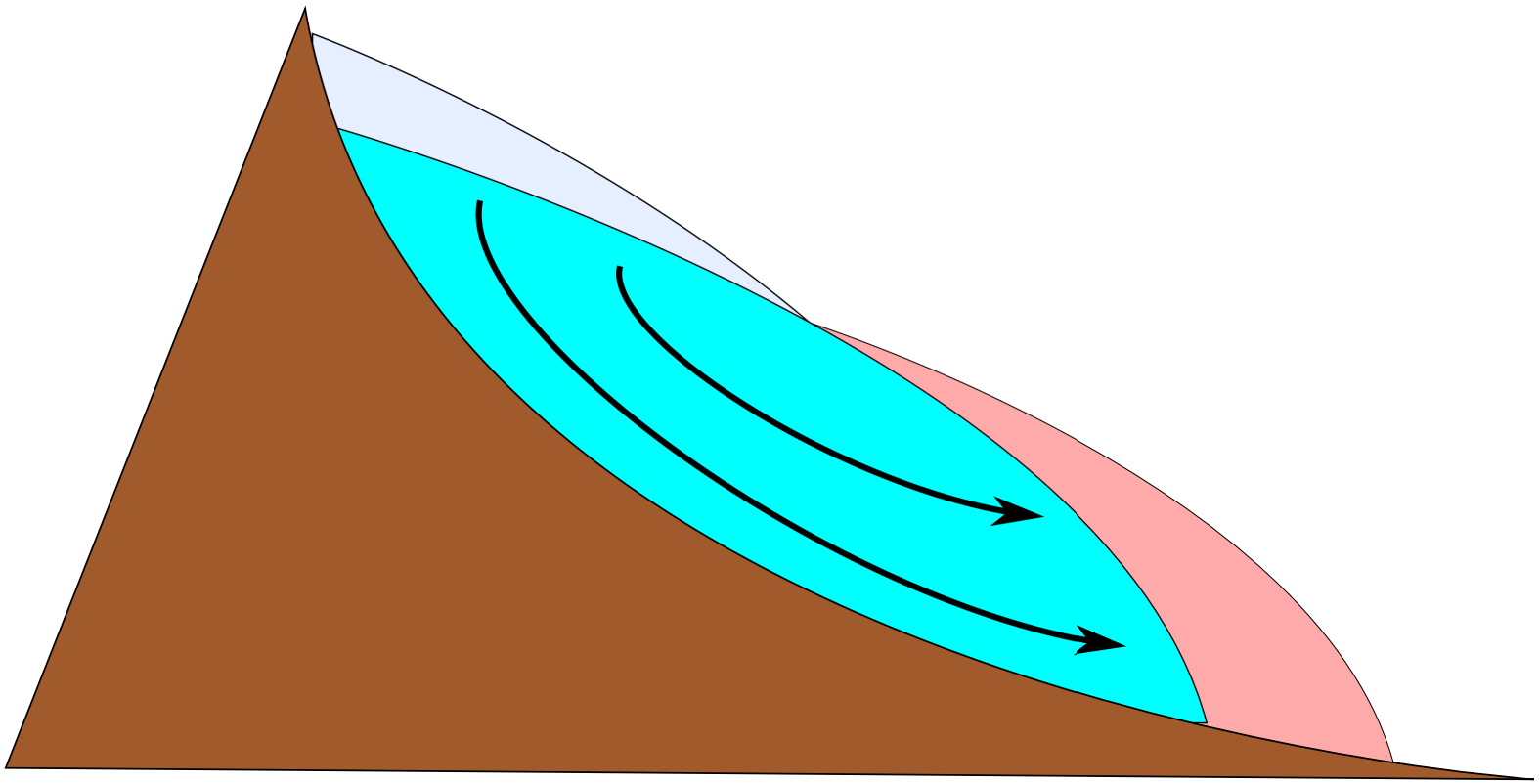
# Glacier modeling in $<$ 10 minutes.

Joseph H Kennedy

Oak Ridge National Laboratory

CCSI Earth System Modeling Workshop
June 9, 2015

# A glacier



# Glacial ice is a viscous fluid

- A non-typical incompressible viscous fluid
- "typical" incompressible viscous fluids (e.g. ocean) modeled with Navier-Stokes equations:

$$\nabla \cdot \mathbf{u} = 0 \qquad \textit{incompressibility}$$

$$\rho\left(\mathbf{u}_t + \mathbf{u} \cdot \nabla \mathbf{u}\right) = -\nabla p + \nu \nabla^2 \mathbf{u} + \rho \mathbf{g} \qquad \textit{stress balance}$$

- these Navier-Stokes equations in 3D are hard ...
  Millennial Prize Problem

Slide adapted from E. Bueler

# Ice is a weird viscous fluid

- not relevant in ice sheet flow:
  - turbulence
  - convection
  - coriolis force
  - density-driven flow (weather)
- ice sheet flow is:
  - slow (inertia is negligible)
  - non-newtonian (viscosity is not constant)
  - highly anisotropic (yeah, let's ignore that)
  - Power law relation (Glen's Law):
    - (strain rate) $=$ A E (stress)$^n$

Slide adapted from E. Bueler

# Ice is a slow, shear-thinning viscous fluid

- notation:
  - $\tau_{ij}$ is deviatoric stress tensor
  - $\mathbf{D}u_{ij}$ is strain rate tensor
- the standard ice flow model is Glen-law Stokes:

