber=ISWS+SR+2005%2D01).

Liang, X.-Z., H. Choi, K.E. Kunkel, Y. Dai, E. Joseph, J.X.L. Wang, and P. Kumar, 2005: Surface boundary conditions for mesoscale regional climate models. *Earth Interactions*, **9**, 1-28.

Liang, X.-Z., M. Xu, W. Gao, K.E. Kunkel, J. Slusser, Y. Dai, Q. Min, P.R. Houser, M. Rodell, C.B. Schaaf, and F. Gao, 2005: Development of land surface albedo parameterization bases on Moderate Resolution Imaging Spectroradiometer (MODIS) data. *J. Geophys. Res*., **110**, D11107, doi:10.1029/2004JD005579.

Liang, X.-Z., M. Xu, J. Zhu, K.E. Kunkel, and J.X.L. Wang, 2005: Development of the regional climate-weather research and forecasting model (CWRF): Treatment of topography. In *Proceedings of the 2005 WRF/MM5 User's Workshop*, Boulder, CO, June 27-30, 5 pp.

Xu, M., X.-Z. Liang, W. Gao, K. R. Reddy, J. Slusser, and K. E. Kunkel, 2005: Preliminary results of the coupled CWRF-GOSSYM system. In *Remote Sensing and Modeling of Ecosystems for Sustainability II*. W. Gao and D. Shaw (Eds.), Proc. SPIE 5884, 588409, doi: 10.1117/12.621017, 7 pp.

Liang, X.-Z., M. Xu, H.I Choi, K.E. Kunkel, L. Rontu, J.-F. Geleyn, M.D. Müller, E. Joseph, and, J.X.L. Wang, 2006: Development of the regional Climate-Weather Research and Forecasting model (CWRF): Treatment of subgrid topography effects. In *Proceedings of the 7th Annual WRF User's Workshop*, Boulder, CO, June 19-22, 5 pp.

Xu, M., X.-Z. Liang, W. Gao, J. Slusser, and K. Kunkel, 2006: Validation of the TUV module in CWRF using USDA-UVB network observations. In *Remote Sensing and Modeling of Ecosystems for Sustainability III*. W. Gao and S.L. Ustin (Eds.), Proc. of SPIE, Vol. 6298, 62980N, doi: 10.1117/12.680122, 8 pp.

Choi, H.I., 2006: 3-D volume averaged soil-moisture transport model: A scalable scheme for representing subgrid topographic control in land-atmosphere interactions. *Ph.D. Dissertation*, University of Illinois at Urbana-Champaign, 189 pp.

Choi, H. I., P. Kumar, and X.-Z. Liang, 2007: Three-dimensional volume-averaged soil moisture transport model with a scalable parameterization of subgrid topographic variability. *Water Resour. Res*., **43**, W04414, doi:10.1029/2006WR005134, 15pp.

Xu, M., X.-Z. Liang, and W. Gao, 2009: Implementation of DSSAT CERES-Maize model into CWRF and preliminary standalone evaluation. *Poster Presentation No. H41G-0991 at the American Geophysical Union 2009 Fall Meeting*, San Francisco, December 14-18.

Choi, H. I., and X.-Z. Liang, 2010: Improved terrestrial hydrologic representation in mesoscale land surface models. *J. Hydrometeorology*, **11**, 797-809.

Ling, T.-J., X.-Z. Liang, M. Xu, Z. Wang, and B. Wang, 2011: A multilevel ocean mixed-layer model for 2-dimension applications. *Acta Oceanologica Sinica*, **33**(03), 1-10.

Yuan, X., and X.-Z. Liang, 2011: Evaluation of a Conjunctive Surface-Subsurface Process model (CCSP) over the contiguous United States at regional–local scales. *J. Hydrometeorology*, **12**, 579-599, doi: 10.1175/2010JHM1302.1.

Liang, X.-Z., M. Xu, W. Gao, K.R. Reddy, K.E. Kunkel, D.L. Schmoldt, and A.N. Samel, 2012: A distributed cotton growth model developed from GOSSYM and its parameter determination. *Agronomy Journal*, **104**, 661-674.

Liang, X.-Z., M. Xu, W. Gao, K.R. Reddy, K.E. Kunkel, D.L. Schmoldt, and A.N. Samel, 2012: Physical modeling of U.S. cotton yields and climate stresses during 1979 to 2005. *Agronomy Journal*, **104**, 675-683.

Liang, X.-Z., M. Xu, X. Yuan, T. Ling, H.I. Choi, F. Zhang, L. Chen, S. Liu, S. Su, F. Qiao, Y. He, J.X.L. Wang, K.E. Kunkel, W. Gao, E. Joseph, V. Morris, T.-W. Yu, J. Dudhia, and J. Michalakes, 2012: Regional Climate-Weather Research and Forecasting Model (CWRF). *Bull. Amer. Meteor. Soc.*, doi: 10.1175/BAMS-D-11-00180.1.

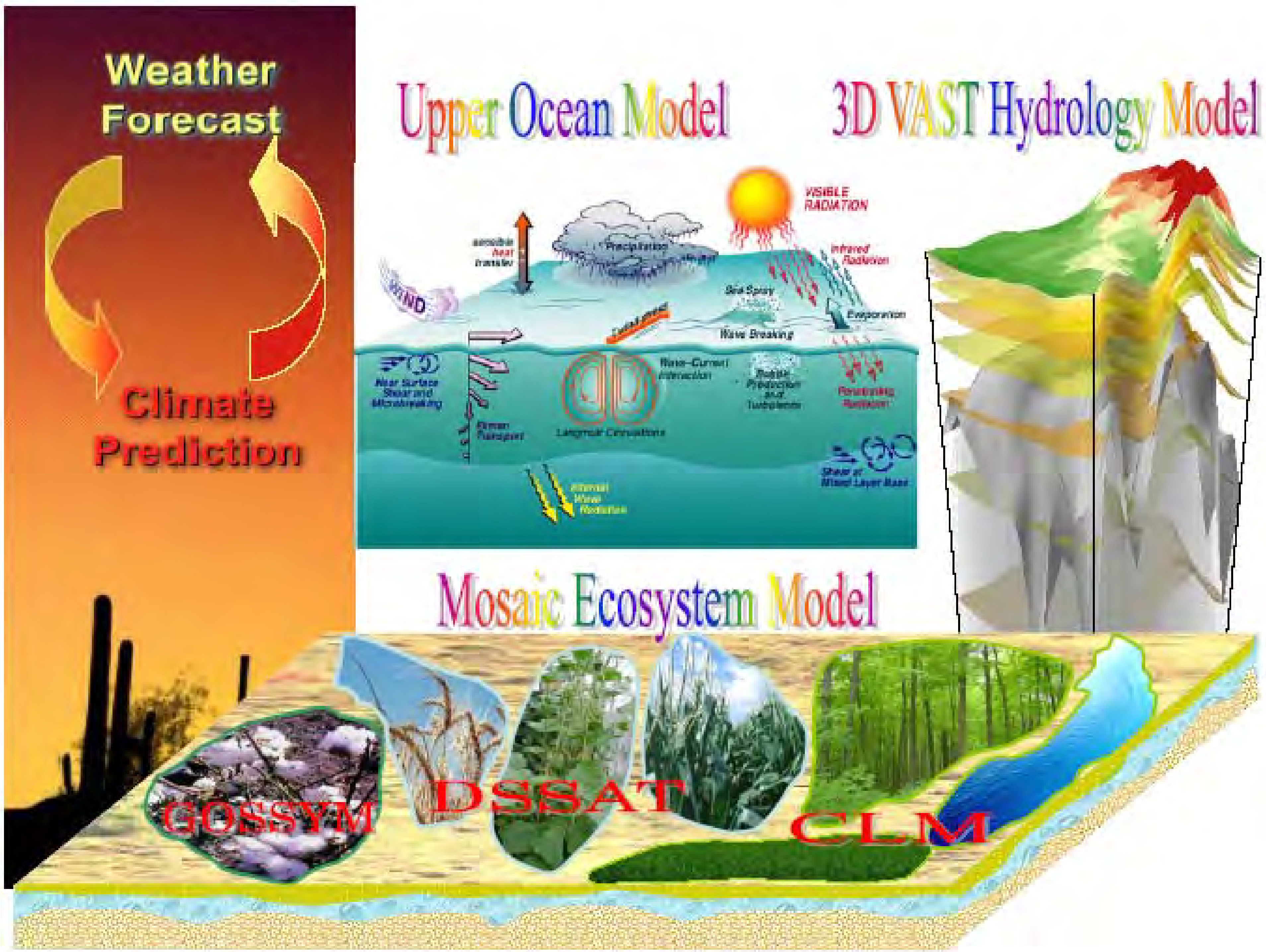
Liang, X.-Z., and F. Zhang, 2012: Cloud-Aerosol-Radiation (CAR) ensemble modeling system. *J. Geophys. Res.* (submitted).

Ling, T., M. Xu, X.-Z. Liang, J.X.L. Wang, and Y. Noh, 2012: A multilevel mixed-layer ocean model resolving the SST diurnal cycle. *J. Oceanography* (in preparation)

Liang, X.-Z., X. Yuan, Y. Dai, H. Choi, and P. Kumar, 2012: Development of CWRF for regional weather and climate prediction: Conjunctive surface-subsurface process model and comparison with other land surface models. *J. Climate* (in preparation).

CWRF Development Principles

- **the *extension* of the WRF**
  - inherits all WRF functionalities for NWP while enhancing the capability to predict climate, thus has unified applications for both weather forecast and climate prediction
- **the grand *ensemble* of alternative physics schemes**
  - millions of physics configurations representing interactions between surface (land, ocean), planetary boundary layer, cumulus (deep, shallow), microphysics, cloud, aerosol, and radiation
  - the ensemble as optimized will result in a likely weather or climate prediction along with its uncertainty estimate
  - weighting individual members by their skills resolving past observations provides strong constraints to the ensemble prediction of future outcome
- **the societal *service* capability for climate impacts**
  - meet the actual need of stakeholders for credible information on natural resource changes at regional-local scales
  - develop the capability of predicting terrestrial hydrology, coastal ocean, UV radiation, crop growth, air quality, water quality, ecosystem...



Weather Forecast
Climate Prediction
Upper Ocean Model
3D VAST Hydrology Model
VISIBLE RADIATION
Infrared Radiation
WIND
Sea Spray
Evaporation
Wave Breaking
Langmuir Circulations
Mosaic Ecosystem Model
GOSSYM
DSSAT
CLM

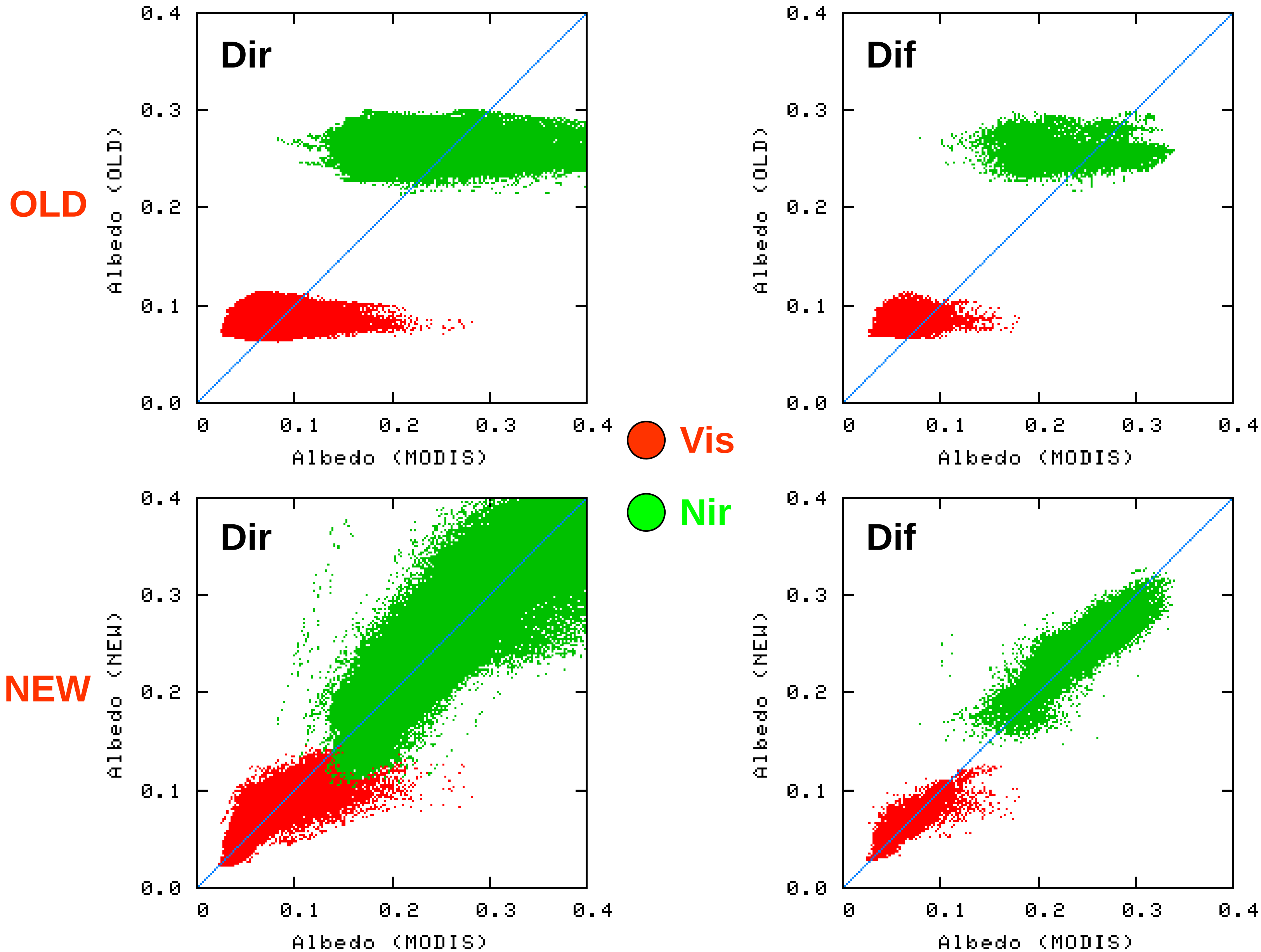
CWRF

Surface Albedo Parameterization

Liang, X.-Z., M. Xu, W. Gao, K.E. Kunkel, J. Slusser, Y. Dai, and Q. Min, 2004: New land surface albedo parameterization based on MODIS data: A preliminary result. In *Remote Sensing and Modeling of Ecosystems for Sustainability*. W. Gao and D. Shaw (Eds.), Vol. 5544, SPIE Press (Bellingham, WA) pp. 55-60.

Liang, X.-Z., M. Xu, W. Gao, K.E. Kunkel, J. Slusser, Y. Dai, Q. Min, P.R. Houser, M. Rodell, C.B. Schaaf, and F. Gao, 2004d: Development of land surface albedo parameterization bases on Moderate Resolution Imaging Spectroradiometer (MODIS) data. *J. Geophys. Res.*, **110**, D11107, doi:10.1029/2004JD005579.

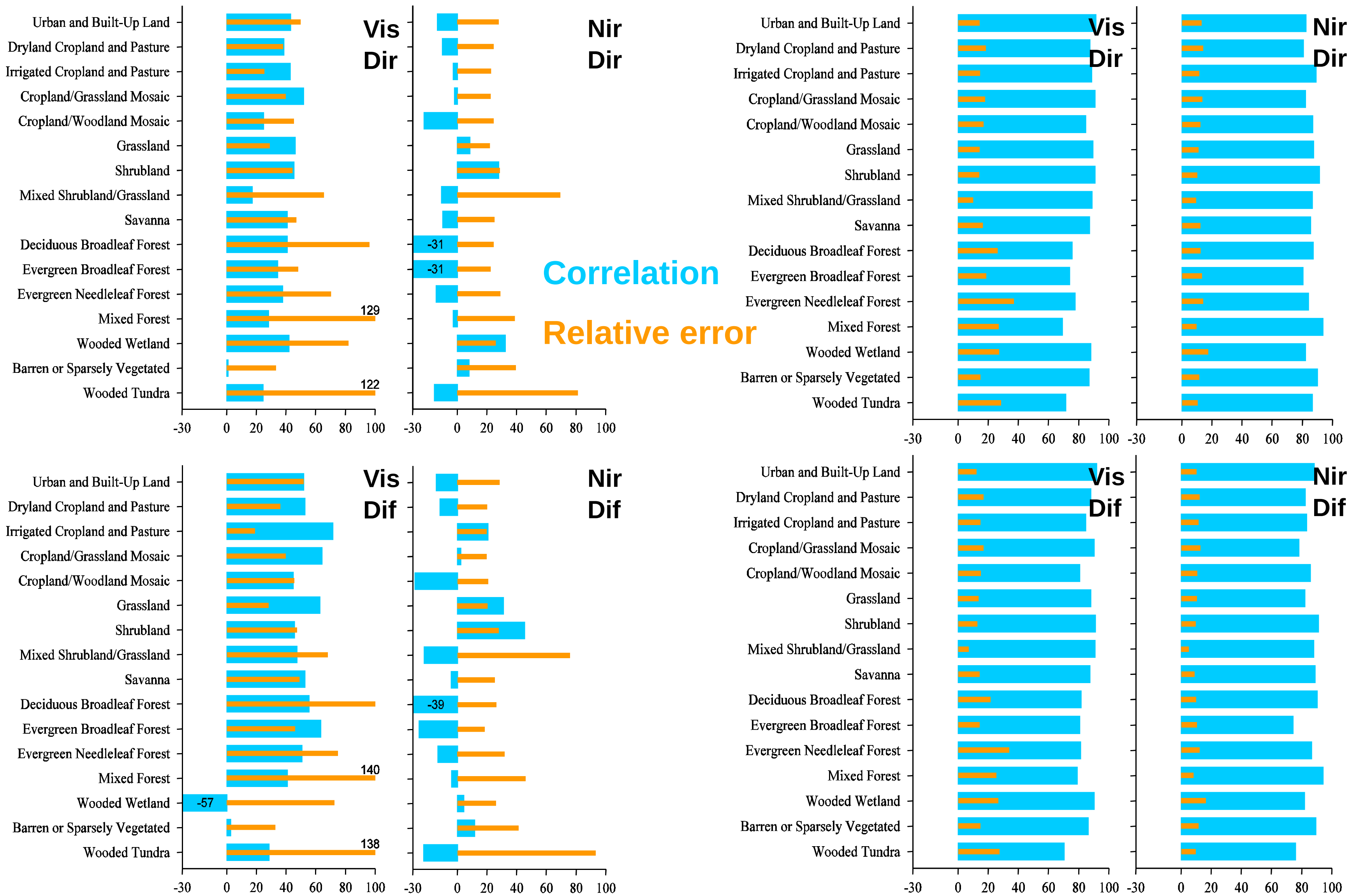
Savanna



OLD
NEW
Dir
Dif
Dir
Dif
Vis
Nir
Albedo (OLD)
Albedo (NEW)
Albedo (MODIS)
0.0
0.1
0.2
0.3
0.4
0

OLD vs MODIS

NEW vs MODIS



Liang, X.-Z., M. Xu, W. Gao, K.E. Kunkel, J. Slusser, Y. Dai, Q. Min, P.R. Houser, M. Rodell, C.B. Schaaf, and F. Gao, 2005: Development of land surface albedo parameterization bases on Moderate Resolution Imaging Spectroradiometer (MODIS) data. *J. Geophys. Res.*, **110**, D11107, doi:10.1029/2004JD005579.