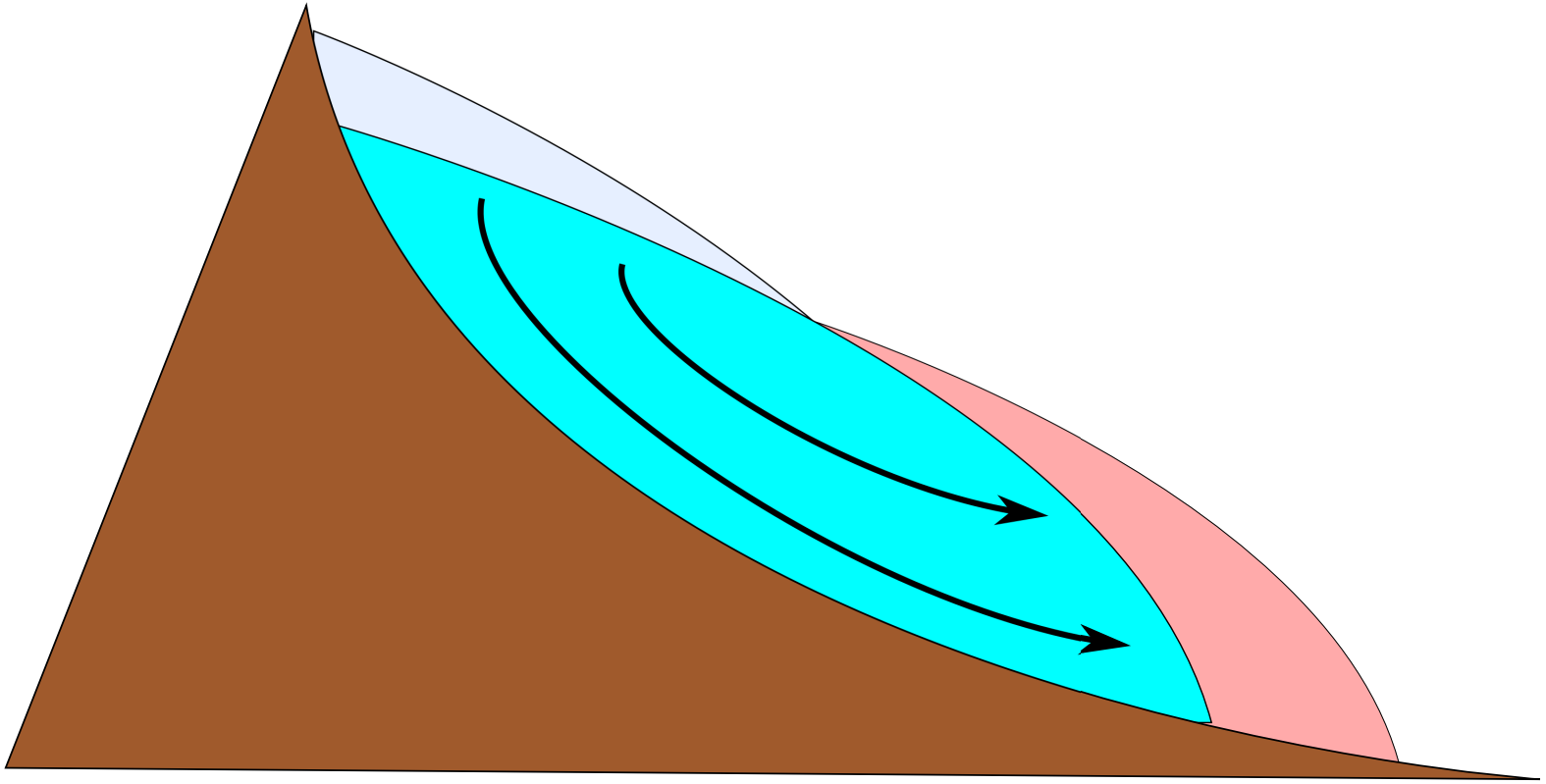
$$\nabla \cdot \mathbf{u} = 0 \qquad \textit{incompressibility}$$

$$0 = -\nabla p + \nabla \cdot \tau_{ij} + \rho \mathbf{g} \qquad \textit{slow stress balance}$$

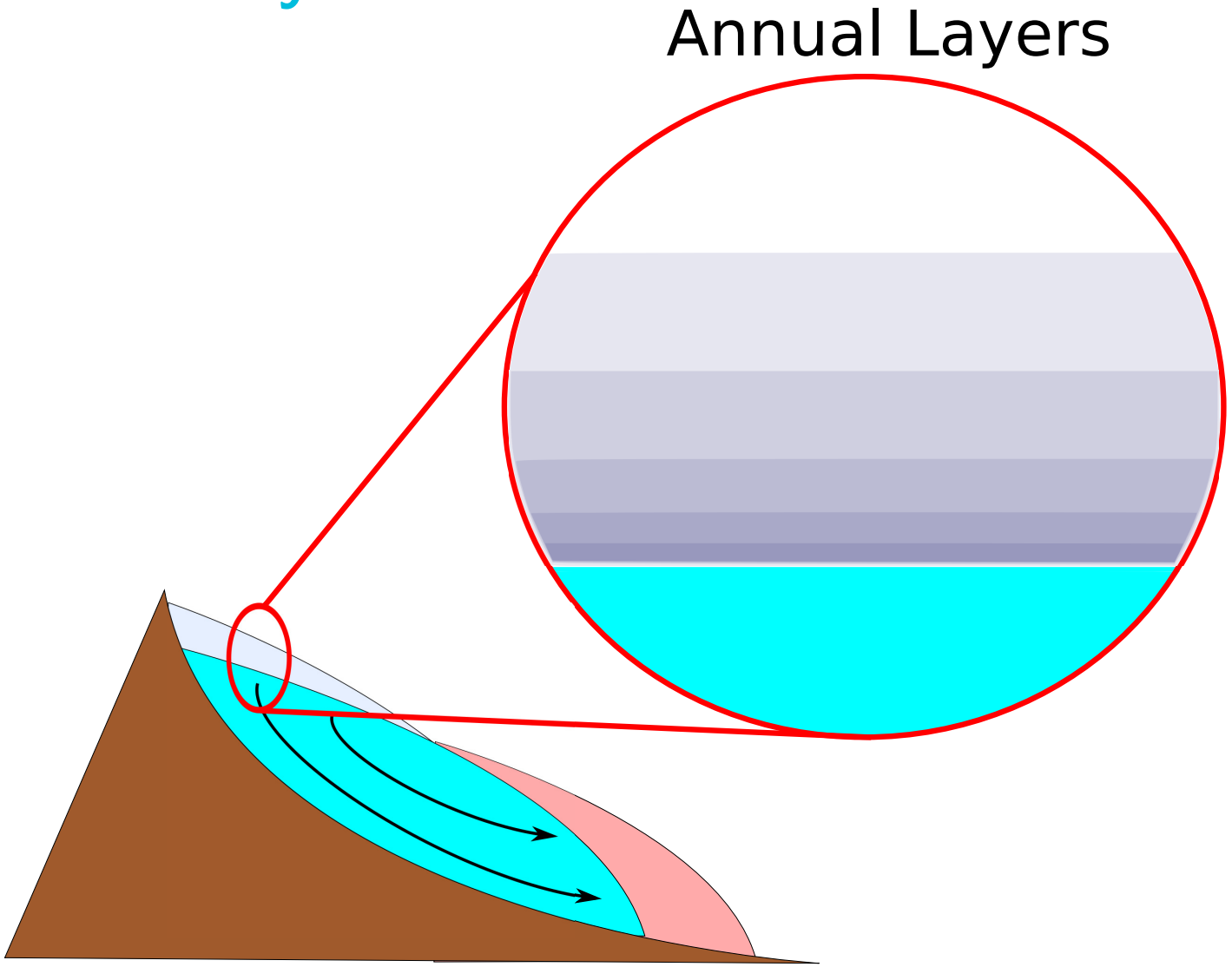
$$\mathbf{D}u_{ij} = AE \left|\tau_{ij}\right|^2 \tau_{ij} \qquad \textit{Glen flow law}$$

Slide adapted from E. Bueler

# Glacier Anatomy



# Glacier Anatomy



# Glacier Anatomy

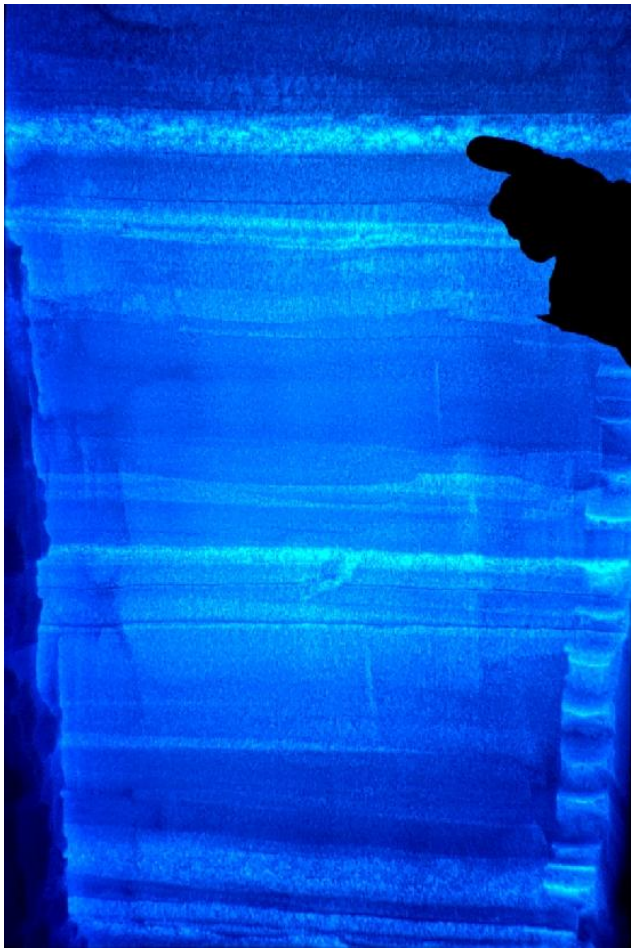


**Figure :** snow pit from Siple Dome, West Antarctica. [NSIDC]

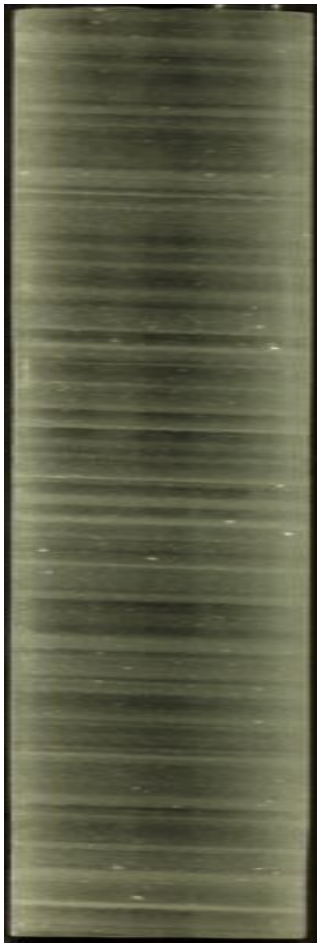
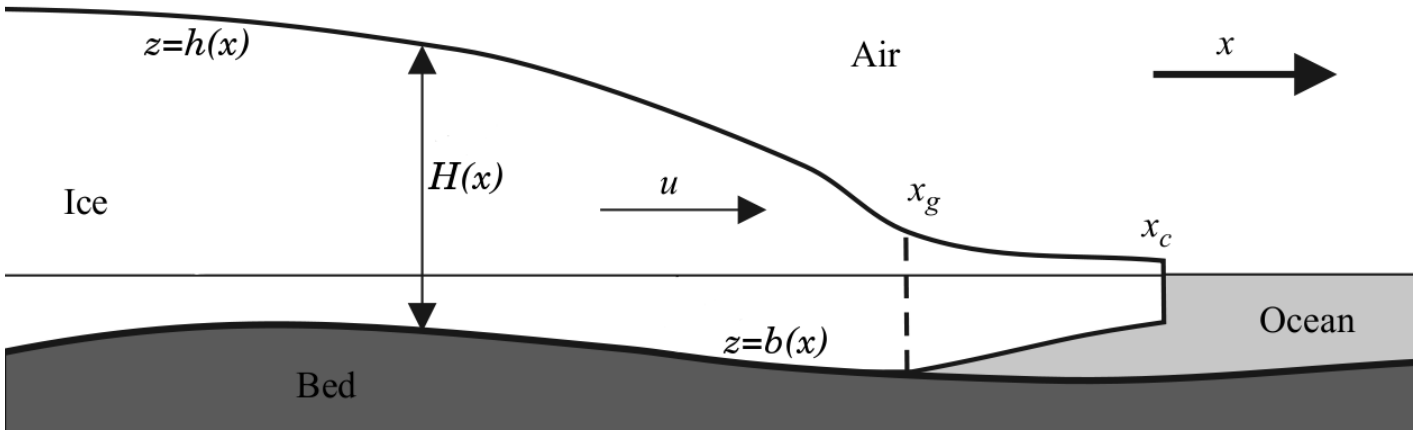


**Figure :** ice core from GISP2, Greenland. 1837 m – 1838 m depth shown. [NSIDC]

# (ill-posed) boundary value problem




other complications (annoyances?):

- fracture (calving, crevassing)
- phase changes
- mass balance
- erosion
- tides
- debris

figure from E. Bueler

# Big data

# A Systematic Bayesian Framework for Uncertainty Quantification in Environmental Modeling

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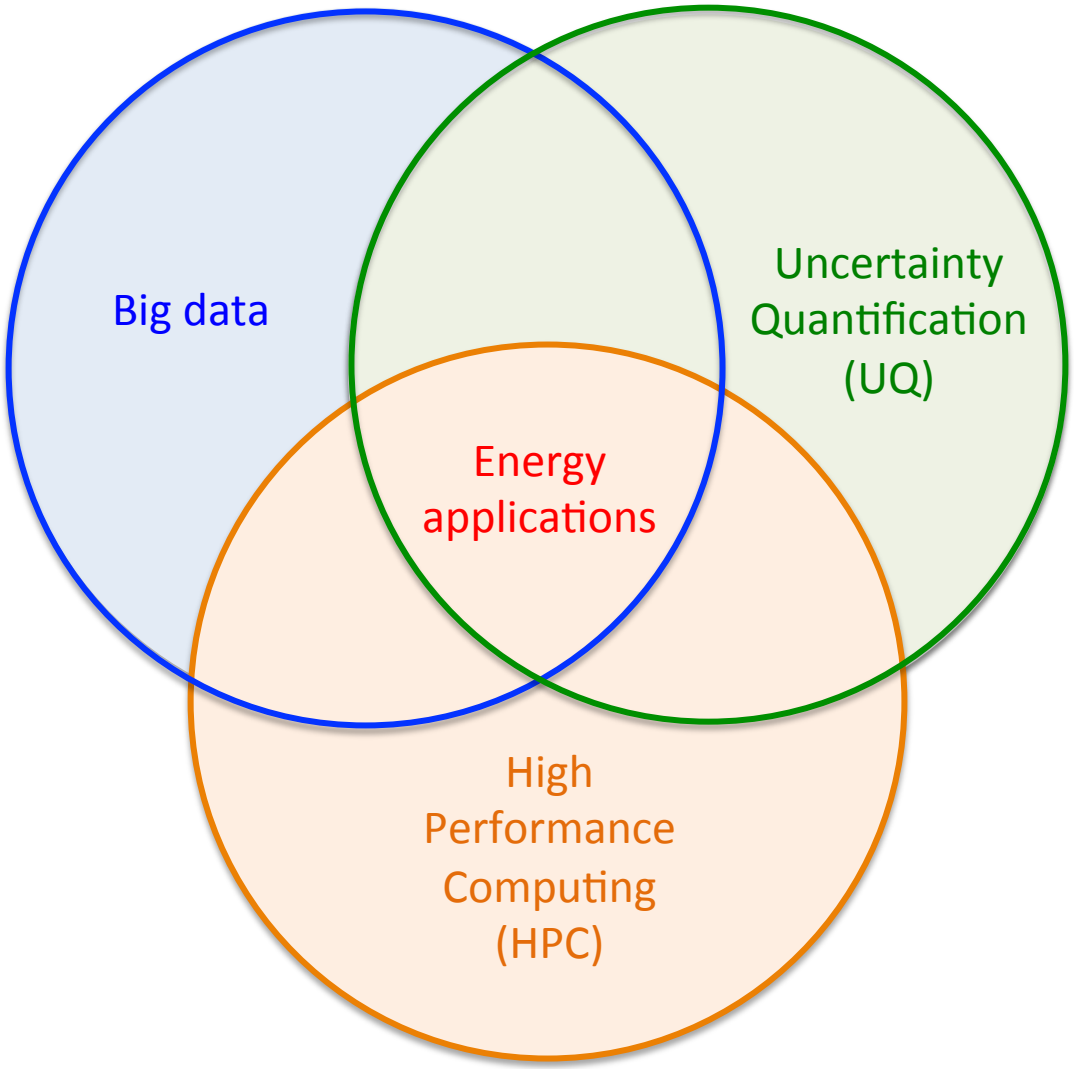
Oak Ridge National Laboratory