Scale & Regime Dependence

Model physics representation and predictive skill depend on spatial scale and climate regime

Challenging

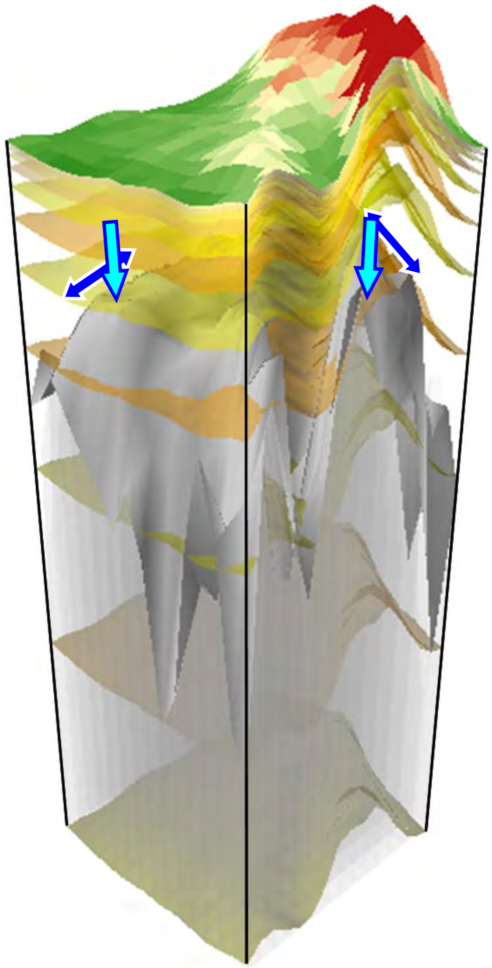
CWRF

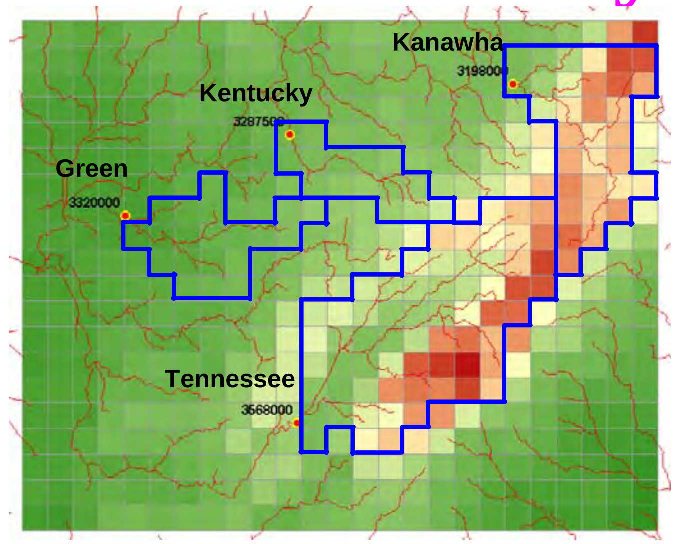
Climate-Hydrology Interaction

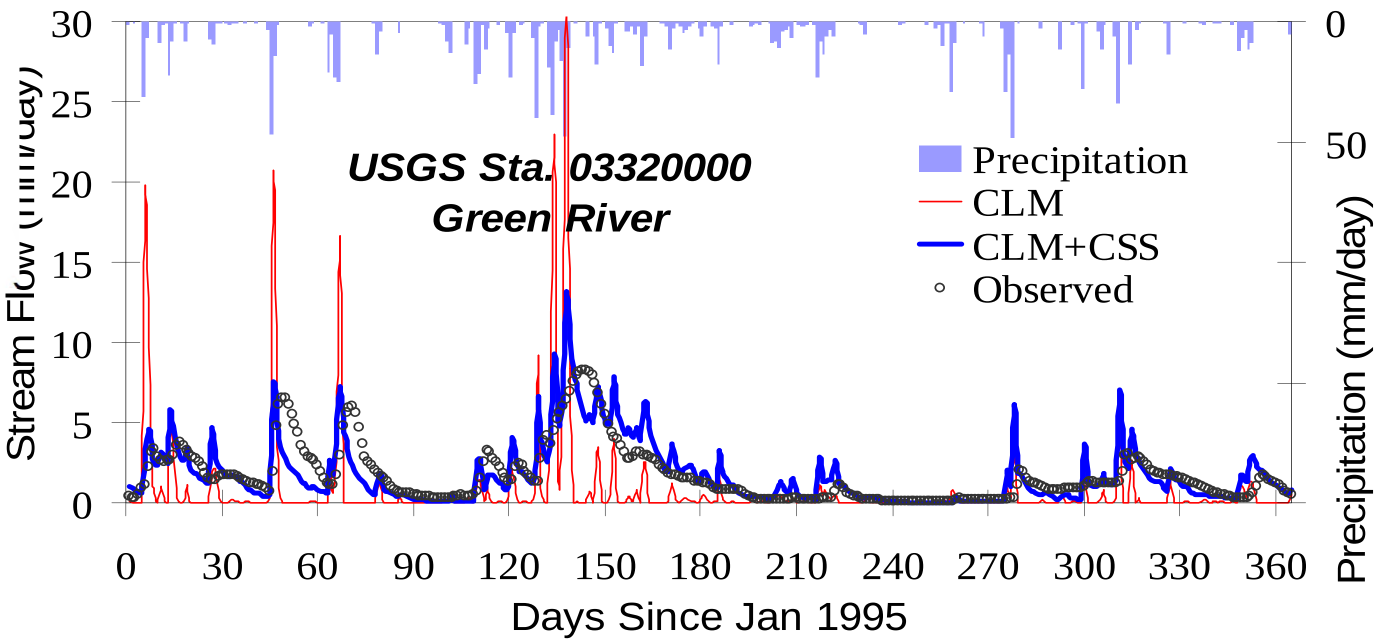
Conjunctive Surface-Subsurface Process Model

CSSP

CWRF Terrestrial Hydrology

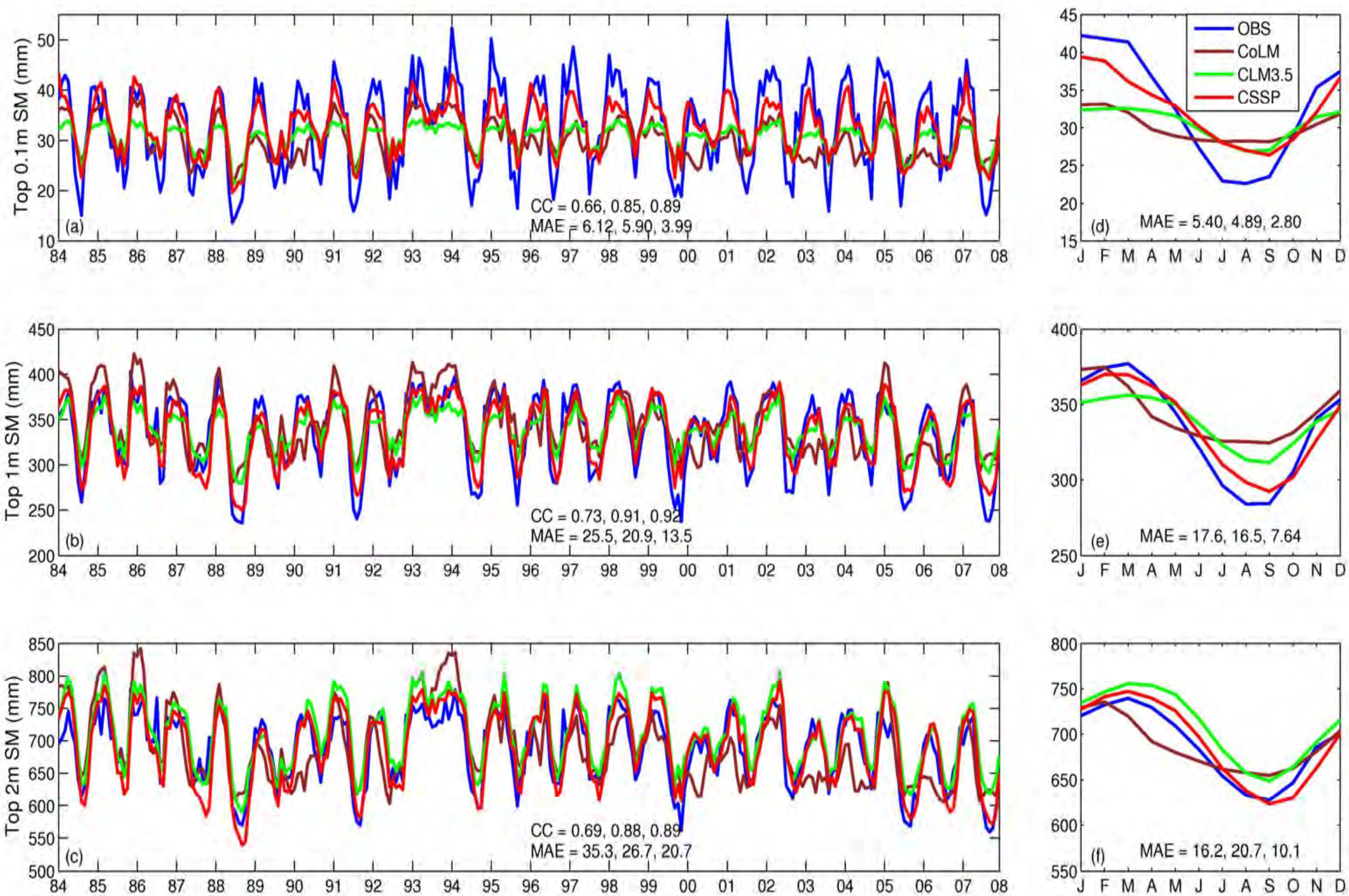






Choi 2006; Choi et al. 2007; Choi and Liang 2010; Yuan and Liang 2010; Liang et al. 2010d

Illinois Soil Moisture Simulations Driven by NARR



CWRF

Climate-Ocean Interaction

Multilevel Upper Ocean Model

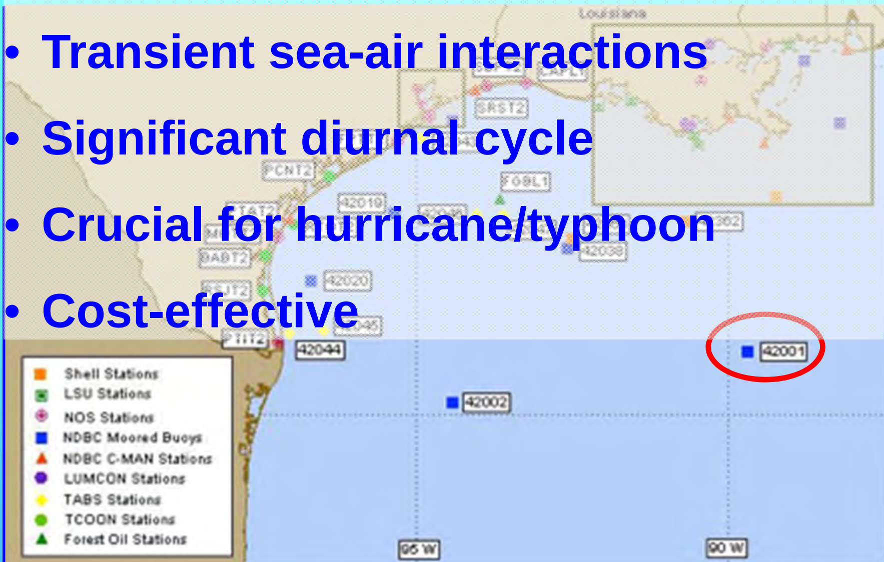
UOM

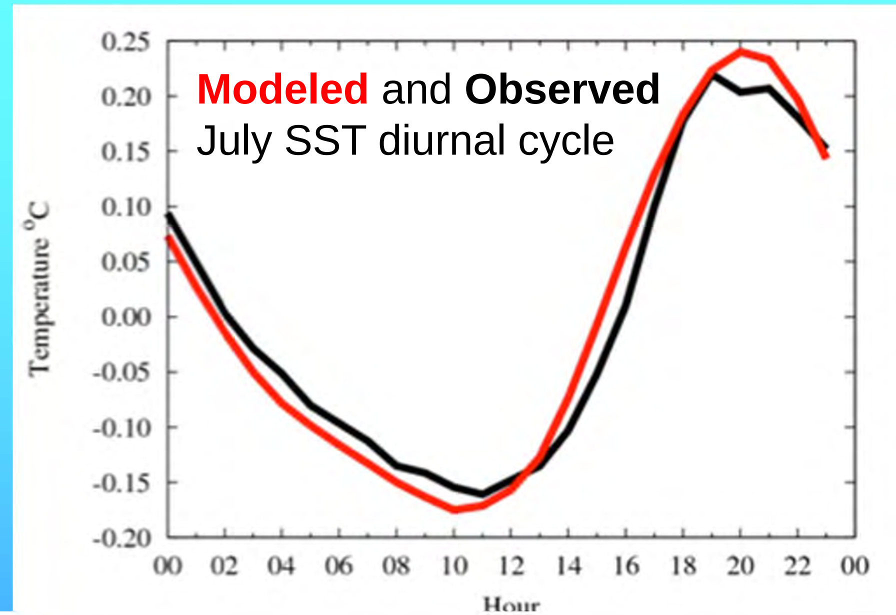
Ling, T.-J., X.-Z. Liang, M. Xu, Z. Wang, and B. Wang, 2011: A multilevel ocean mixed-layer model for 2-dimension applications. *Acta Oceanologica Sinica*, **33**(03), 1-10.

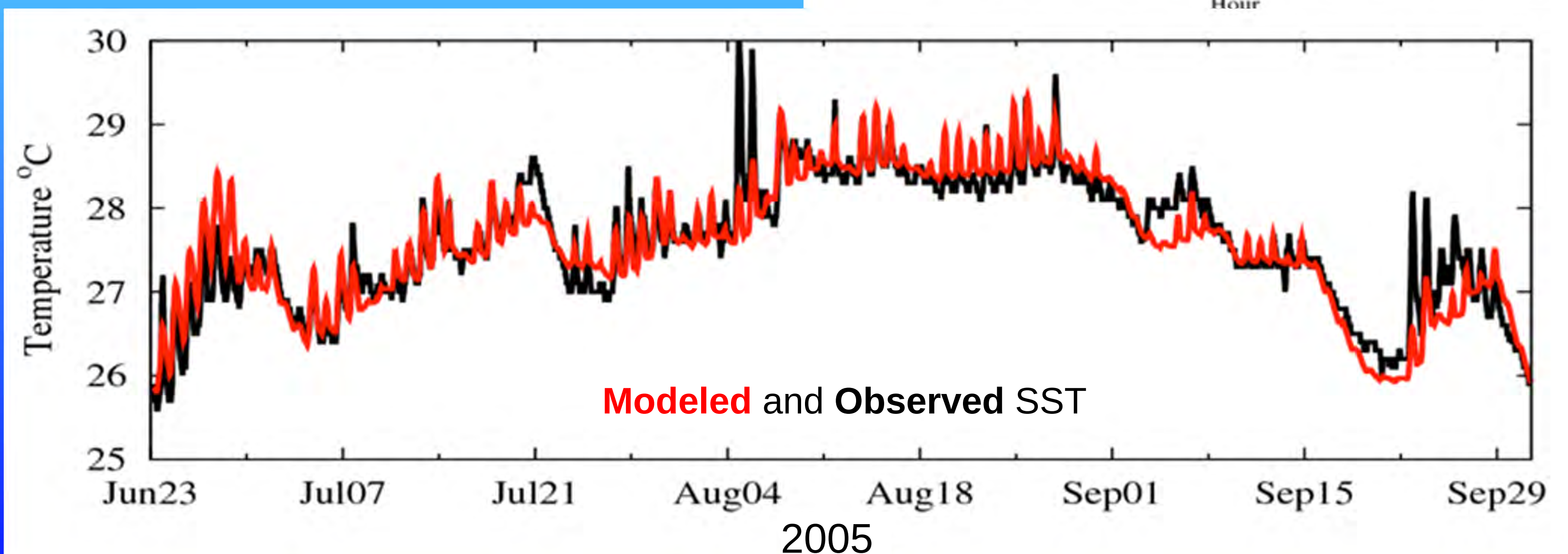
Ling, T.-J., M. Xu, X.-Z. Liang, J.X.L. Wang, and Y. Noh, 2012: A multilevel ocean mixed-layer model: Development and application. *J. Phys. Ocean.* (to be submitted).

CWRF MLO (upper 300m ocean)

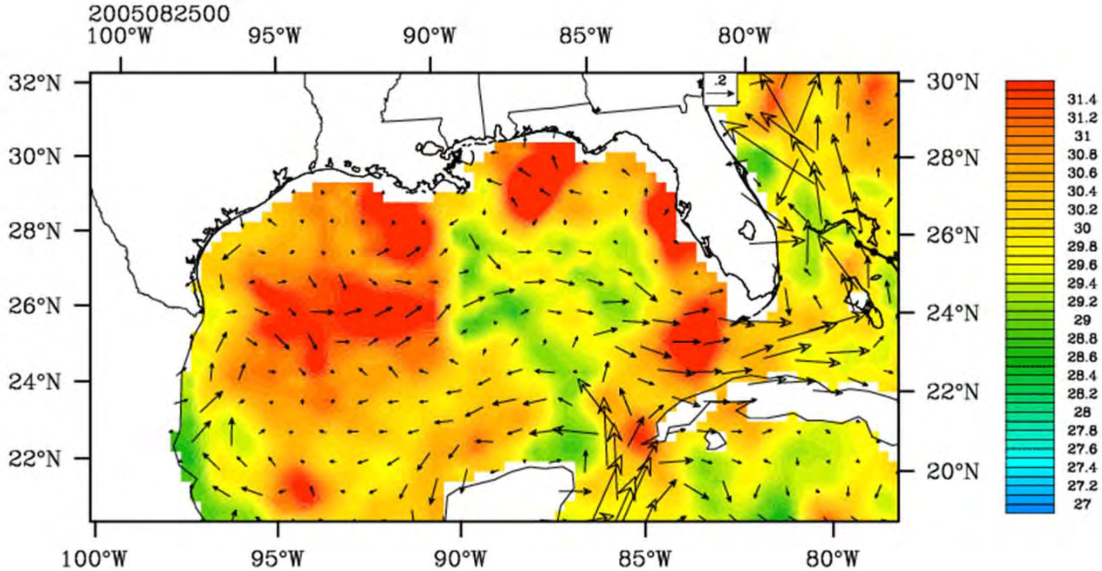
- **Transient sea-air interactions**
- **Significant diurnal cycle**
- **Crucial for hurricane/typhoon**
- **Cost-effective**



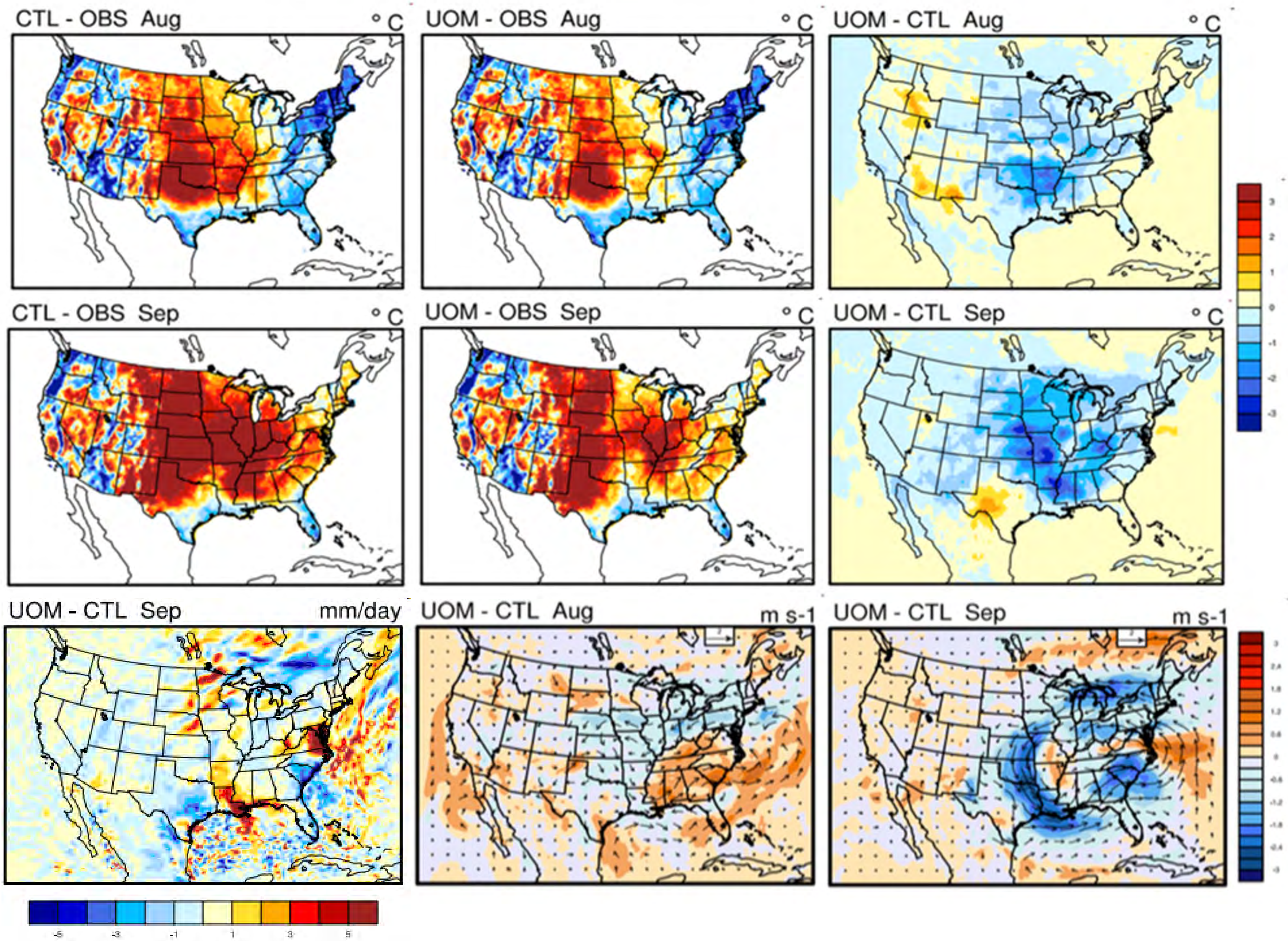




Hurricane Katrina August 23-30, 2005



Coupling an Upper Ocean Model with CWRF



CWRF

Cumulus Convection

Optimized Ensemble Cumulus Parameterization

ECP

Qiao, F., and X.-Z. Liang, 2012: An ensemble cumulus parameterization: Optimization for mesoscale modeling over oceans. *J. Climate* (in preparation).