June 9th, 2015

ORNL is managed by UT-Battelle
for the US Department of Energy

# Core areas of DOE's mission in computational science

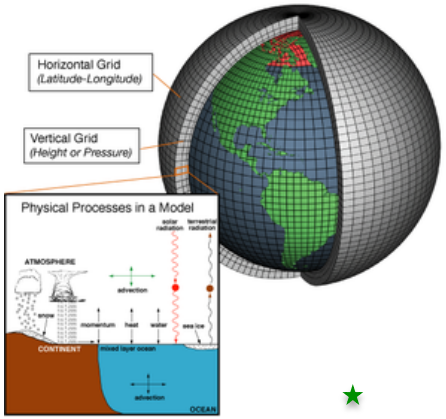


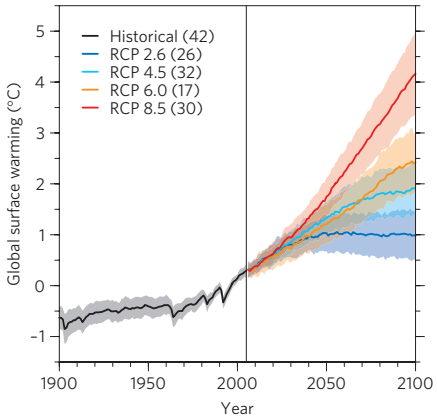
# Uncertainty is everywhere and UQ is needed

## Two examples

## Climate modeling

Various sources of uncertainty

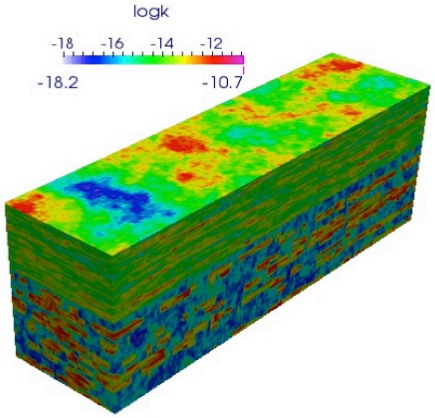


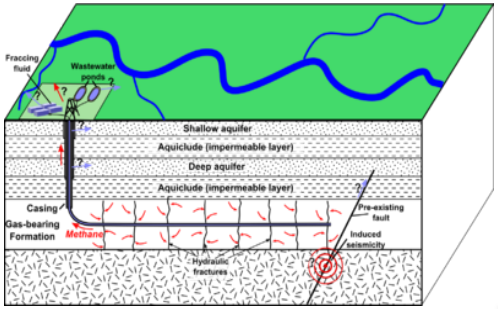

Quantify uncertainty for decision making

## Subsurface hydrology and petroleum geology

Large uncertainty due to limited data




Field size: 1200 x 2200 x 170 (m)



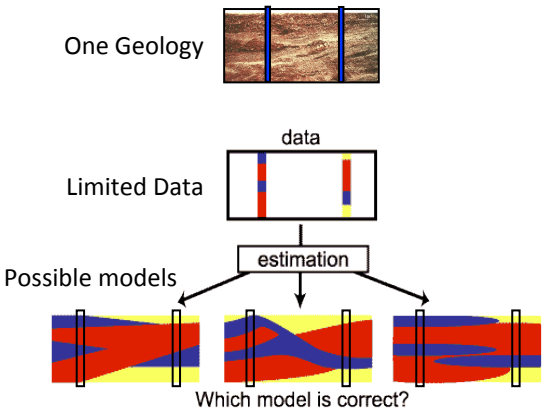

Decision making needs UQ

★ Pictures from R. C. Smith, SIAM, 2013

◆ Picture from Knutti and Sedlacek, Nature Climate Change, 2012

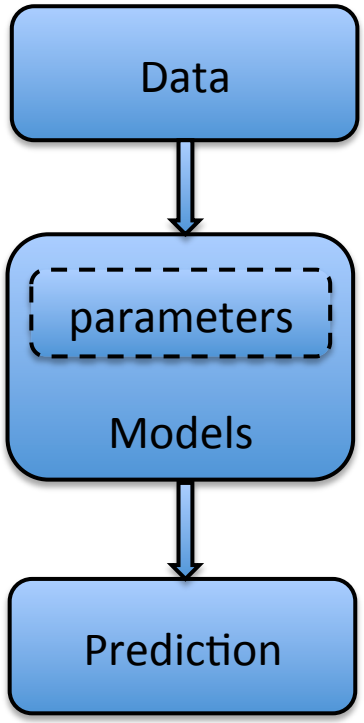
# Uncertainty in the predictive process

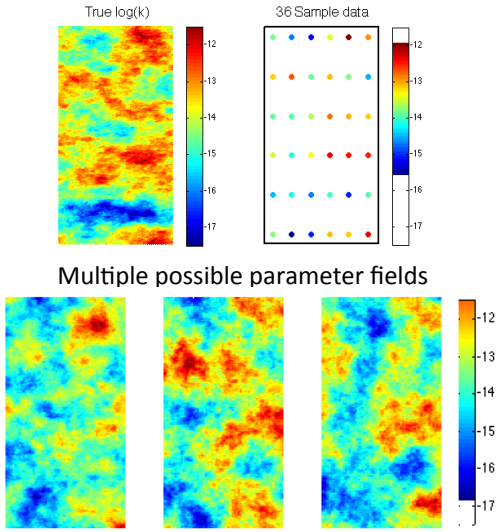
**Data uncertainty**




★

**Model uncertainty**



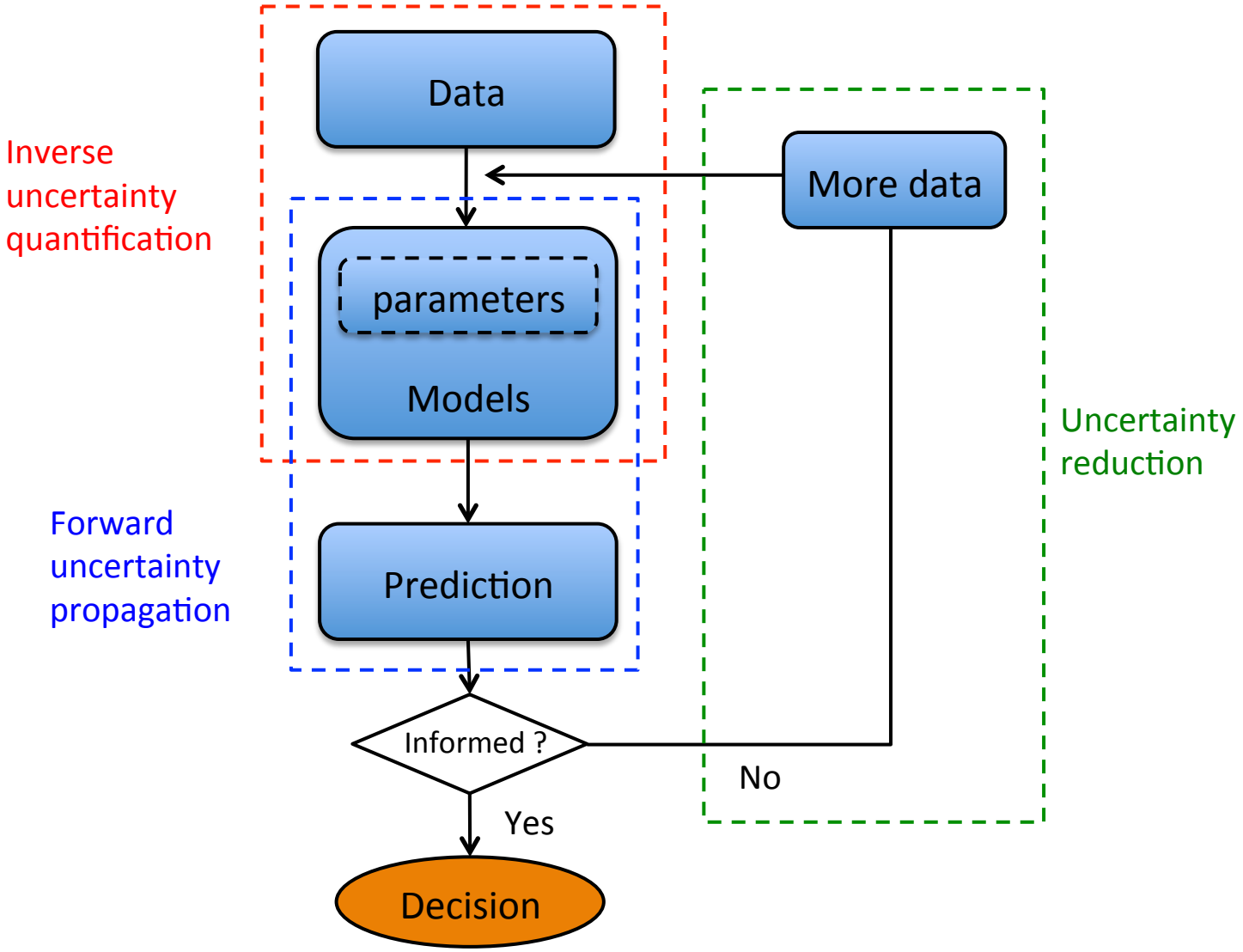




**Parameter uncertainty**

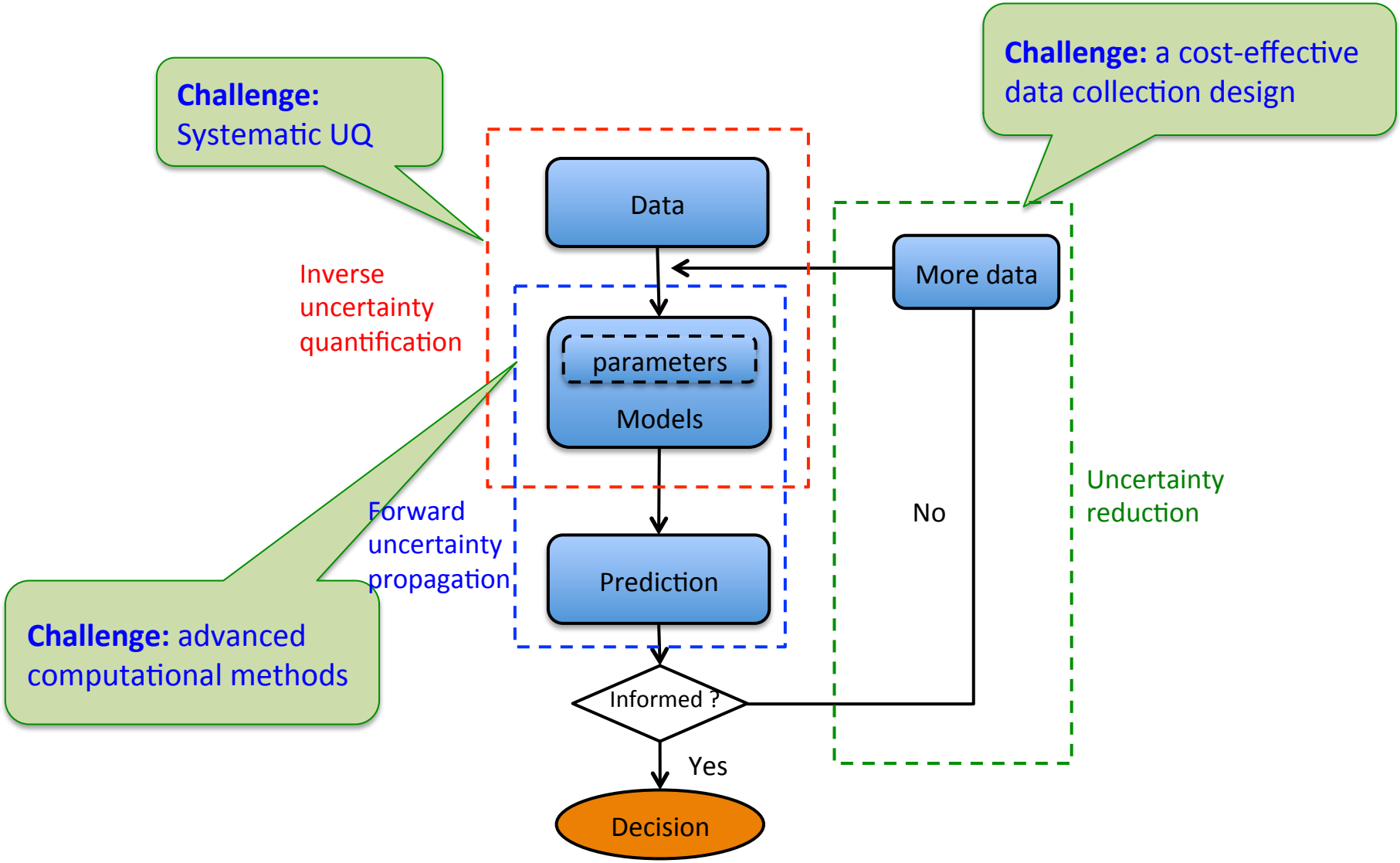
**Uncertainty in prediction**

★ Picture from people.clemson.edu/~smoysey

# Three classes of uncertainty quantification (UQ) problems



# Challenges in systematic UQ



# Challenges and solutions in systematic UQ

**Challenge:** Systematic UQ

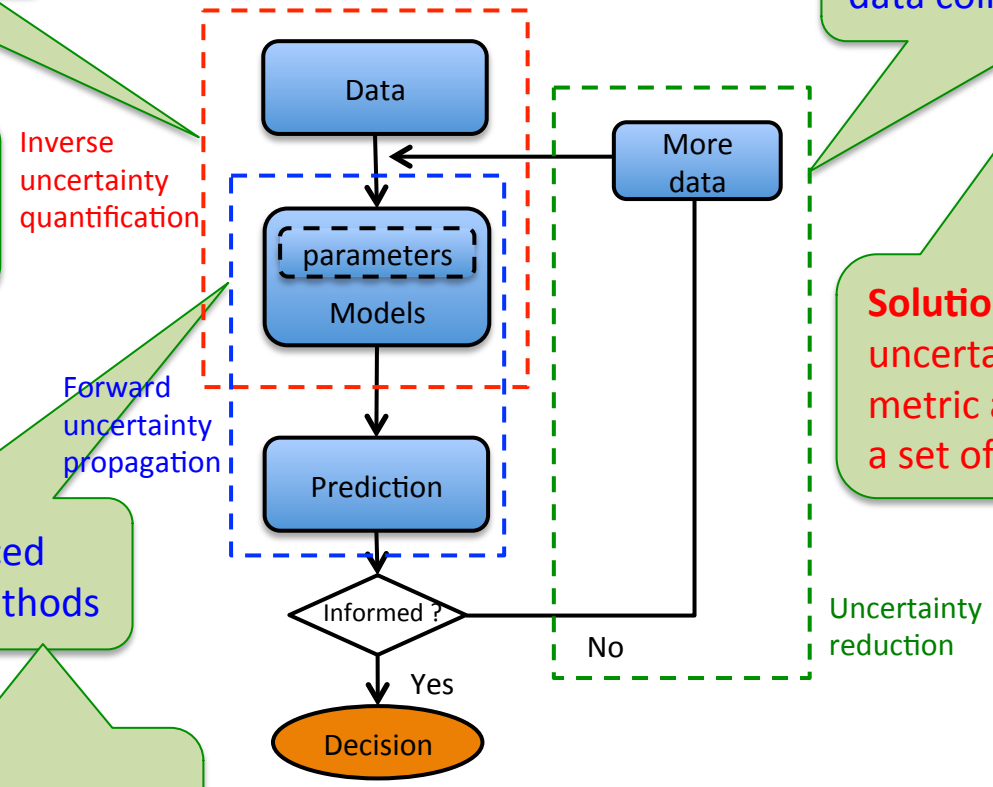
**Solution:** Hierarchical Bayesian framework

**Challenge:** a cost-effective data collection design

**Solution:** Define an uncertainty reduction metric and evaluate it for a set of potential data

**Challenge:** advanced computational methods

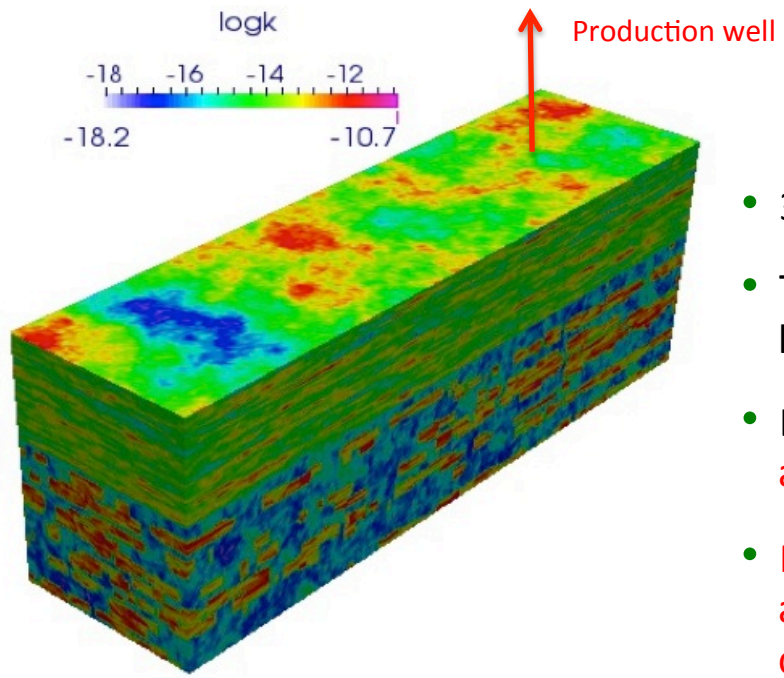