Qiao, F., and X.-Z. Liang, 2012: An ensemble cumulus parameterization: Optimization for mesoscale modeling over land. *J. Climate* (in preparation).

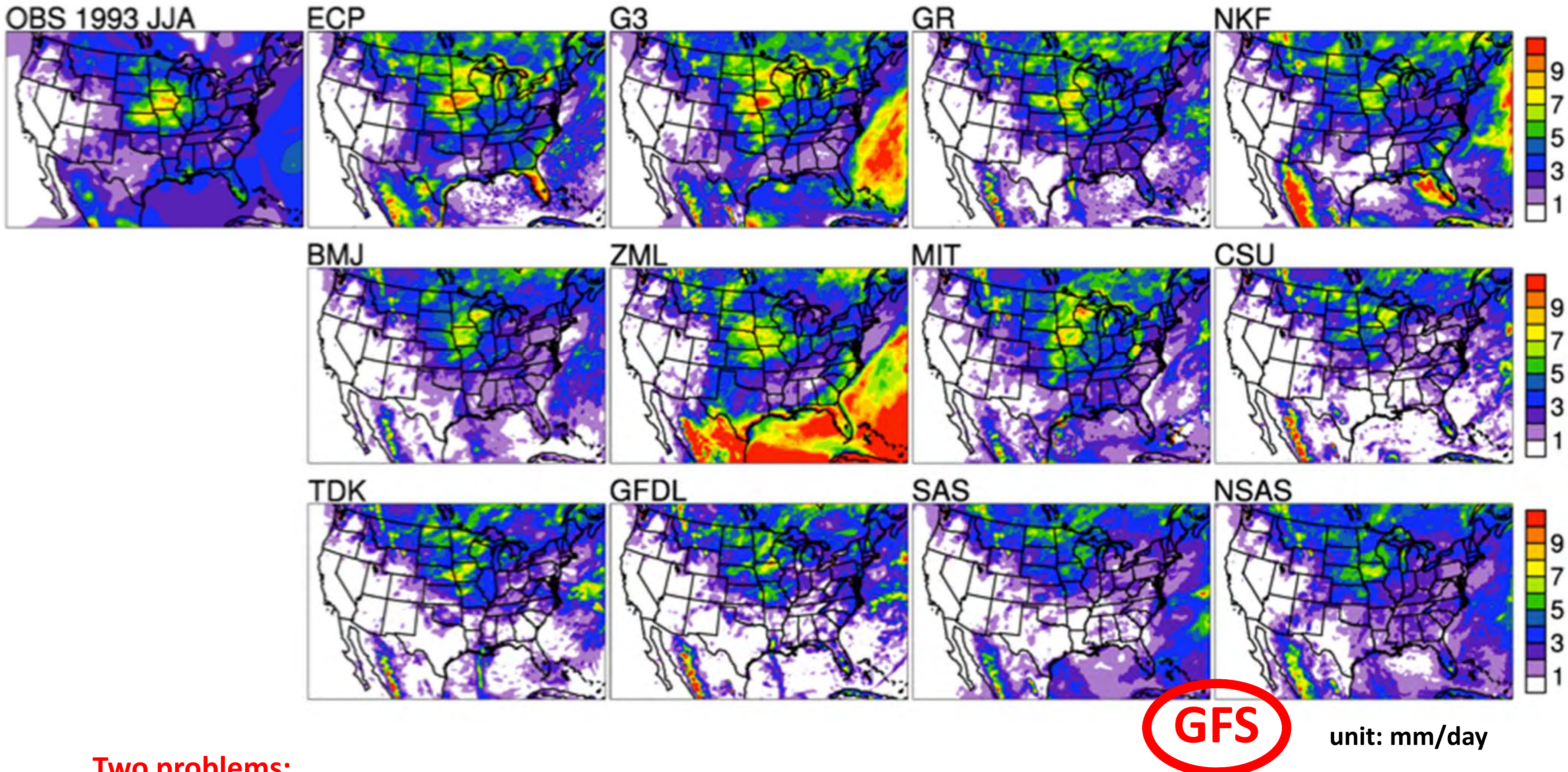
Qiao, F., and X.-Z. Liang, 2012: Precipitation diurnal cycle sensitivity to cumulus parameterization. *J. Climate* (in preparation).

Cumulus Parameterization Schemes in CWRF

ECP (Ensemble Cumulus Parameterization, modified from G3) **multiple cumulus closures and variants that can be selectively used with different weights**	**ZML (Zhang-McFarlane Parameterization modified by Liang)** **quasi-equilibrium assumption** **free tropospheric large-scale forcing**
G3 (Grell and Dvénéyi 2002) **Ensemble cumulus closures**	**MIT (Emanuel 1991)** quasi-equilibrium assumption
GR (Grell 1993) quasi-equilibrium assumption	**CSU (Pan and Randall 1998)** quasi-equilibrium assumption Prognostic cumulus kinetic energy
NKF (New Kain-Fritsch) **remove the CAPE in a convective timescale**	**TDK (Tiedtke scheme)** **remove the CAPE in a convective timescale**
BMJ (Bett-Miller-Janjic) **Convective adjustment scheme**	**GFDL (Donner 1993, Donner et al. 2001)** **remove the CAPE in a convective timescale** **Convective scale vertical velocities**
NSAS (New Simplified Arakawa-Schubert) quasi-equilibrium assumption	**SAS (Simplified Arakawa-Schubert)** quasi-equilibrium assumption

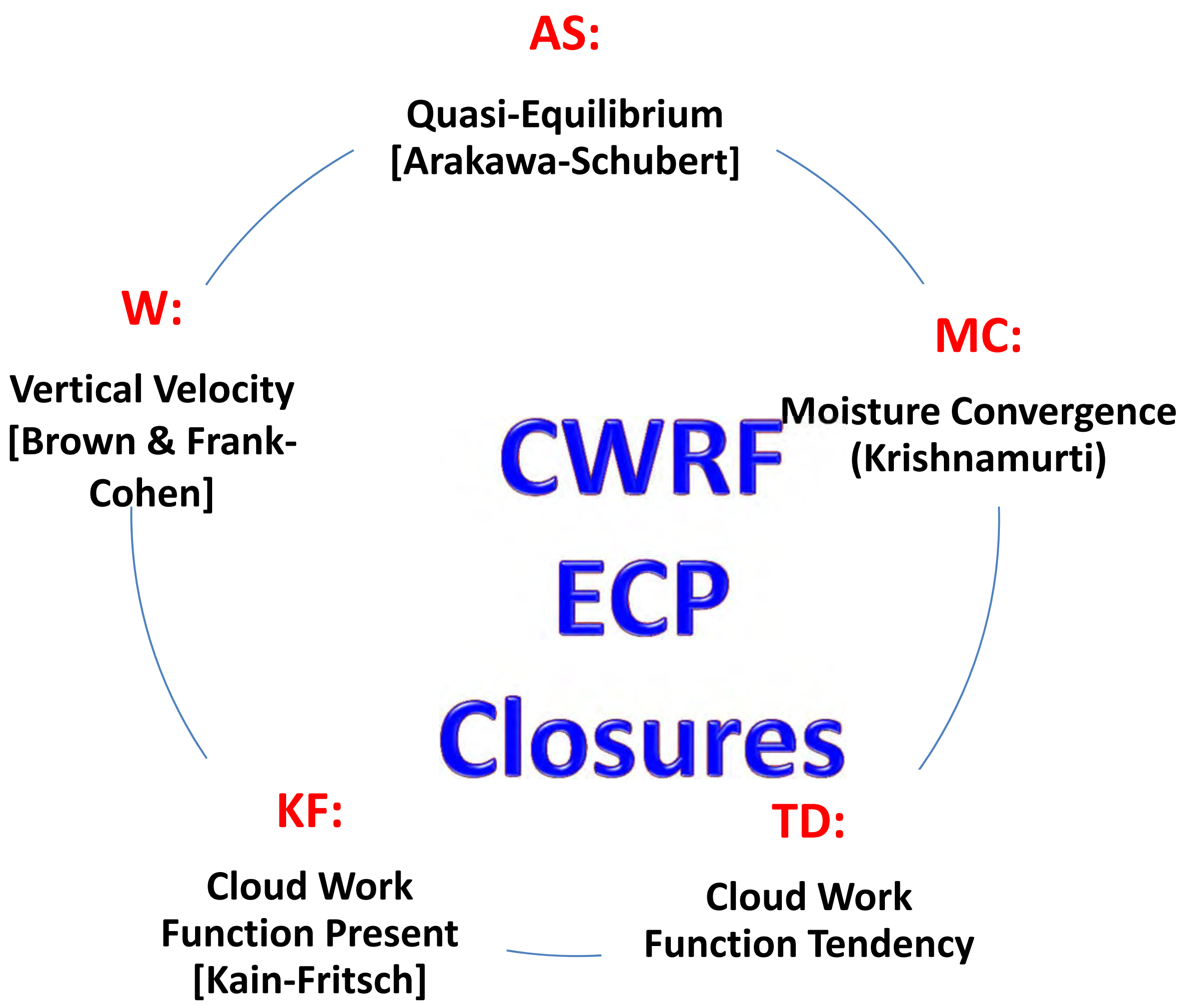
CWRF Simulation of 1993 Summer Flood

Comparing 12 widely-used cumulus schemes



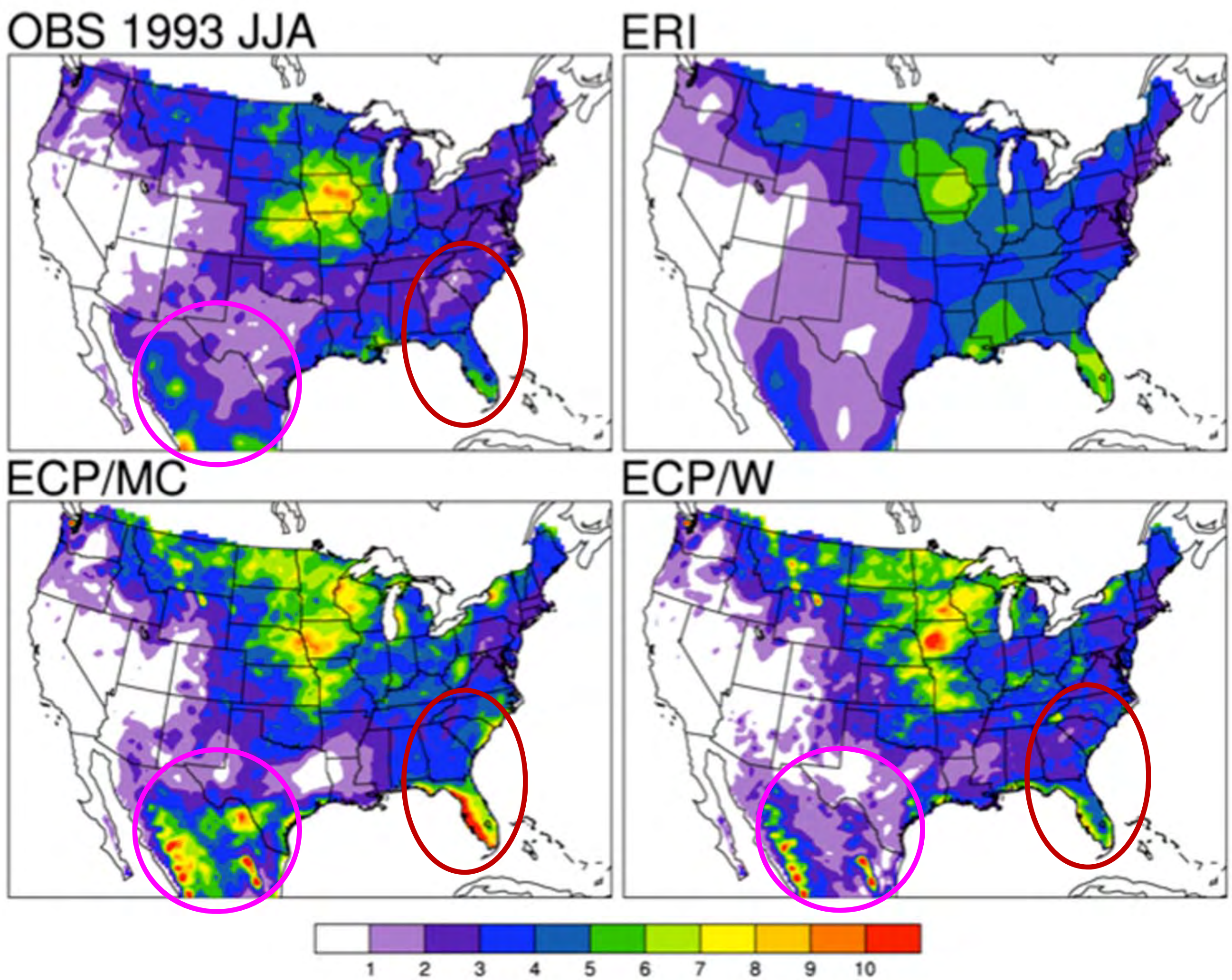
Two problems:

1. ECP most realistically captures the U.S. Midwest flood, but still overestimates the rainfall over the Southeast U.S., implying the moisture convergence closure is not suitable for all the U.S. land area;
2. G3,NKF,ZML schemes all overestimate the precipitation over the U.S. east coastal ocean. However, ECP using cloud work function tendency closure over the ocean significantly alleviates this wet bias.


AS:
Quasi-Equilibrium [Arakawa-Schubert]
MC:
Moisture Convergence (Krishnamurti)
TD:
Cloud Work Function Tendency
KF:
Cloud Work Function Present [Kain-Fritsch]
W:
Vertical Velocity [Brown & Frank-Cohen]
CWRF
ECP
Closures

Precipitation Prediction Improvement over Land

ECP: Moisture Convergence Closure versus Vertical Velocity Closure



Precipitation Prediction Improvement over the U.S. East Coast Ocean

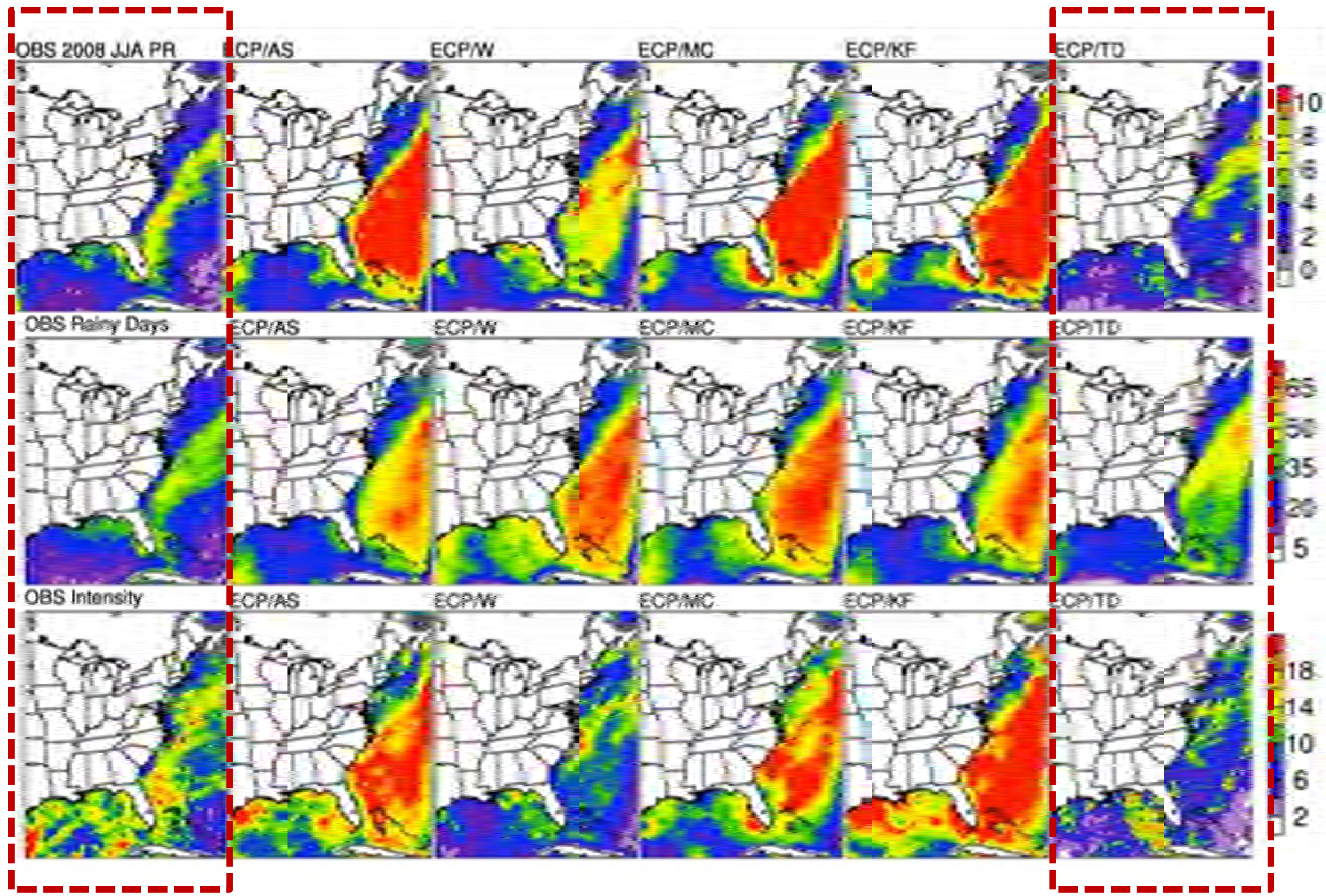
Land: MC closure

Ocean: Sensitivity Experiments [AS, W, MC, KF, TD]

2008 JJA Mean Rainfall [mm/day]

Number of Rainy Days

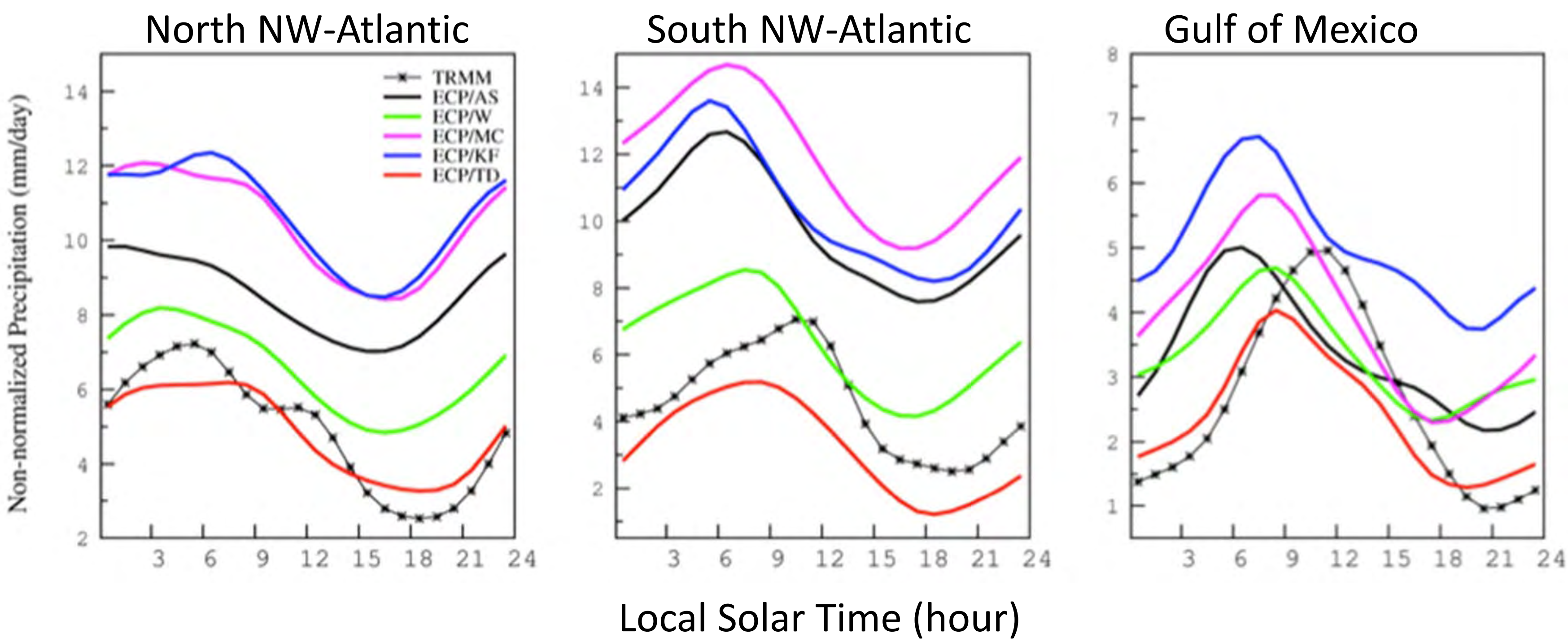
Rainfall Intensity [mm/day]



Precipitation Diurnal Cycle Simulated by CWRF/ECP with different closures over the U.S. East Coast Ocean (2008 JJA)

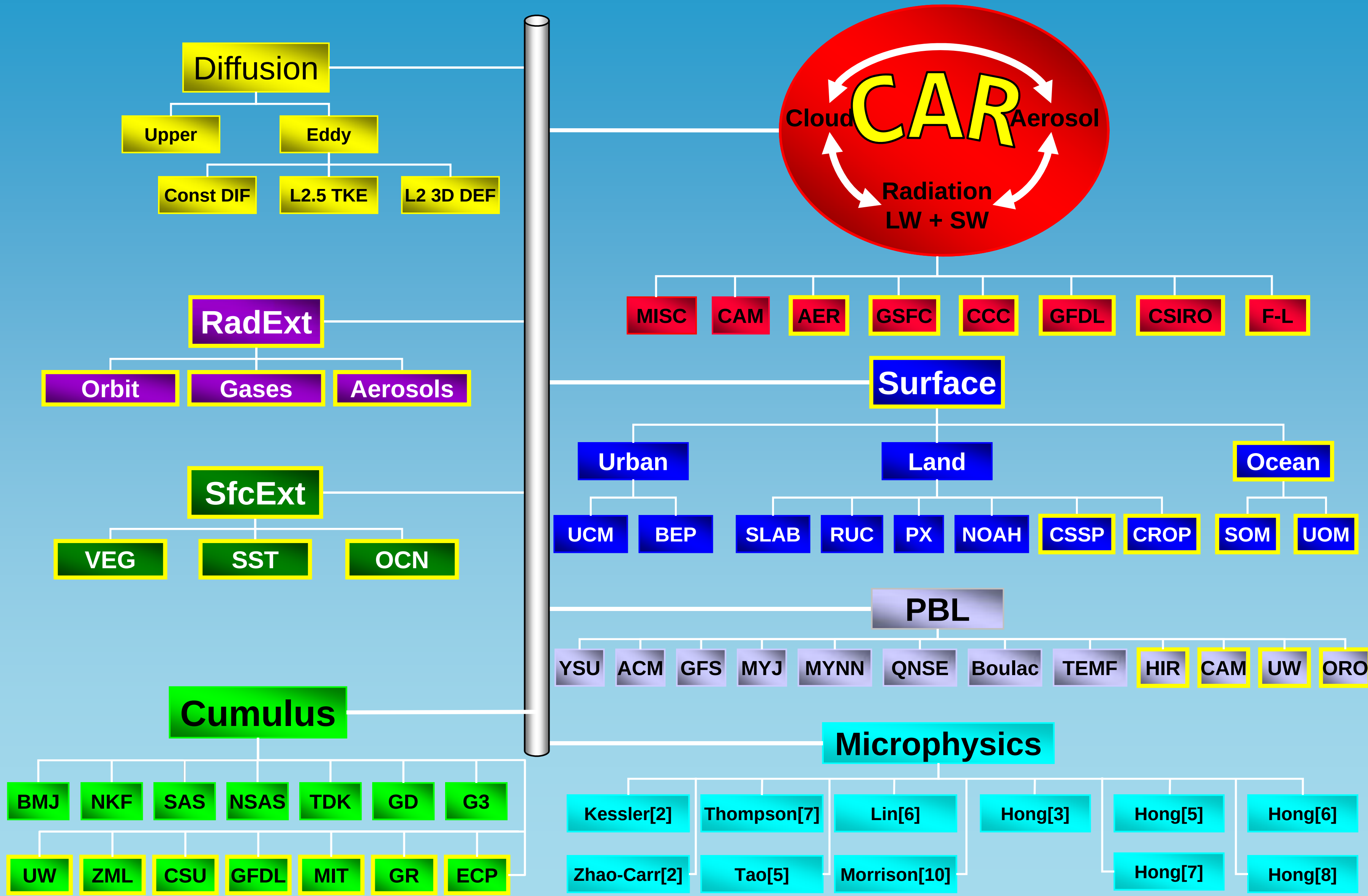
Land: MC closure

Ocean: Sensitivity Experiments [AS, W, MC, KF, TD]



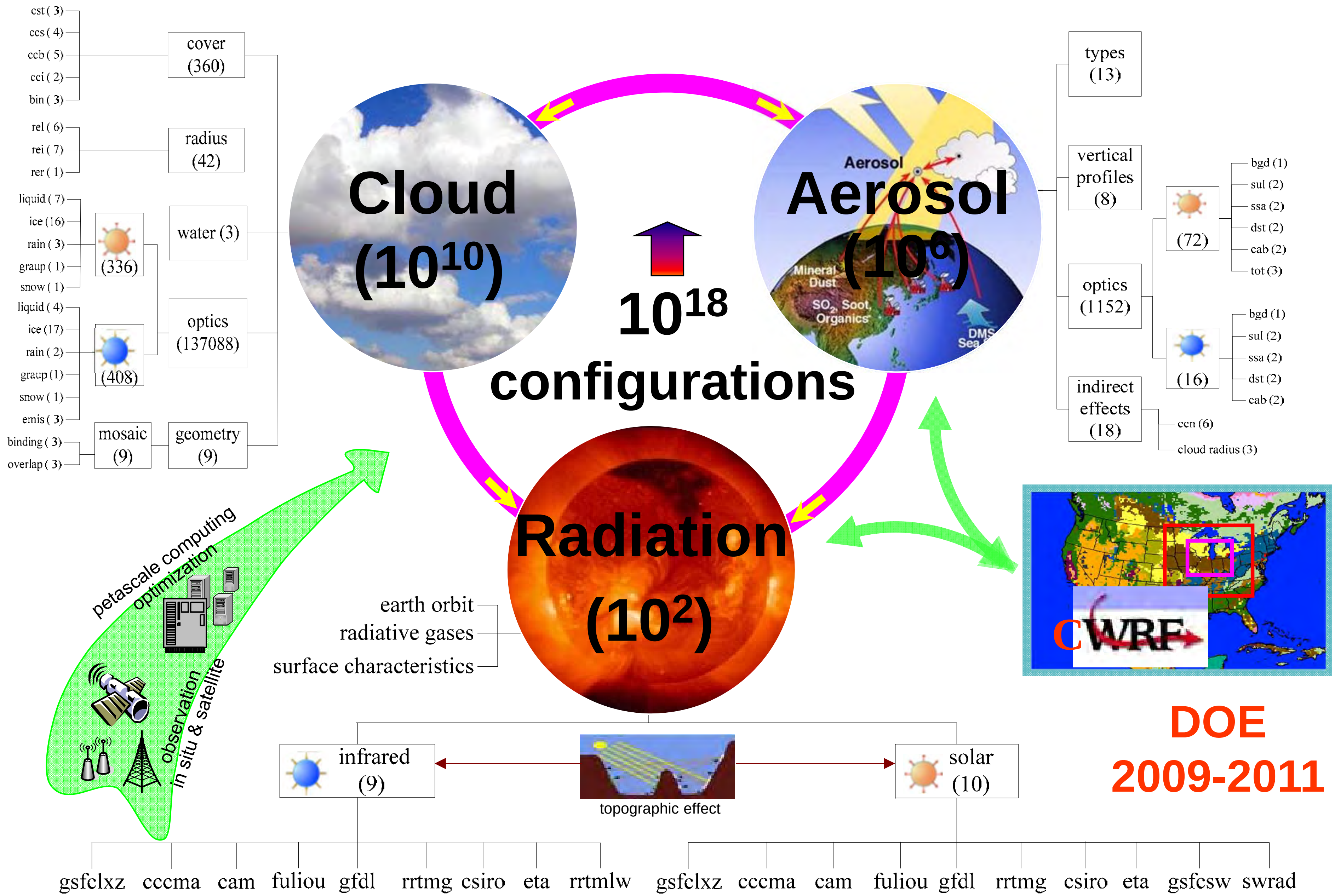
TD closure over the ocean most realistically reproduce the rainfall diurnal cycle

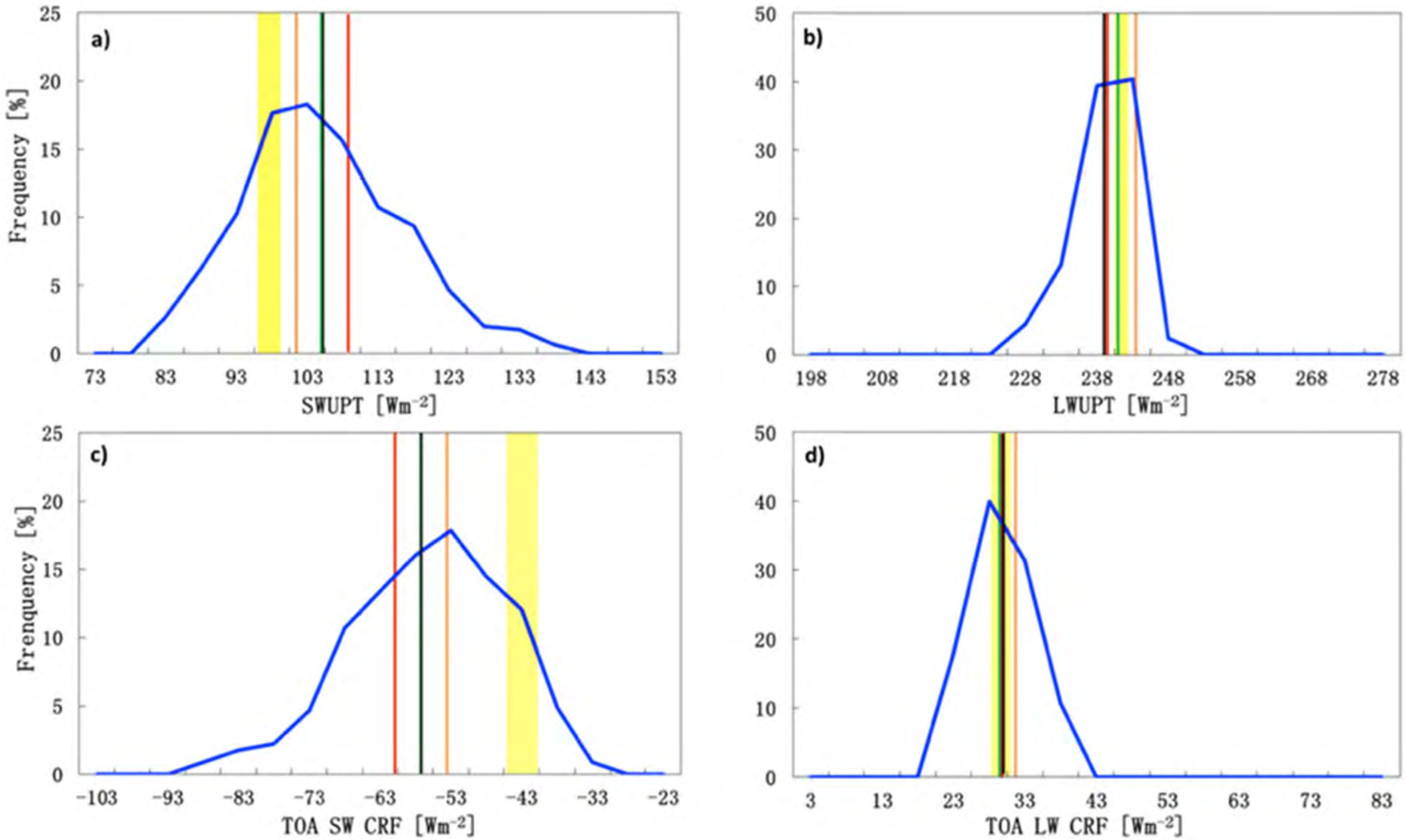
CWRF Physics Options



http://cwrf.umd.edu

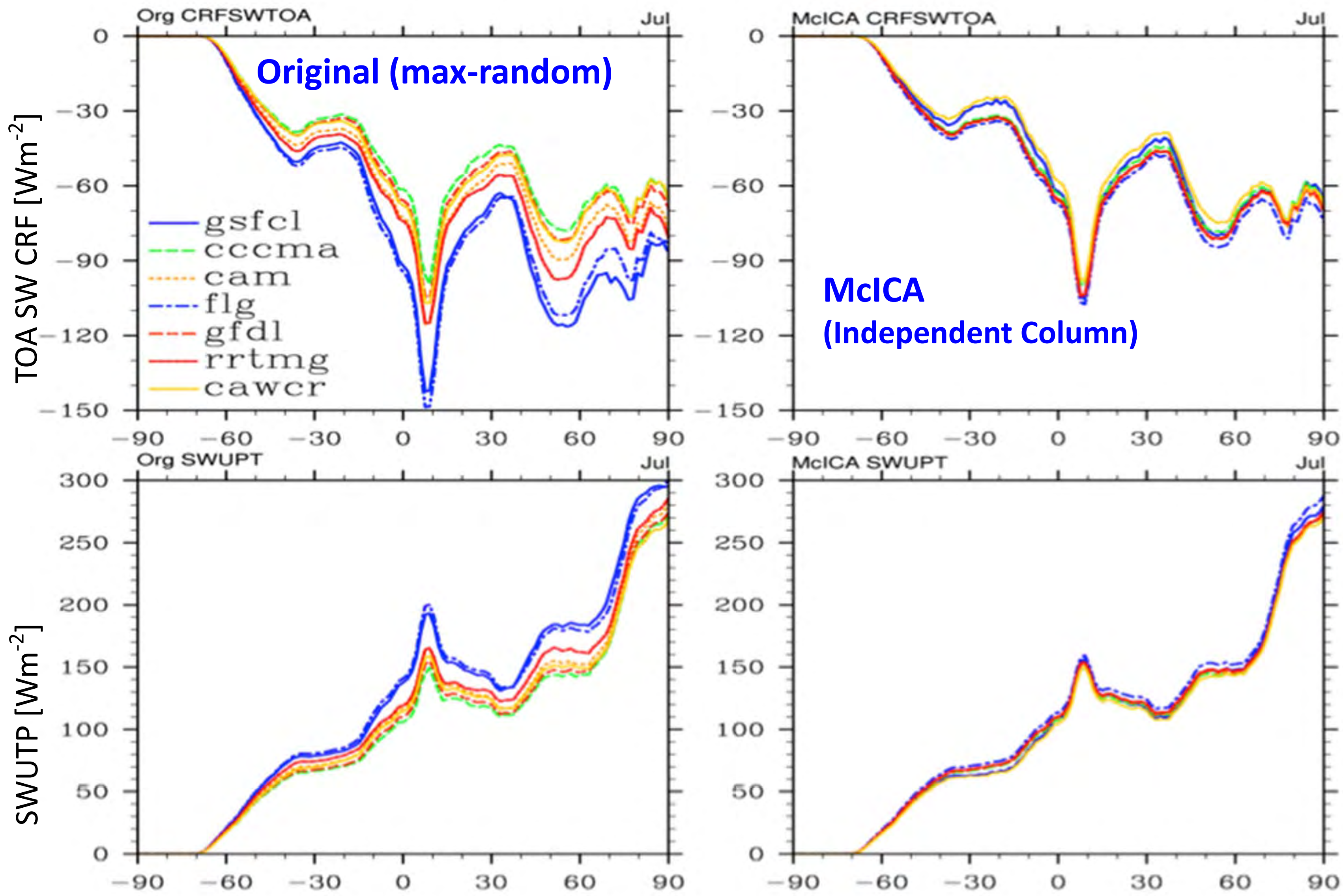
Cloud-Aerosol-Radiation Ensemble Model





Frequency distribution of TOA radiative flux and CRF averaged over [60ºS, 60ºN] in January 2004 from the CAR ensemble of 960 members

CAR Identifies Key Cloud Geometry Effect



Stratiform Cloud Prediction

CAM5:

$$a_{l,st} = \begin{cases} 1 & \text{if } U_l \geq \hat{U}_l, \\ 1 - \left[C3\sqrt{2} \cdot (C\hat{U}_l - U_l\hat{U}_l - U_{cl})\right]^{\frac{2}{3}} & \text{if } C16 \cdot (5 + U_{cl}) \leq U_l \leq \hat{U}_l, \\ 4 \cdot \cos\left[C13 \cdot \left\{acos\left(C32 \cdot \sqrt{2} \cdot (CU_l - U_{cl}\hat{U}_l - U_{cl})\right) - 2 \cdot \pi\right\}\right] & \text{if } U_{cl} \leq U_l \leq C16 \cdot (5 + U_{cl}), \\ 0 & \text{if } U_l \leq U_{cl} \end{cases}$$

$$a_{i,st} = [CU_i - U_{ci}\hat{U}_i - U_{ci}]^2 \qquad U_i = [Cq_v + q_i q_{s,i}]$$

$$ast = \max(a_{l,st}, a_{i,st})$$

NMM (Brad Ferrier):

$$ast = \begin{cases} 1.0 & RH_{tot} \geq RH_{max}, \\ \int_{RH_{min}}^{RH_{tot}} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-u)^2}{2\sigma^2}} dx & RH_{min} \leq RH_{tot} \leq RH_{max}, \\ 0 & RH_{tot} \leq RH_{min} \end{cases}$$

$$a_{l,st} = \begin{cases} ast & t \geq 263.15, \\ 0 & t \leq 253.15, \\ ast \times \frac{t - 253.15}{10} & 253.15 < t < 263.15 \end{cases}$$

$$a_{i,st} = \begin{cases} ast & t \leq 263.15, \\ 0 & t \geq 273.15, \\ ast \times \frac{273.15 - t}{10} & 263.15 < t < 273.15 \end{cases}$$