**Solution:** surrogate-based methods, Multilevel Monte Carlo



# Multilevel Monte Carlo (MLMC) method

## Application: an oil reservoir model

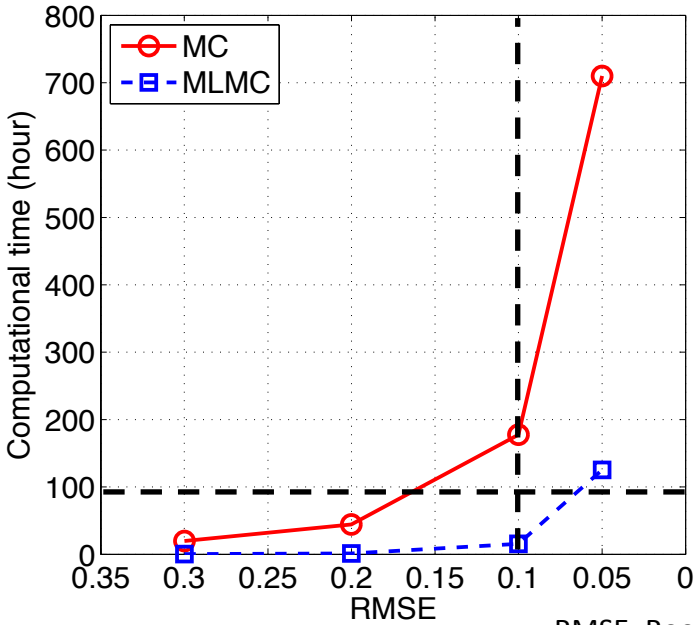
Current LDRD project:
hydraulic fracturing




- 3-D reservoir model with 1.0e6 cells;
- The geological parameters are only known at 3.0e3 cells;
- Large number of unknown parameters, a high-dimensional problem;
- Purpose: to predict the flow rate of oil and gas at the production well with considering parameter uncertainty.
- Methods: classic Monte Carlo (MC) and multilevel Monte Carlo (MLMC).

# Multilevel Monte Carlo (MLMC) method

## Application: an oil reservoir model




RMSE: Root Mean Square Error

The MLMC method is effective and efficient for high-dimensional UQ problems.

- **Lu**, Zhang, Webster, and Barbier, A Multilevel Monte Carlo Method with Application to Uncertainty Quantification in Oil Reservoir Simulation, Water Resour. Res., 2015.
- This work was selected as **a "story tip" by DOE** and was picked up by several media outlets, one is **"The BAKKEN" Magazine**.