Old

$u = 1.0$

$\sigma = 0.04\ (0.01)$

$RH_{min} = 0.879\ (0.969)$

$RH_{max} = 1.121\ (1.031)$

For convective (non-convective) grid

New

$u = 0.99 (0.96)$

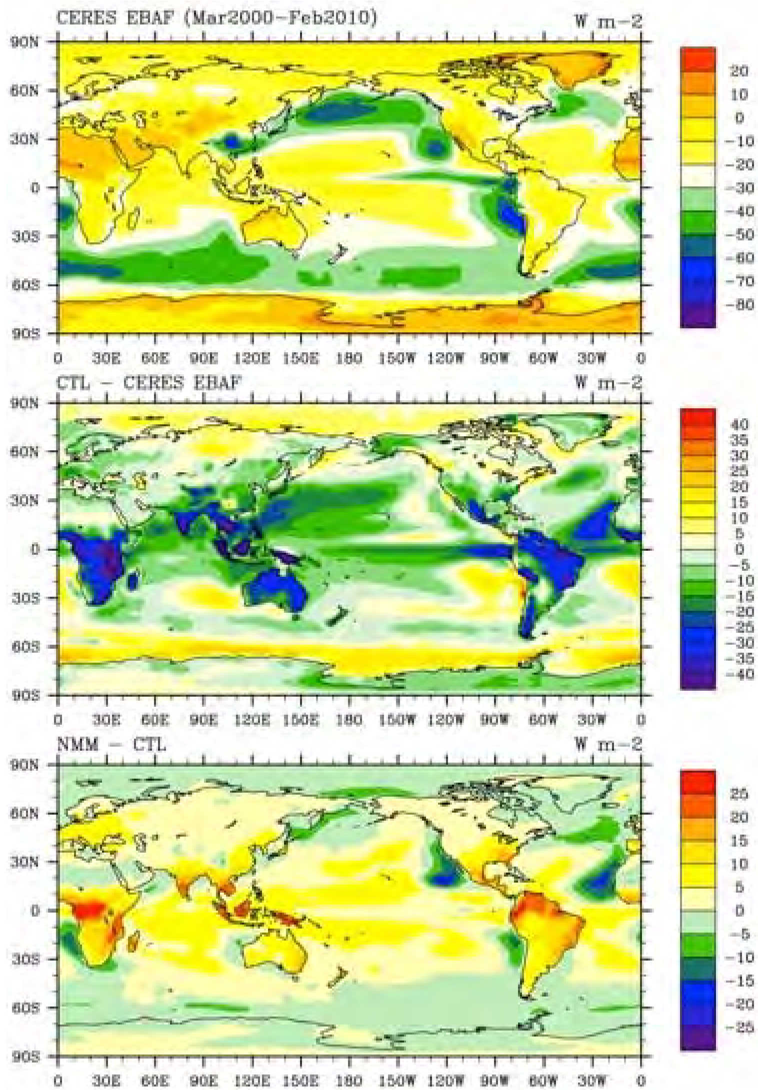
$\sigma = 0.03\ (0.02)$

$RH_{min} = 0.897\ (0.898)$

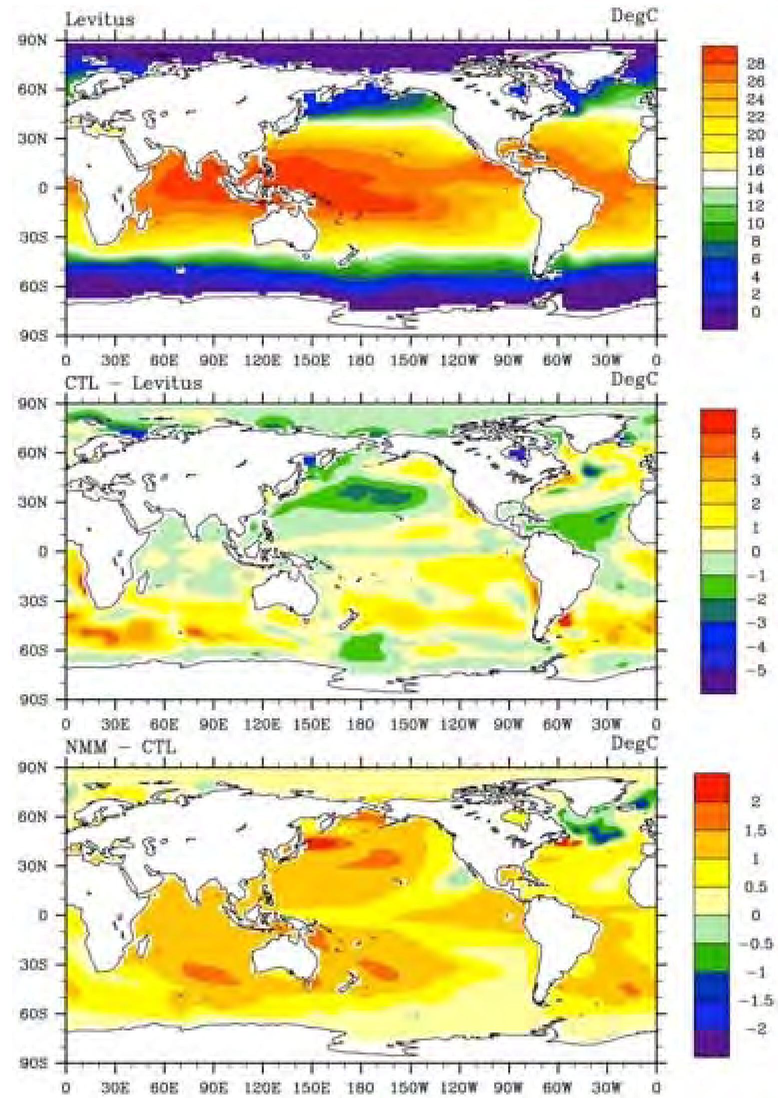
$RH_{max} = 1.083\ (1.022)$

For convective (non-convective) grid

Net Cloud Radiative Forcing (Annual)

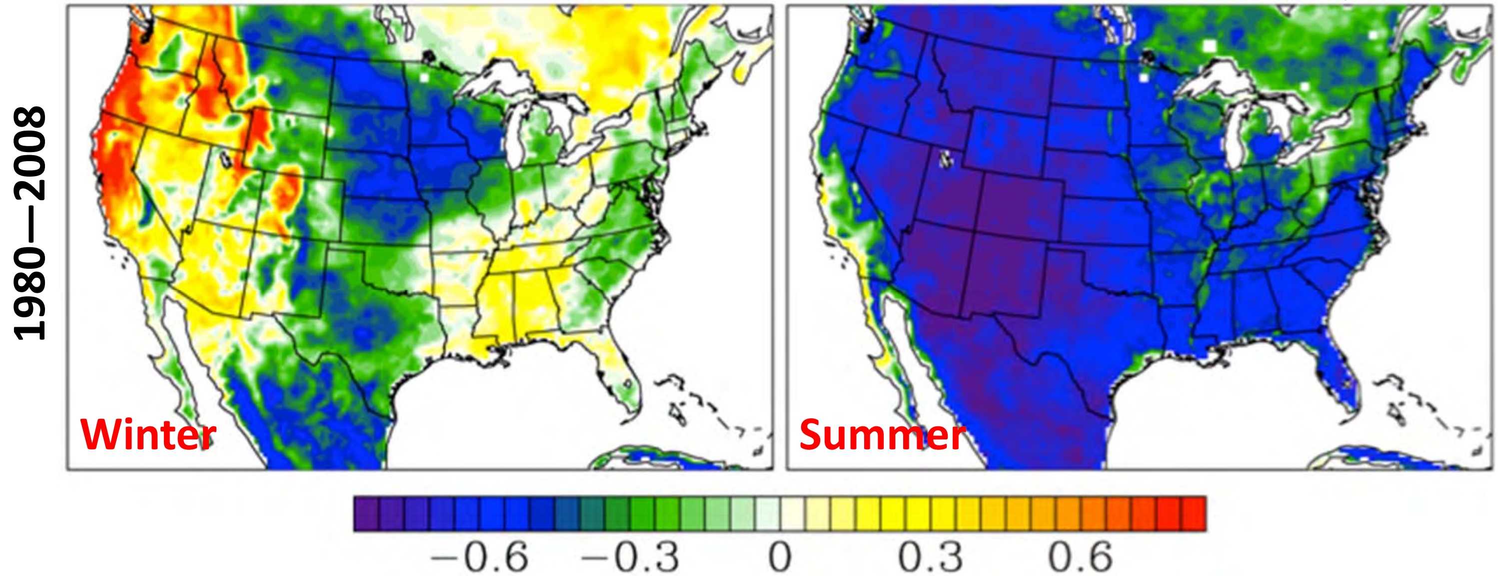


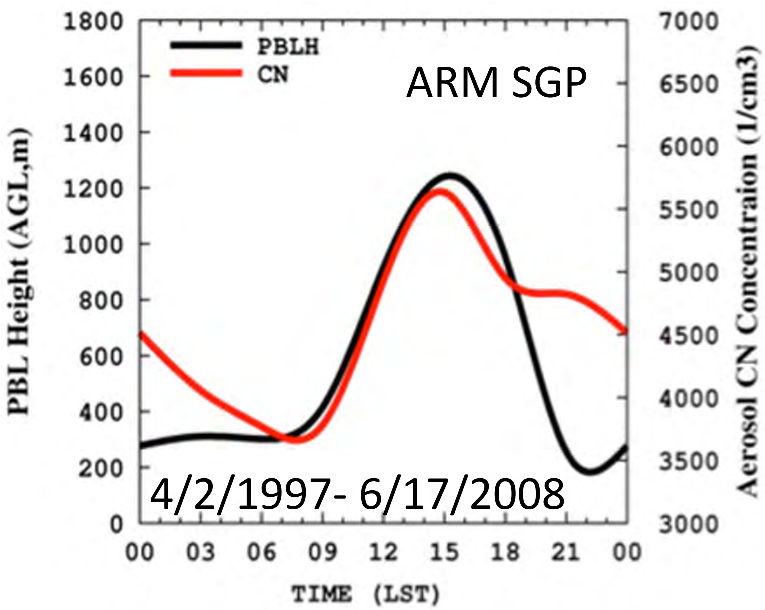
SST (Annual)

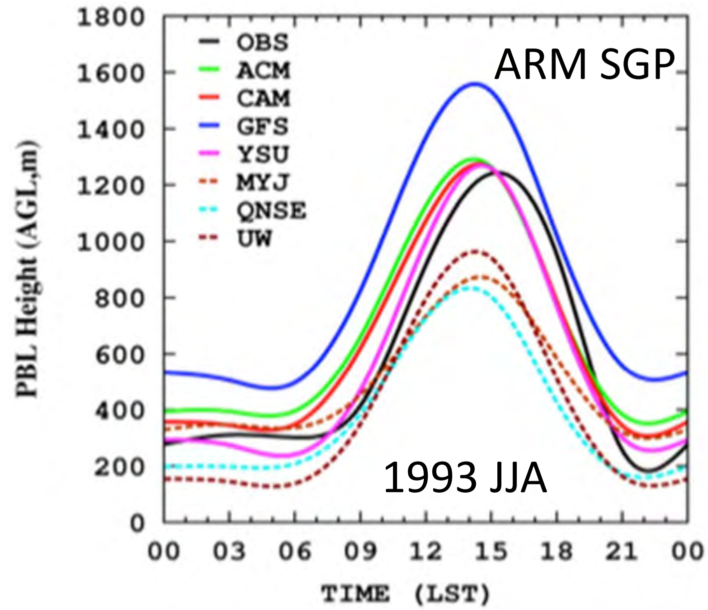


Relationship between PBL height and Precipitation, Aerosol CN

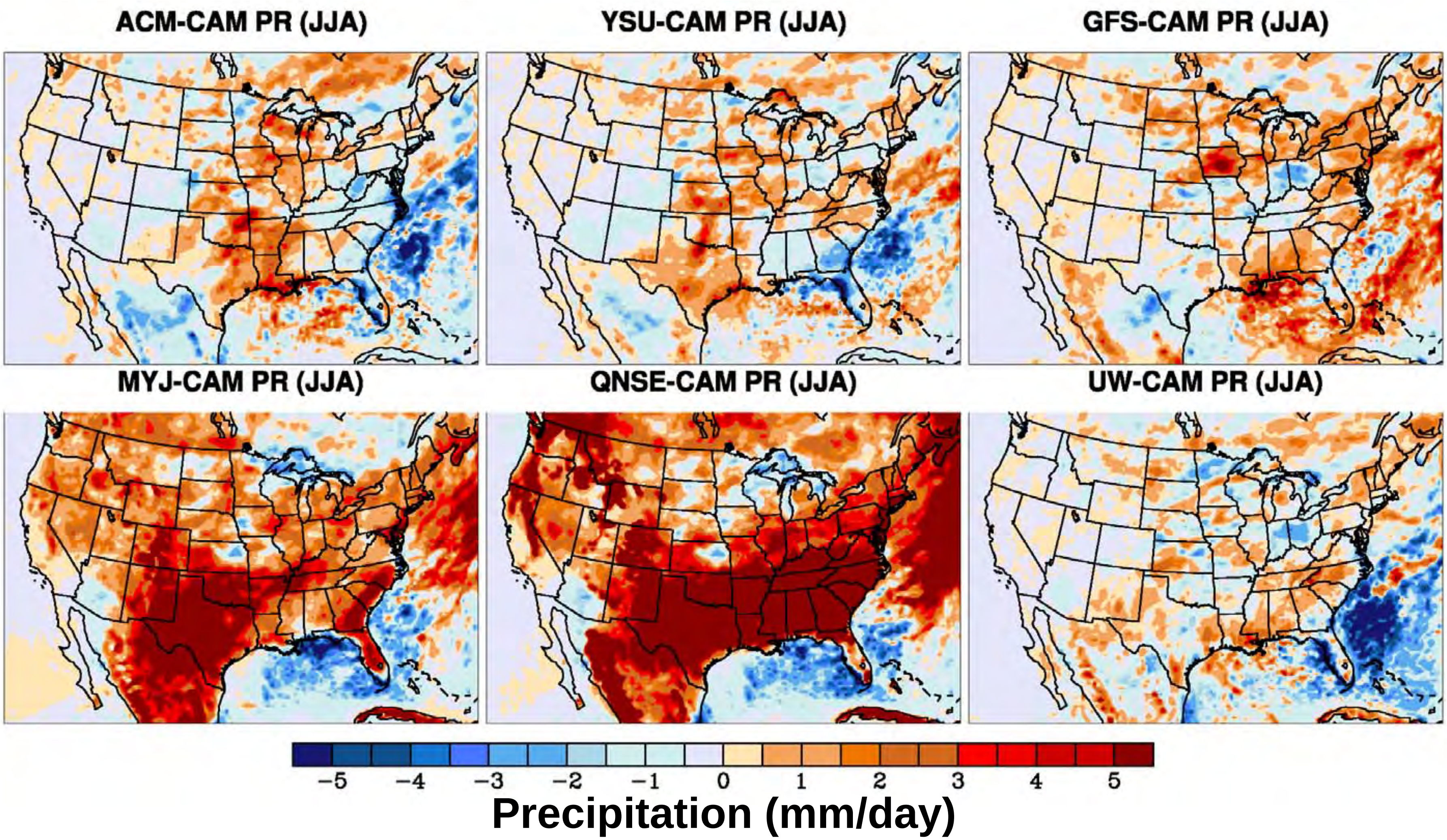
Correlation Coefficient between CWRF Simulated PBLH and Precipitation







CWRF Climate Sensitivity to PBL Schemes

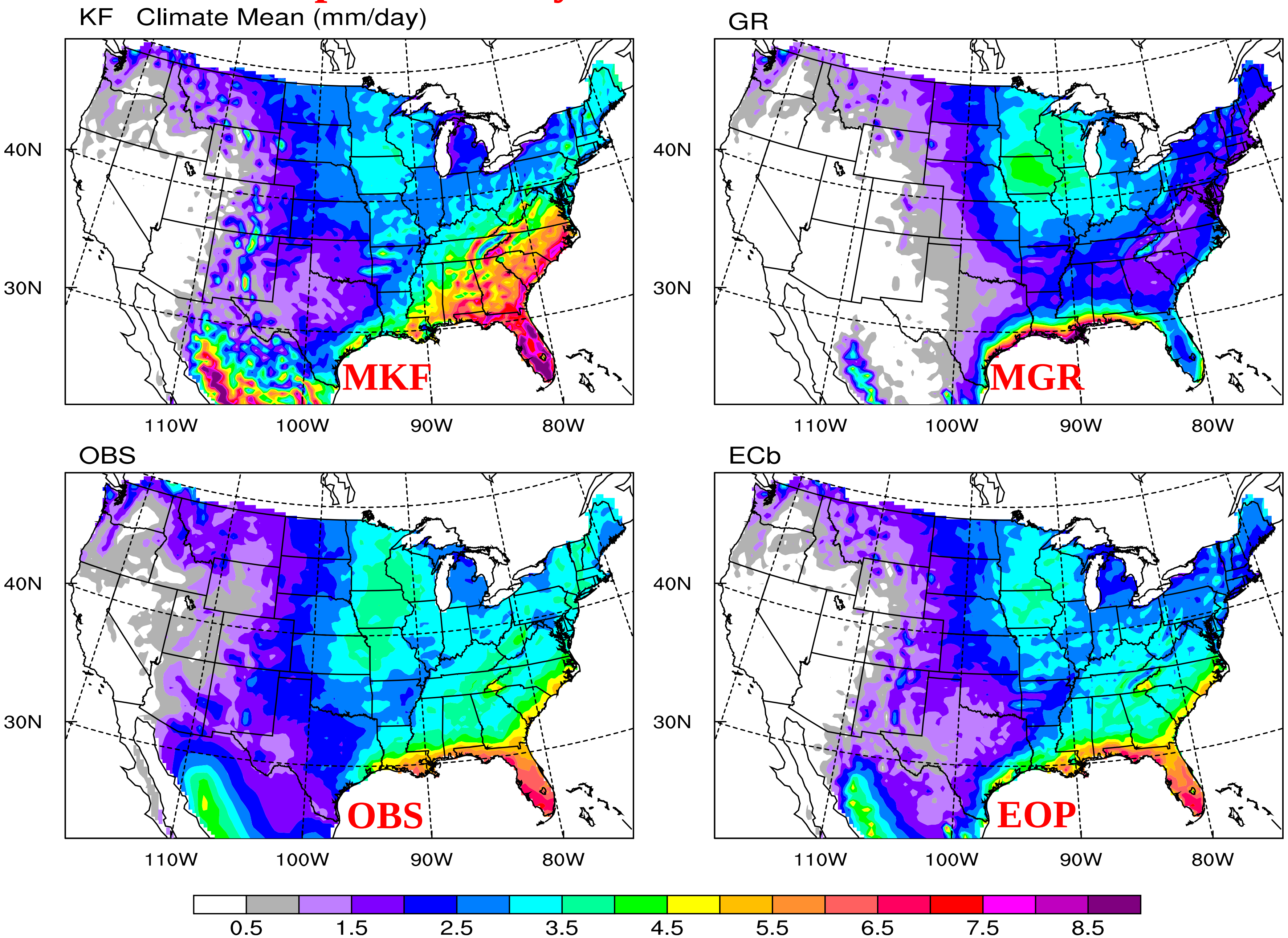


Optimized Physics Ensemble

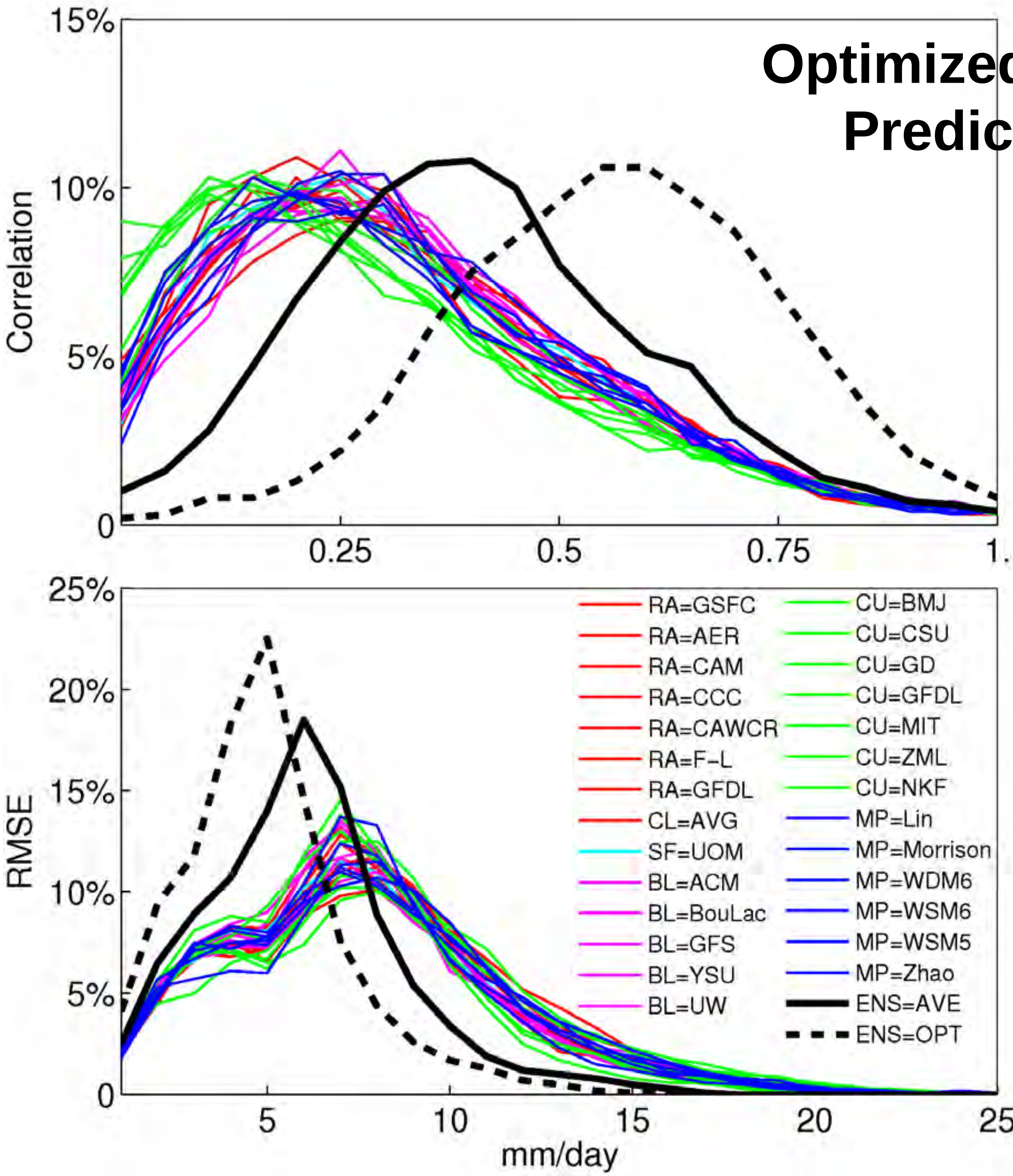
Increasing predictive skill

Quantifying uncertainty

Optimized Physics-Ensemble Prediction



Optimized Physics Ensemble Prediction of Precipitation In summer 1993



The physics ensemble mean substantially increases the skill score over individual configurations, and there exists a large room to further enhance that skill through intelligent optimization.