# Thank you for your attention!

# Dominating Controls for Wetter South Asian Summer Monsoon in the Twenty-First Century

**Rui Mei**

June 08, 2015

Climate Change Science Institute
AT OAK RIDGE NATIONAL LABORATORY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE U.S. DEPARTMENT OF ENERGY

U.S. DEPARTMENT OF ENERGY

# Paper

- Mei R, Ashfaq M, Rastogi D, Leung R, Dominguez F (2015). Dominating Controls for Wetter South Asian Summer Monsoon in the 21st Century, Journal of Climate, *28, 3400-3419.*

# Outline

- Introduction
- Data and Methods
- Results and Summary

# Motivation

The South Asian summer monsoon exerts profound impact through South Asia.

Two recent examples: Flooding events in Pakistan in July-Aug 2010 and extreme precipitation in North India in June 2013.

Therefore, robust projection of summer monsoon precipitation in response to elevated greenhouse gas concentration is critical over this region.

# Literature review

Both in CMIP3 and CMIP5, most studies conclude an increase of South Asian summer monsoon precipitation in response to the increase in radiative forcing (e.g., review of Turner and Annmalai 2012).

The two competing effects: the thermodynamic effects (through increase in atmospheric moisture content) dominates overwhelms the dynamic effects (through weakening of monsoon circulation) (e.g.,Cherchi et al. 2011, Endo and Kitoh 2014).

However, lack of perspective on moisture sources for precipitation: where the moisture comes from and how the source affects the future precipitation change?

# Objective

To investigate the impact of anthropogenic global warming on South Asian summer precipitation using CMIP5 data, examining not only the **monsoon circulation and "apparent" moisture supply**, but also the **moisture sources for precipitation.**

# Data and methods

Datasets:

6-hourly precipitation, evaporation, 3-D horizontal wind, specific humidity and temperature from (1) ***CMIP5*** (18 models for ***historical*** 1965-2005, 14 models for ***RCP8.5*** 2010-2099), (2) ***NCEP I reanalysis*** (1965-2005), ***ERA and CFSR reanalysis*** (1979-2009).

Methods:

**(1) Monsoon circulation and "apparent" moisture supply**

**(2) Moisture sources attribution** (a Lagarangian moisture tracking method)

# Circulation dynamic indicators

(1) ***MTG- Meridional Tropospheric temperature Gradient***:

- difference of monthly mean temperature in the upper tropospheric layers (200mb to 500mb) between 5N and 30N, averaged over 65-85E.

(2) ***U-wind shear- local "Walker circulation index"***

- Easterly vertical shear of zonal winds between 200mb and 850mb averaged over 0-15N,50-85E.

(3) ***V-wind shear- local "Hadley circulation index"***

- Vertical meridional wind shear between 200mb and 850mb averaged over 5-30N,70-110E.

# A semi analytical moisture tracking method

Gridcell recycling ratio $\rho_i$ is the amount of precipitation that falls in that cell i from evapotranspiration within defined region B with the following formula:

$$\rho_i = \frac{P_{mi}}{P_i}$$

where $P_{mi}$ is the precipitation from recycled origin B at grid cell i, $P_i$ is the total precipitation at grid cell i.

Regional recycling ratio r within the region B consisting of n cells can then be formulated with this:

$$r = \frac{P_m}{P} = \frac{\sum_{i=1}^{n} \rho_i P_i \Delta A_i}{\sum_{i=1}^{n} P_i \Delta A_i}$$

For a given gridcell i within the region B, the **water vapor conservation equation** can be separated into the advected (a) and recycled (m) components:

Equation 1

$$\frac{\partial(w_a)}{\partial t} + \frac{\partial(w_a u)}{\partial x} + \frac{\partial(w_a v)}{\partial y} = -P_a$$

$$\frac{\partial(w_m)}{\partial t} + \frac{\partial(w_m u)}{\partial x} + \frac{\partial(w_m v)}{\partial y} = E - P_m$$

**The assumption of a well-mixed atmosphere:**

Equation 2

$$\rho_i = \frac{P_{mi}}{P_i} = \frac{w_{mi}}{w_i}$$

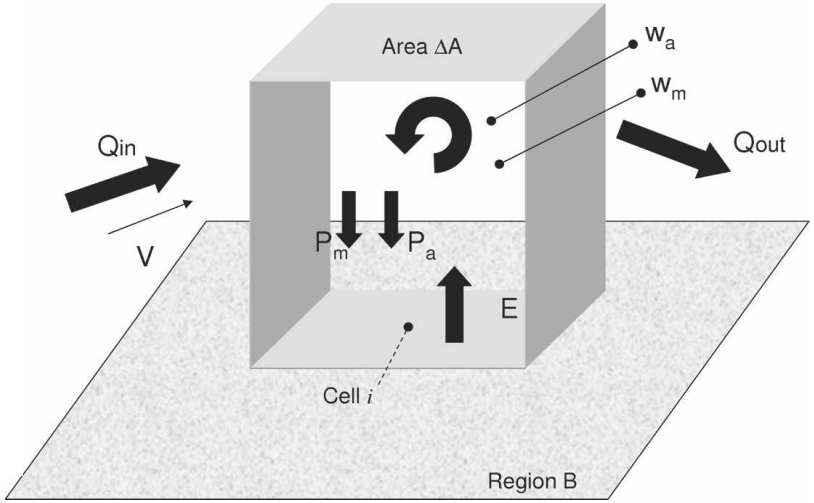
Combining the above equations, we can derive the fundamental equation for recycling ratio:

$$w\frac{\partial(1-\rho)}{\partial t} + wu\frac{\partial(1-\rho)}{\partial x} + wv\frac{\partial(1-\rho)}{\partial y} = E - P_m$$

Method derives from the precipitation recycling ratio method in Dominguez et al. 2006:

**Eq1: atmospheric water vapor conservation equation**

**Eq2: atmospheric column is well mixed with local recycled and advected moisture**

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To solve local recycling ratio ρ, a Lagrangian coordinate system [χ,ξ,τ] is introduced to obtain the semi-analytical expression for ρ:

$$\chi = x - ut$$

$$\xi = y - vt$$

$$\tau = t$$

With this new coordinate system, evaporation (E(x,y,t)), recycling ratio (ρ(x,y,t)), and precipitable water (w(x,y,t)) are represented as ε, R and ω. Then, we can solve local recycling ratio (the ratio of precipitation attributed from a pre-defined source region to the precipitation over a specific single target grid cell) with this expression:

Equation 3

$$R(\chi,\xi,\tau) = 1 - \exp\left[-\int_0^{\tau} \frac{\varepsilon(\chi,\xi,\tau)}{\omega(\chi,\xi,\tau)}\, d\tau\right]$$

where integration is performed from current time τ for the target grid cell backward until time 0, when the back-trajectory of the advected moisture reaches beyond the pre-defined evaporative source region.