Spatial frequency distributions of correlations (*top*) and rms errors (*bottom*) between CWRF and observed daily mean rainfall variations in summer 1993. Each line depicts a specific configuration in group of the five key physical processes (*color*). The ensemble result (ENS) is the average of all runs with equal (Ave) or optimal (OPT) weights, shown as *black solid* or *dashed* line.

CWRF Refined Prediction

It is misleading to use the word "downscaling" for the CWRF refined prediction. CWRF is developed with detailed physics at regional to local scales. These advanced physics representations are the crucial factor that enables CWRF to have superior performance than the driving GCMs and other RCMs.

CWRF resolves physics processes at regional-local scales.

CWRF

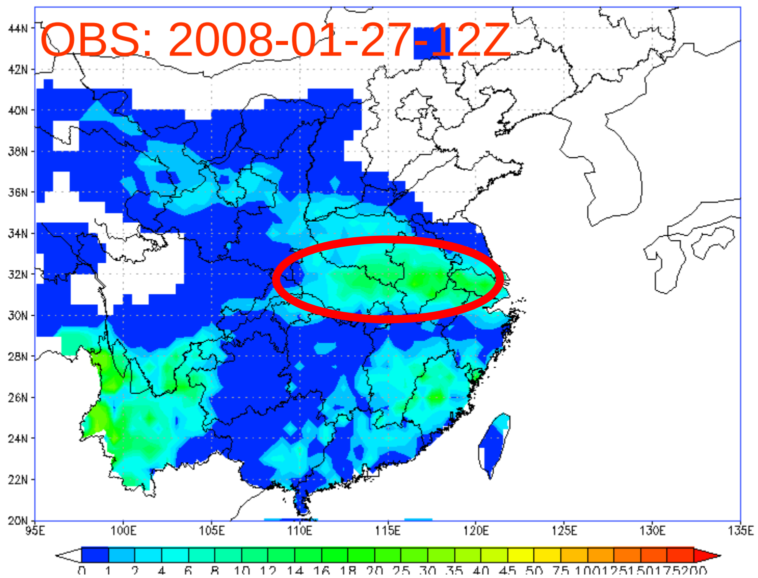
Operational Weather Forecast

Nested with NOAA Operational
GFS

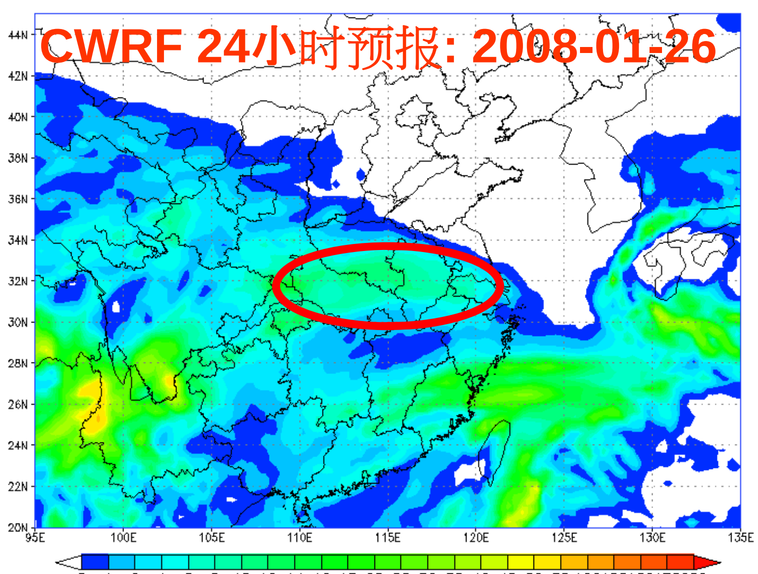
China

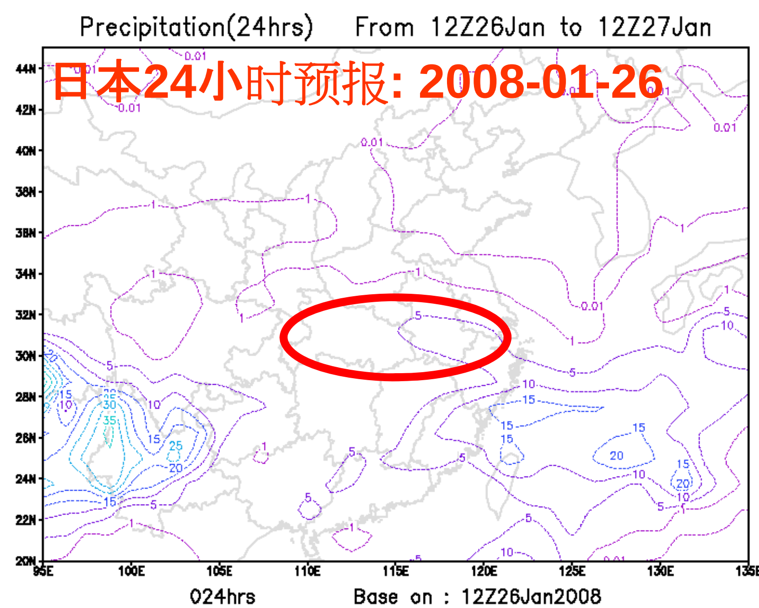
2008年中国春节南方大暴雪

2008年中国春节南方大暴雪实时预报

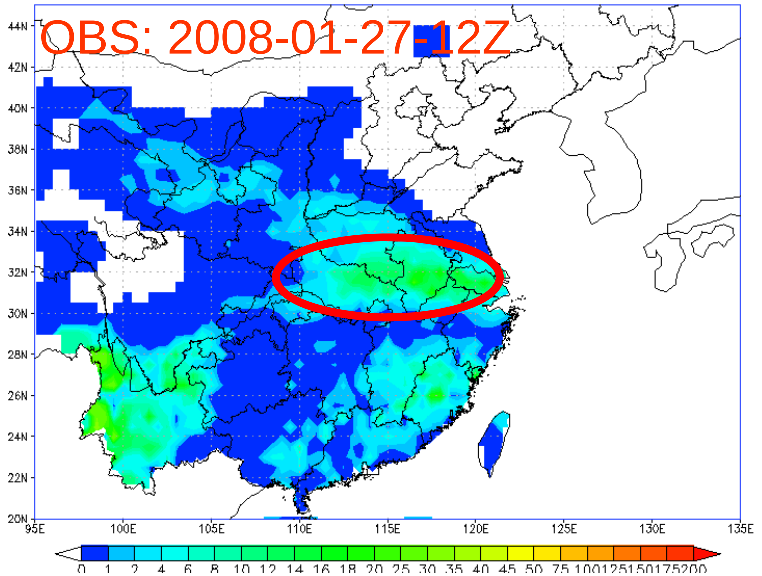


1月27日华北降水
日本24小时预报**失败**
CWRF24小时预报**准确**

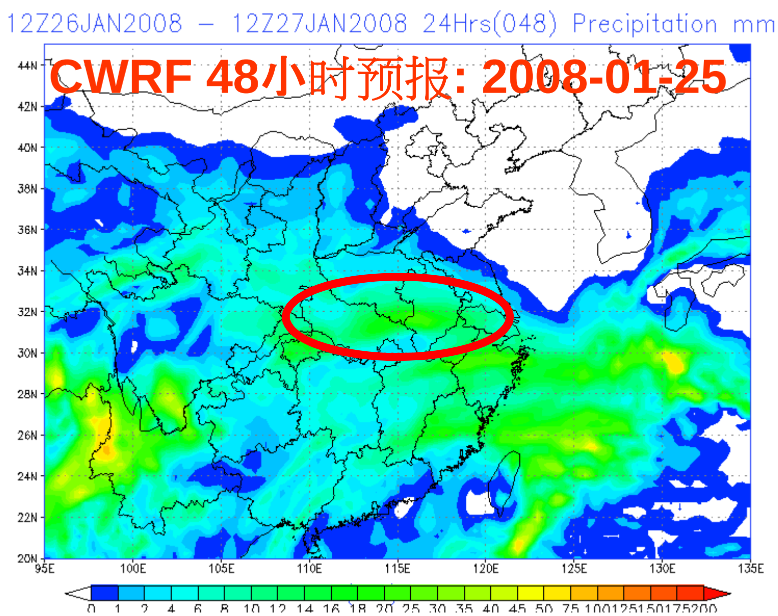


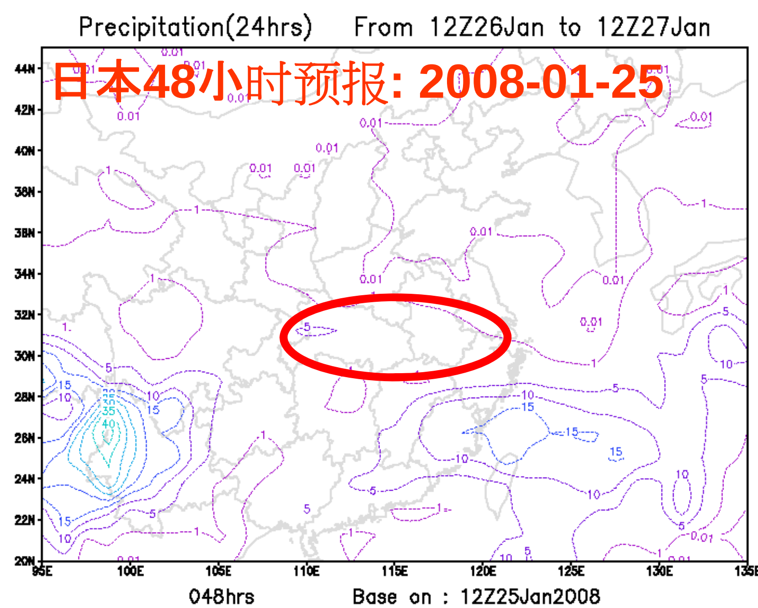


2008年中国春节南方大暴雪实时预报

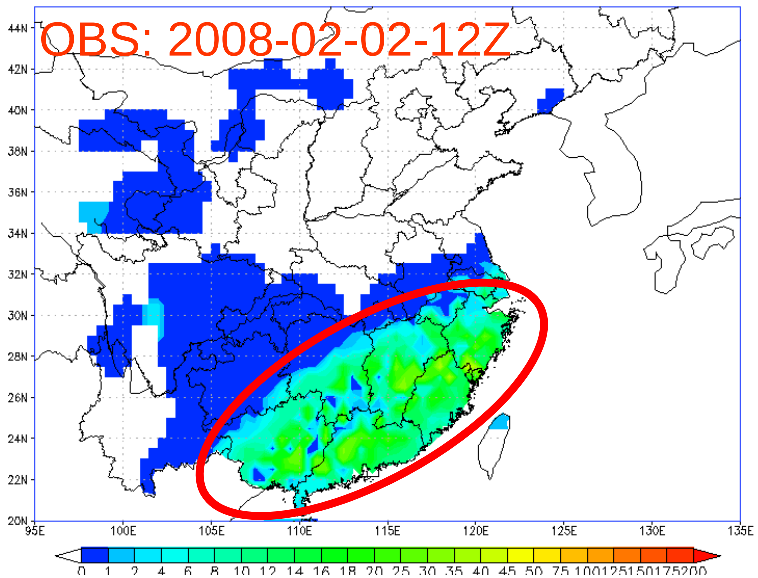


1月27日华北降水
日本48小时预报**失败**
CWRF48小时预报**准确**



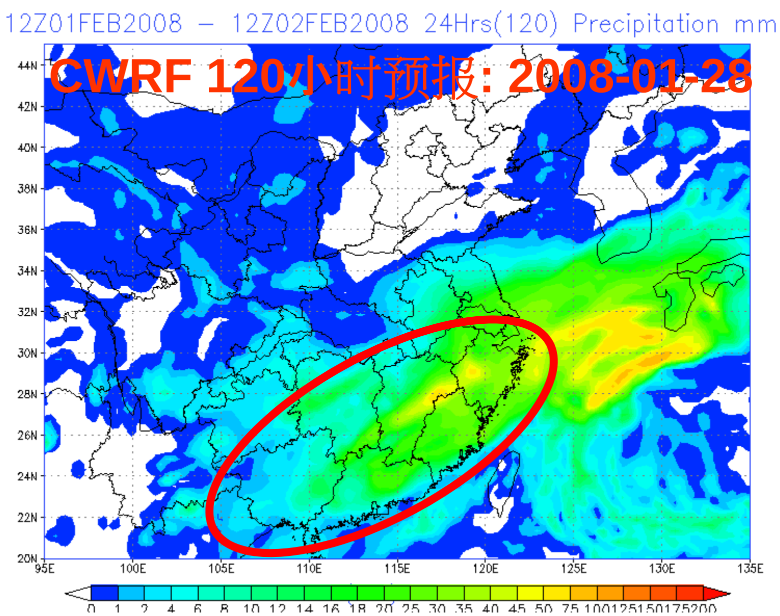


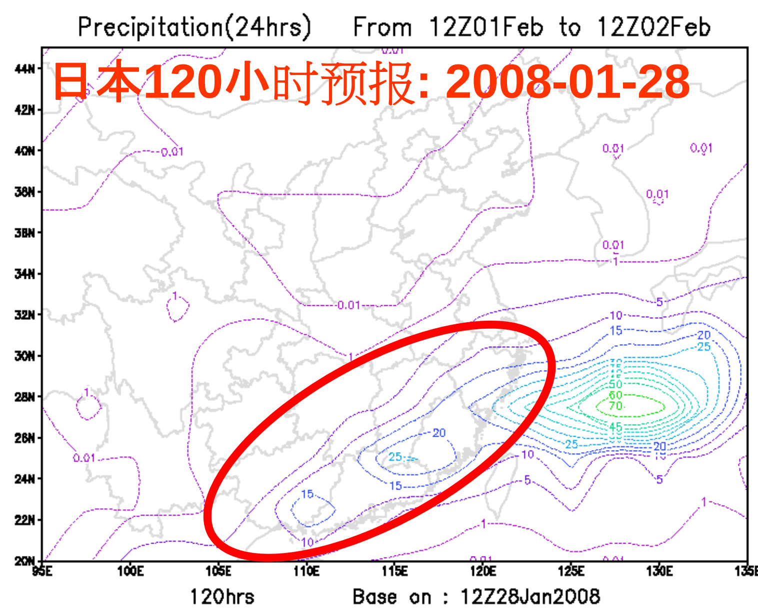
2008年中国春节南方大暴雪实时预报

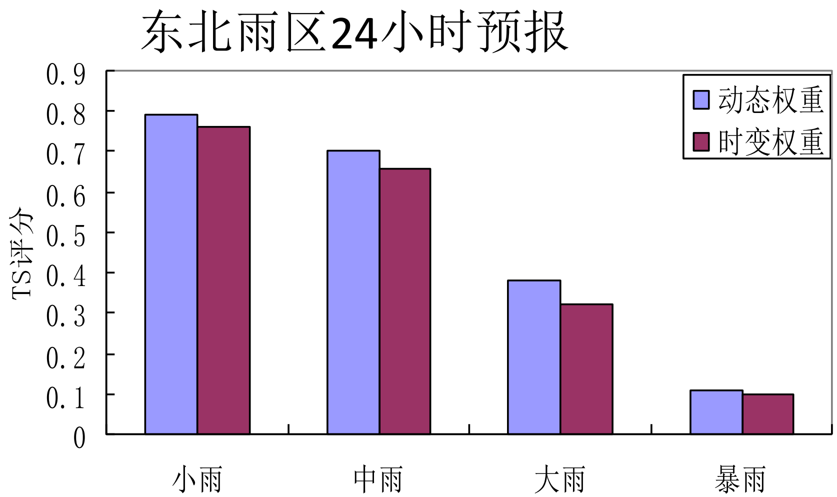


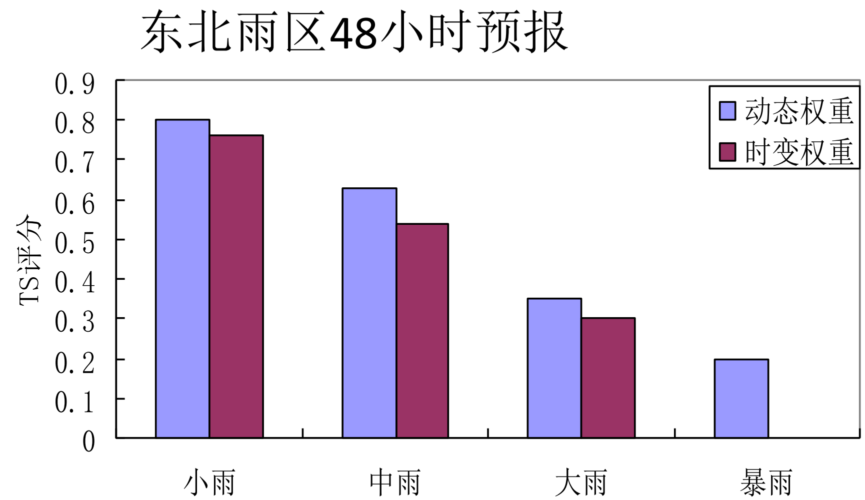
随着预报时间的增长，
CWRF预报能力高于日本。

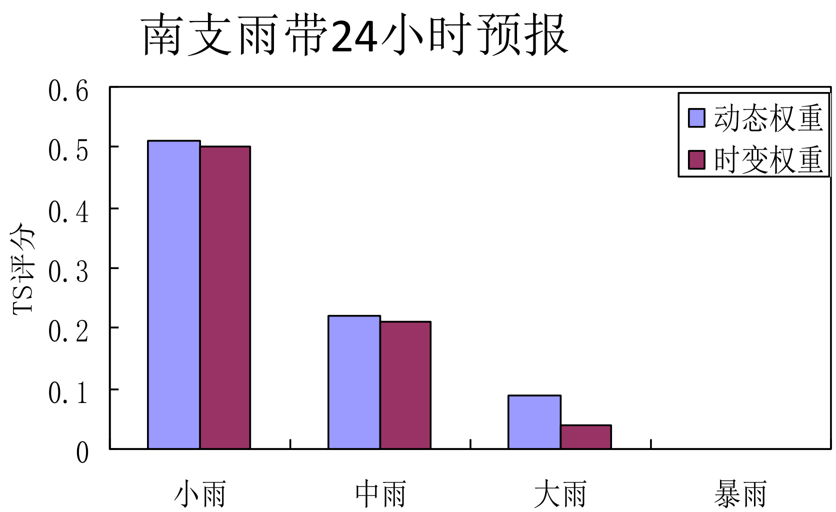
2008年2月2日长江以南的降水，
日本的120小时预报基本失败，
CWRF的结果很好。

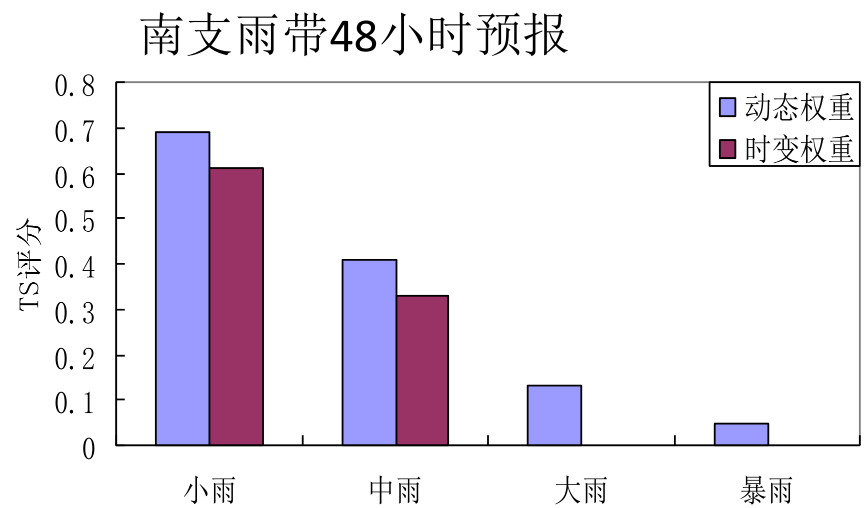




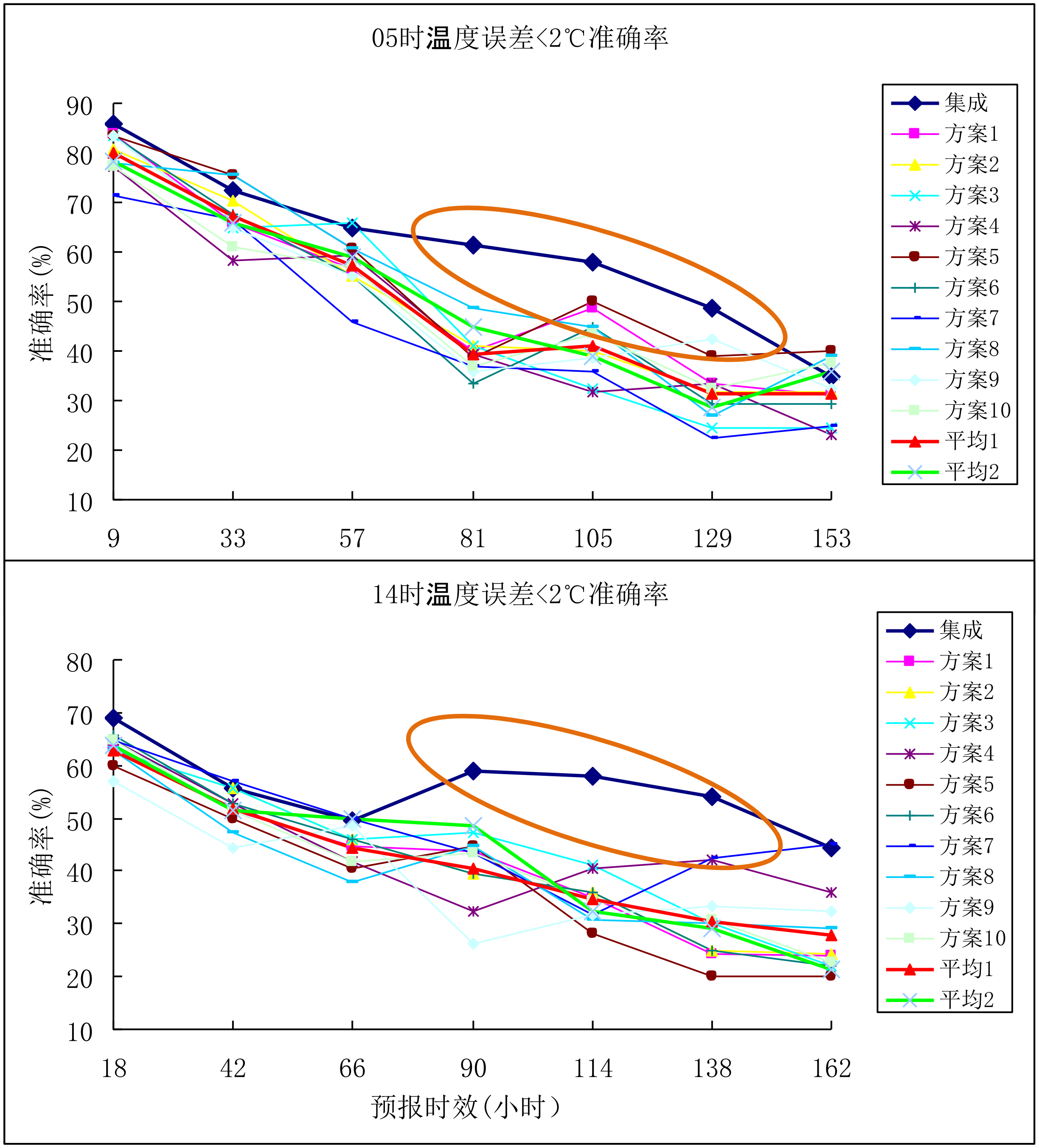








通过对南北两个雨区预报效果的综合评分，可以得到依据前期预报误差进行的动态权重的分配方案能有效地反映出不同参数化组合物理方案和在不同预报时效上的预报性能，比采用时滞权重的分配方案具有明显的预报优势。



CWRF 10套不同的物理参数化方案集成预报南京地区日最低、最高温度，结果表明，此种方法具有良好预报效果。

CWRF

Seasonal-Interannual Climate Prediction

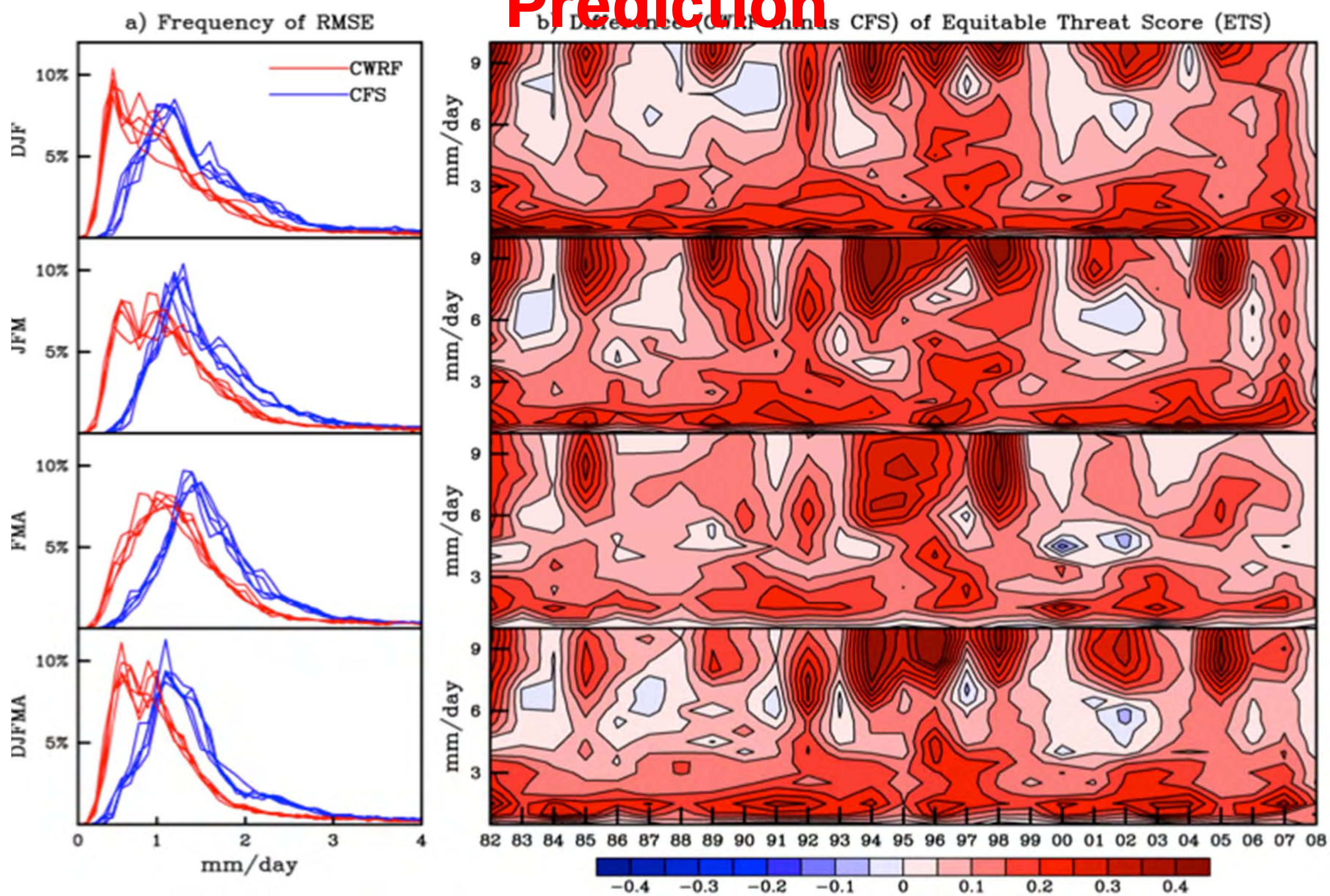
Nested with NOAA Operational

CFS

ECHAM

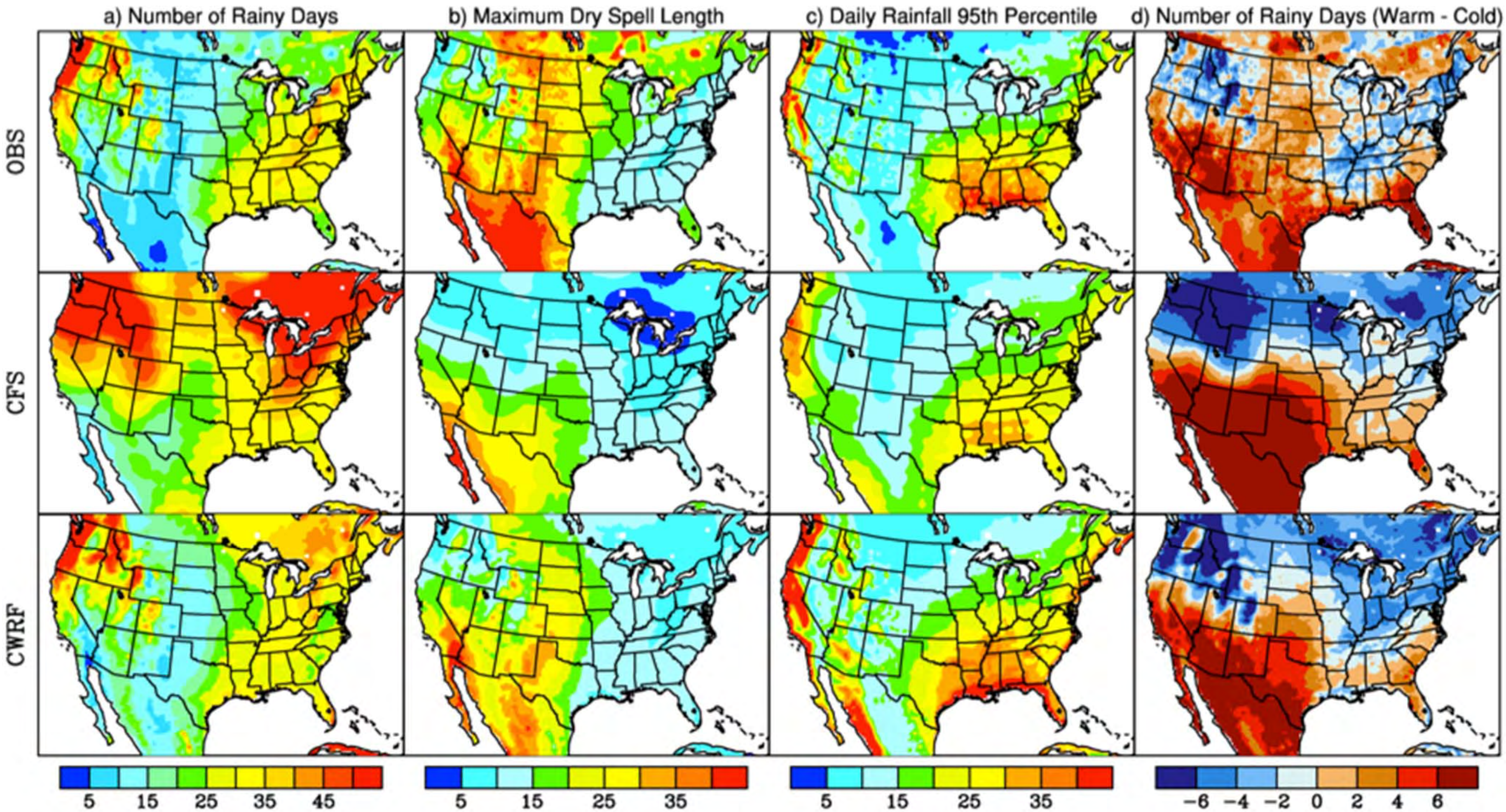
Yuan, X., and X.-Z. Liang, 2011: Improving cold season precipitation prediction by the nested CWRF-CFS system. *Geophys. Res. Lett.*, **38**, L02706, doi:10.1029/2010GL046104 .

CWRF Improves Seasonal Climate Prediction



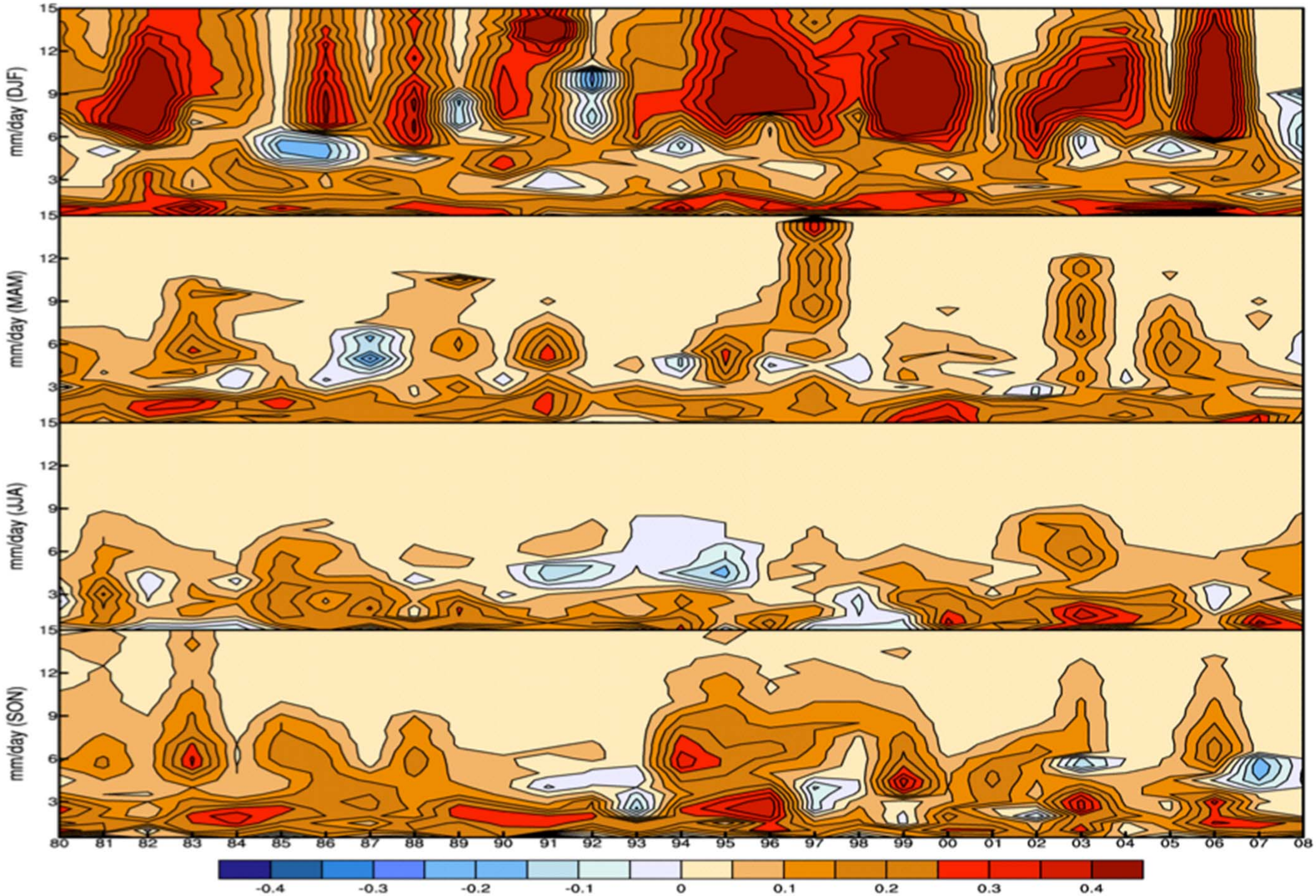
a) Spatial frequency distributions of root mean square errors (*RMSE*, mm/day) predicted by the CFS and downscaled by the CWRF and **b)** CWRF minus CFS differences in the equitable threat score (*ETS*) for seasonal mean precipitation interannual variations. The statistics are based on all land grids over the entire inner domain for DJF, JFM, FMA, and DJFMA from the 5 realizations during 1982-2008. *From* Yuan and Liang 2011 (GRL).

CWRF Downscaling Seasonal Climate Prediction: Extreme Events

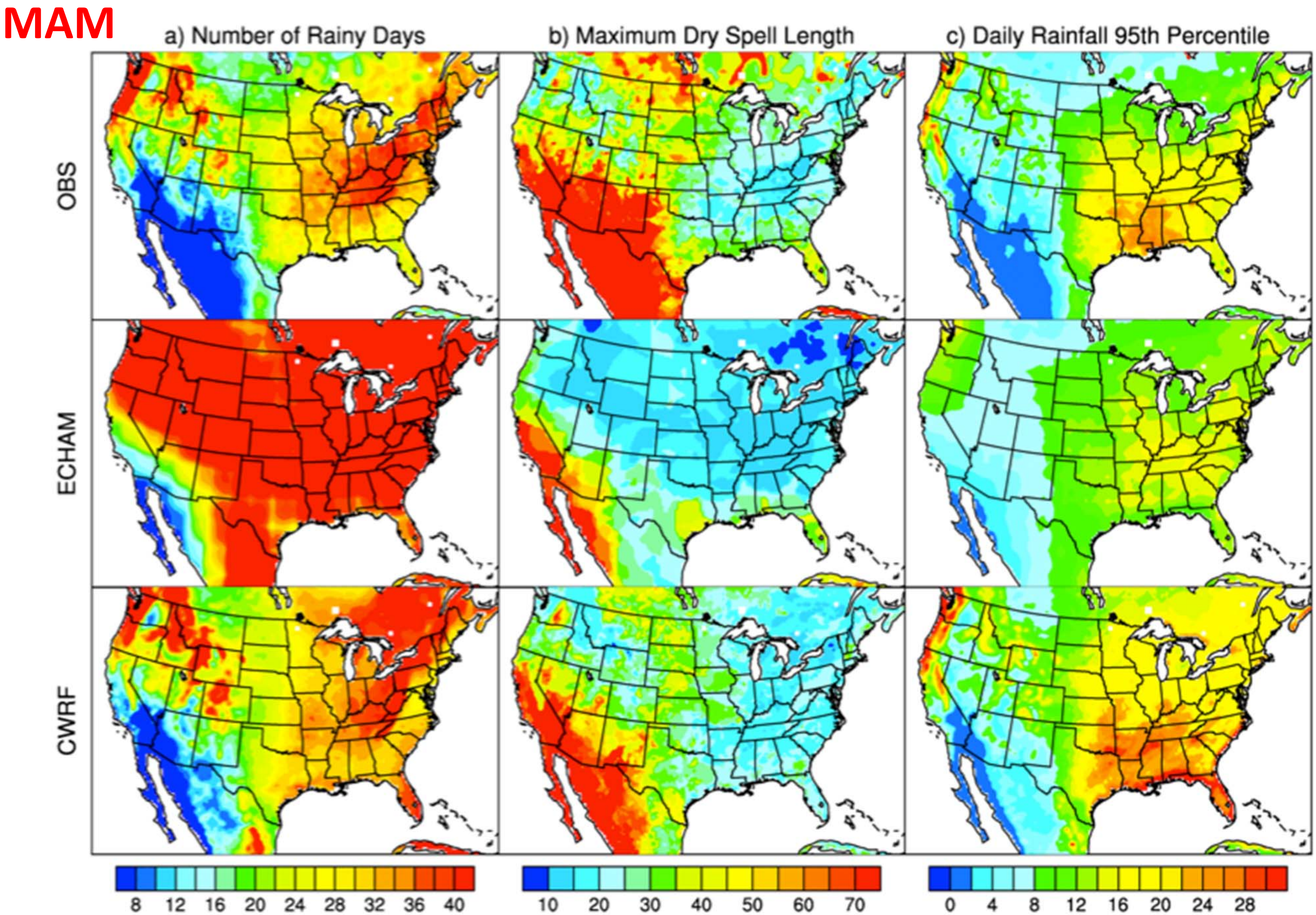


Observed (OBS), CFS-predicted, and CWRF-downscaled: **a)** number of rainy days, **b)** maximum dry spell length (day), **c)** daily rainfall 95th percentile (mm/day), and **d)** difference in number of rainy days averaged between the El Niño (warm) and La Niña (cold) events for JFM during 1983-2008.

CWRF minus ECHAM U.S. Land Precipitation ETS



CWRF Downscaling Improves ECHAM Extreme Events



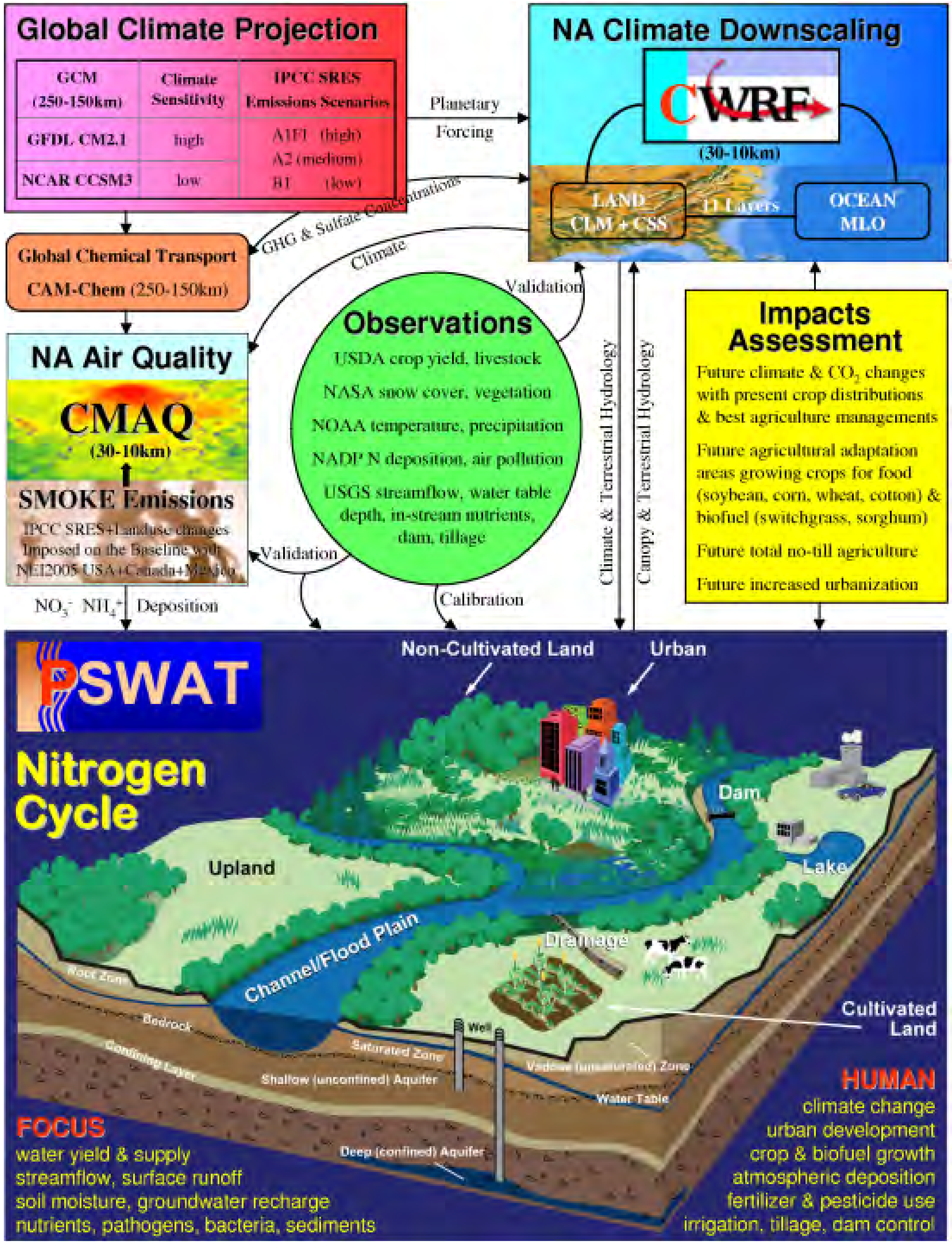
EPA STAR
2003-2011

FOCUS

Consolidate
O_3

Elaborate
PM

Explore
Hg



EPA STAR
2009-2012

FOCUS

Nutrients

Pathogens

Bacteria

Sediments

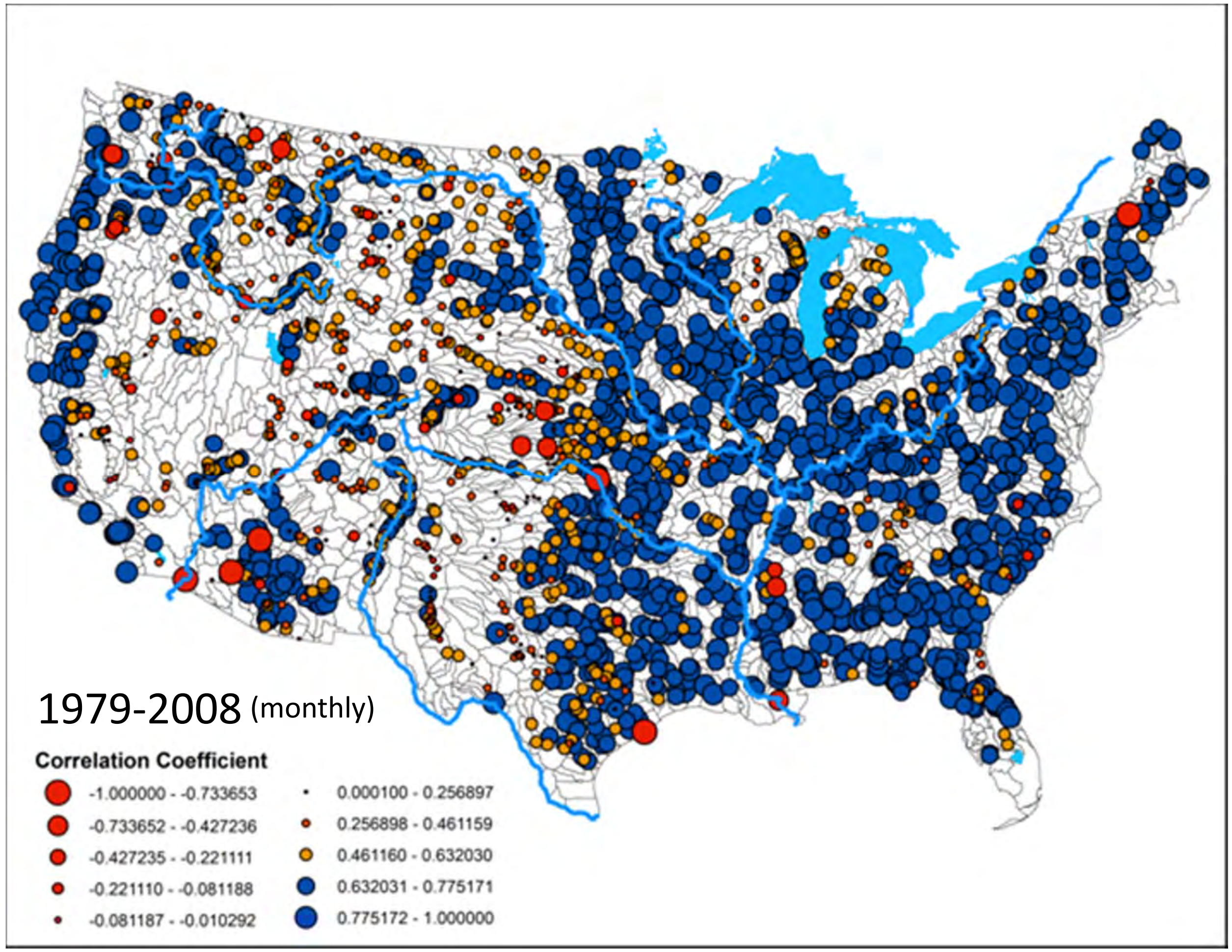
Agriculture

Urban

PSWAT Performance over the U.S.

(Stream flow correlation between USGS stations and PSWAT simulation)

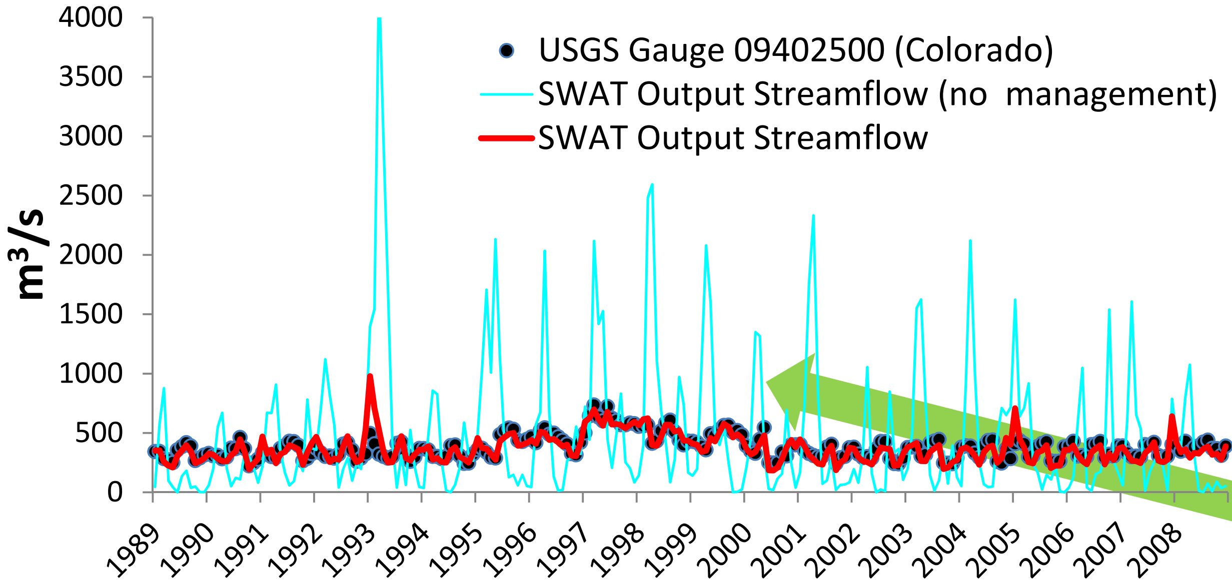
- The performance is better in the eastern and central U.S. than the western mountain semi-arid regions
- The poor skill may partially result from precipitation observational data uncertainty



Simulating Human Management

from Historical Records to Future Predictions

- Numerical schemes in macroscale hydrological models for simulating reservoir outflow, irrigation, and other management strategies are very limited, especially lacking operation-based predictive schemes
- We have developed such a predictive scheme for
  - Reservoir management
  - Irrigation
  - Point sources, non point sources



CWRF Advances for NCEP Operational Use

Intermediate Coupled Model (ICM)

IOM + statistical anomaly model

Atmos: **A SVD-based wind stress model**

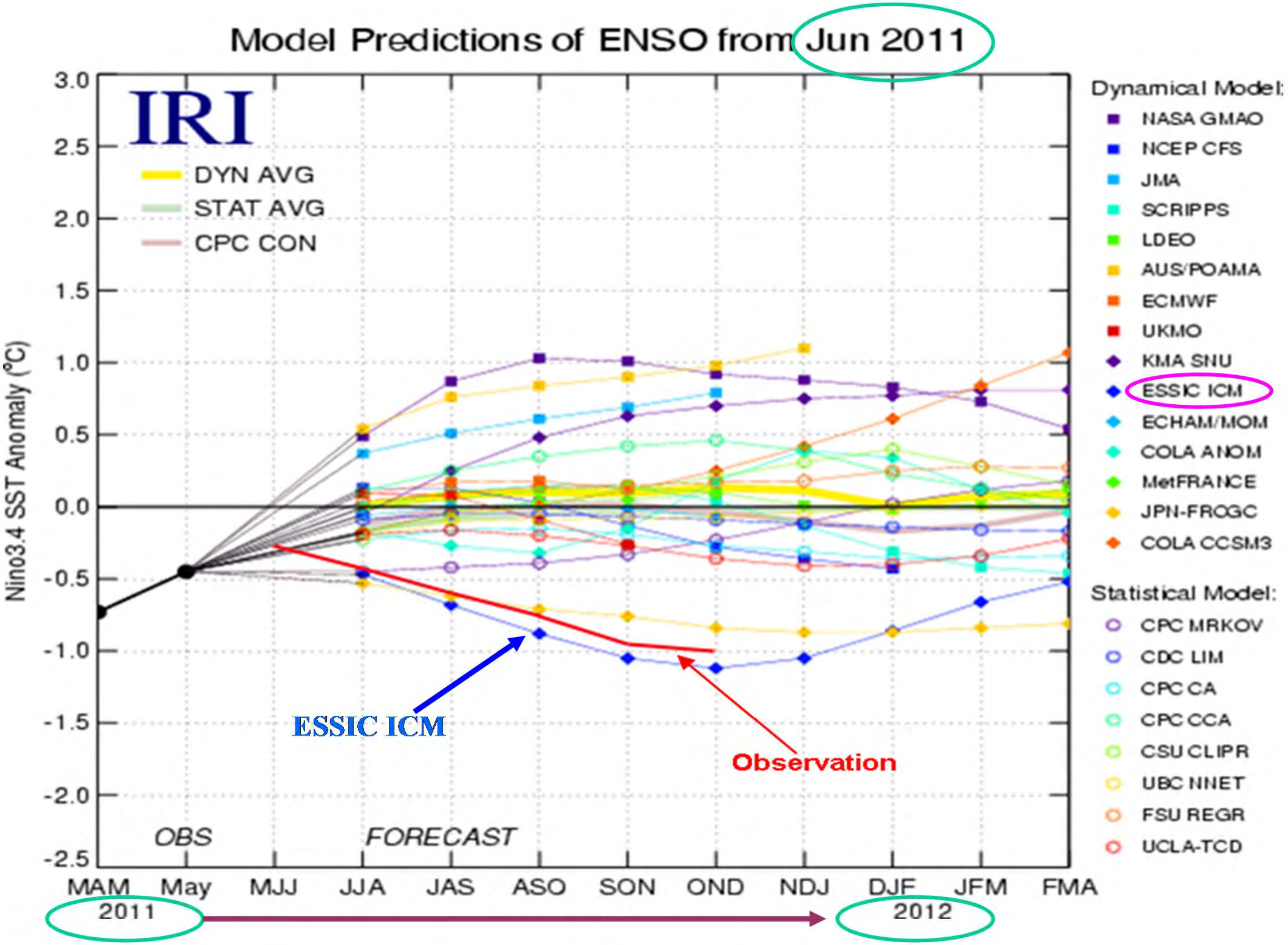
Wind stress anomalies (τ) from the ECHAM4.5 24-member ensemble mean

Coupling

Ocean: **Intermediate Ocean Model (IOM)**

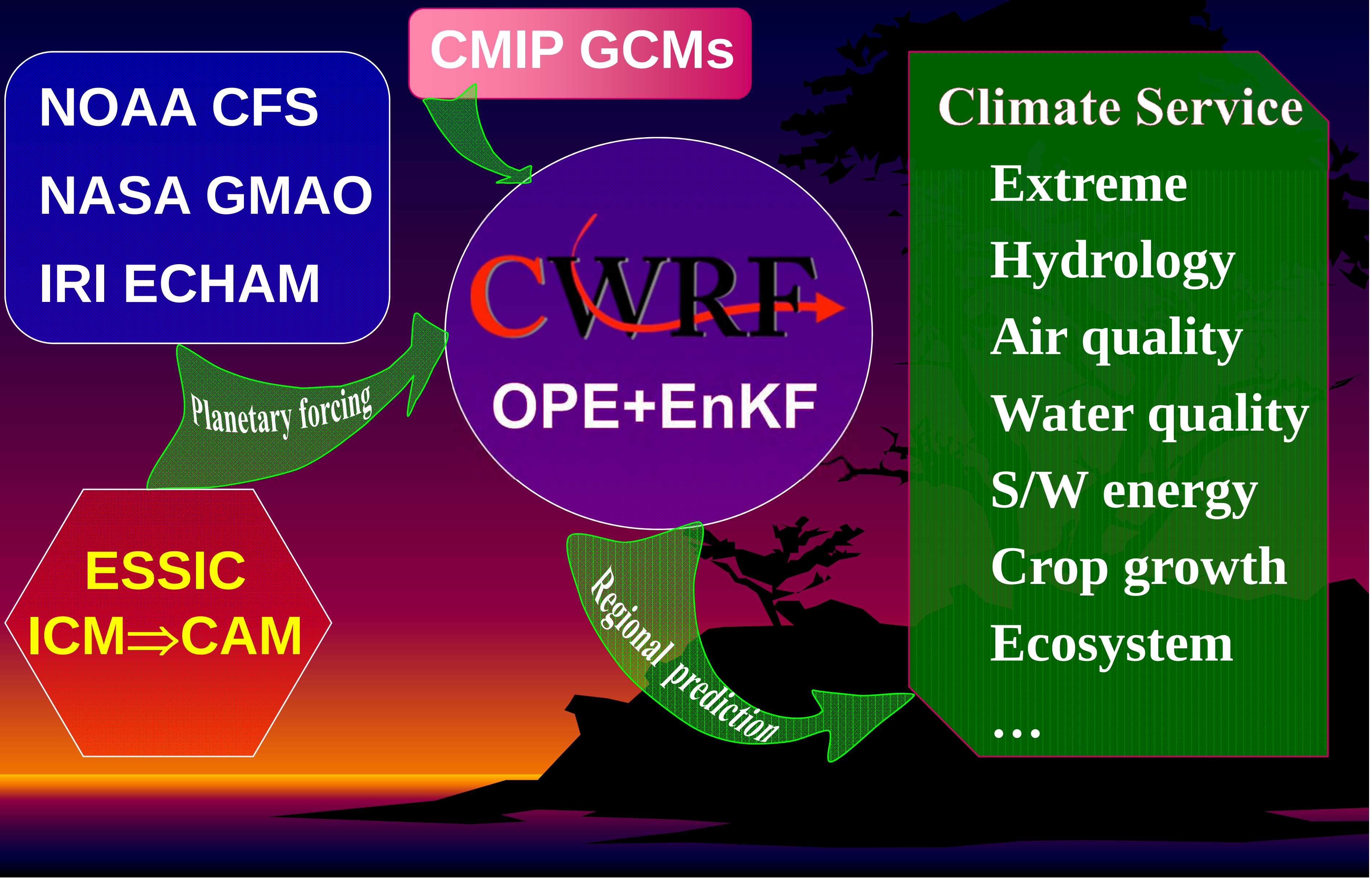
- ✓ Varying stratification in space
- ✓ 10 vertical modes
- ✓ Non-linearity in momentum equation
- ✓ Subsurface entrainment T_e parameterization

Zhang et al. (2003, 2005)



Model Predictions of ENSO from Jun 2011
IRI
DYN AVG
STAT AVG
CPC CON
Nino3.4 SST Anomaly (°C)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
OBS
FORECAST
ESSIC ICM
Observation
MAM
May
MJJ
JJA
JAS
ASO
SON
OND
NDJ
DJF
JFM
FMA
2011
2012
Dynamical Model:
NASA GMAO
NCEP CFS
JMA
SCRIPPS
LDEO
AUS/POAMA
ECMWF
UKMO
KMA SNU
ESSIC ICM
ECHAM/MOM
COLA ANOM
MetFRANCE
JPN-FRCGC
COLA CCSM3
Statistical Model:
CPC MRKOV
CDC LIM
CPC CA
CPC CCA
CSU CLIPR
UBC NNET
FSU REGR
UCLA-TCD

CWRF OPE Prediction



CWRF OPE Physics

CWRF
OPE Physics

R&D

Demo

ESSIC Test
NCEP G/CFS

NCEP G/CFS
- Cumulus
- Cloud
- Aerosol
- Radiation
- Hydrology
- PBL
- MLO
- …

High-Resolution

Weather & Climate

CWRF

Looking Forward to

Collaborating with

NCEP