That also means that for any specific precipitation target grid cell, the contributed percentage during small time interval $dt$ over $[\tau 1, \tau 1 - dt]$ ( $\tau > \tau 1 > \tau 1 - dt > 0$) is from the cell m where back-trajectory of moisture falls into during that time interval $[\tau 1, \tau 1 - dt]$, and therefore make the following stand:

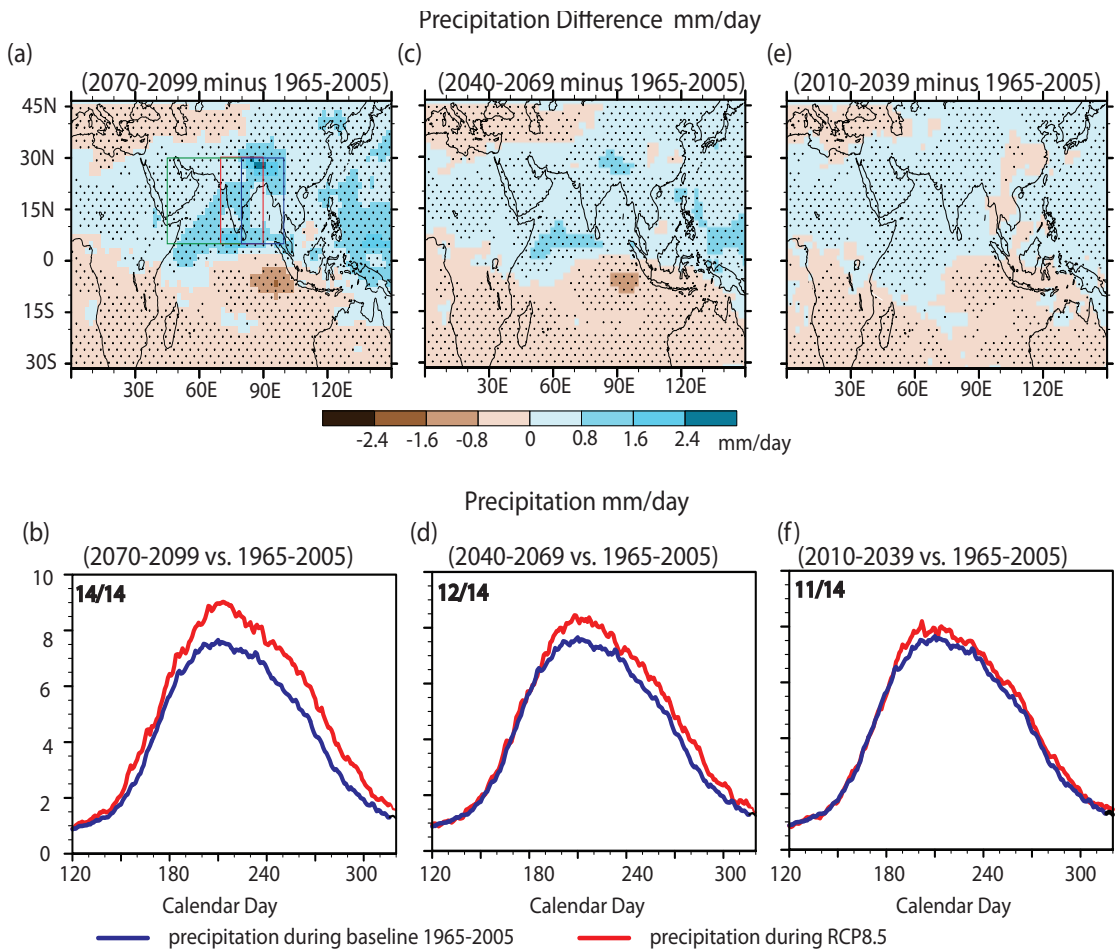
Equation 4

$$R(\chi,\xi,\tau,m)|(\tau 1 - dt) = R(\chi,\xi,\tau,m)|(\tau 1) - \exp\left[-\int_{\tau 1 - dt}^{\tau} \frac{\varepsilon(\chi,\xi,\tau)}{\omega(\chi,\xi,\tau)}\, d\tau\right] + \exp\left[-\int_{\tau 1}^{\tau} \frac{\varepsilon(\chi,\xi,\tau)}{\omega(\chi,\xi,\tau)}\, d\tau\right]$$

where $R(\chi,\xi,\tau,m)|\tau t$ is the contributed percentage from cell m at time moment $\tau t$

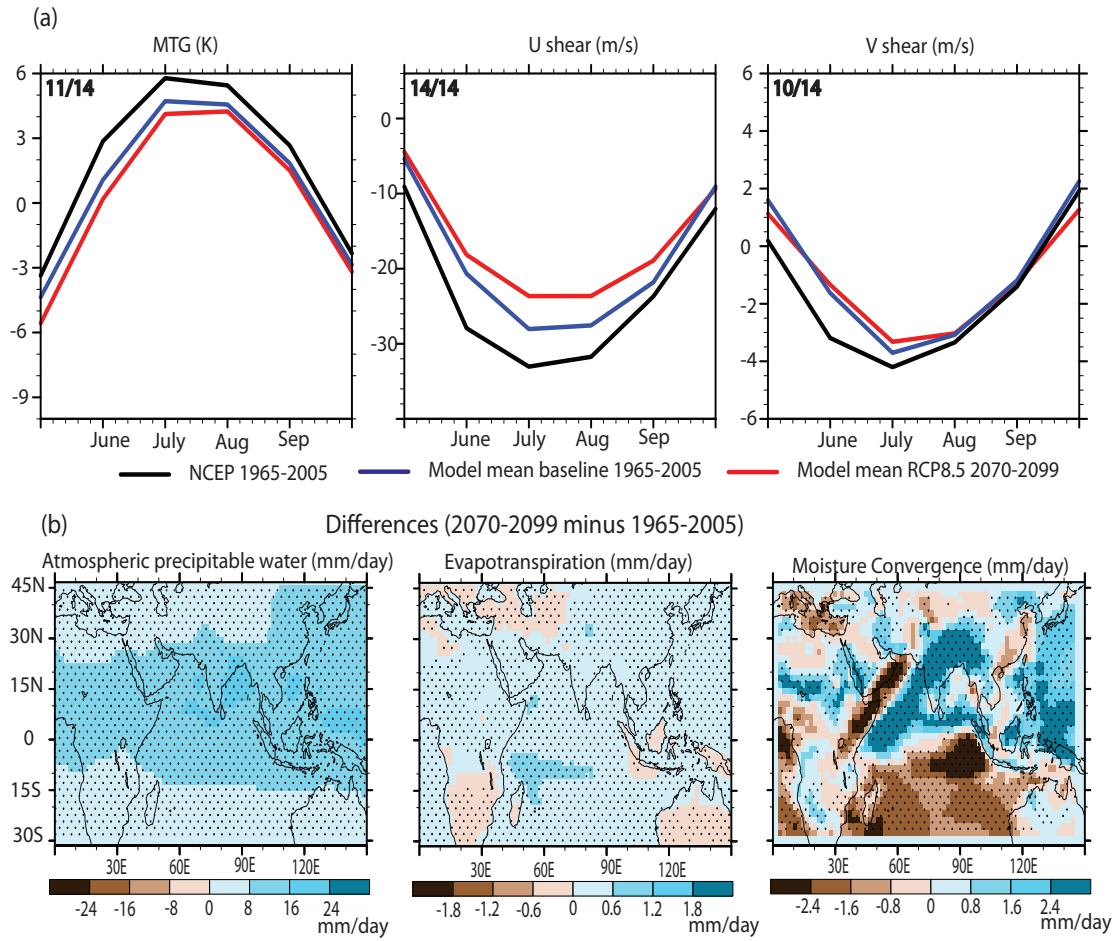
**With the above said, we can derive the contributed precipitation for any target grid cell from any moisture source grid cell.**

# Monsoon Precipitation response




A gradual strengthening of the positive precipitation response throughout the 21st century

# Monsoon circulation and “apparent” moisture supply response

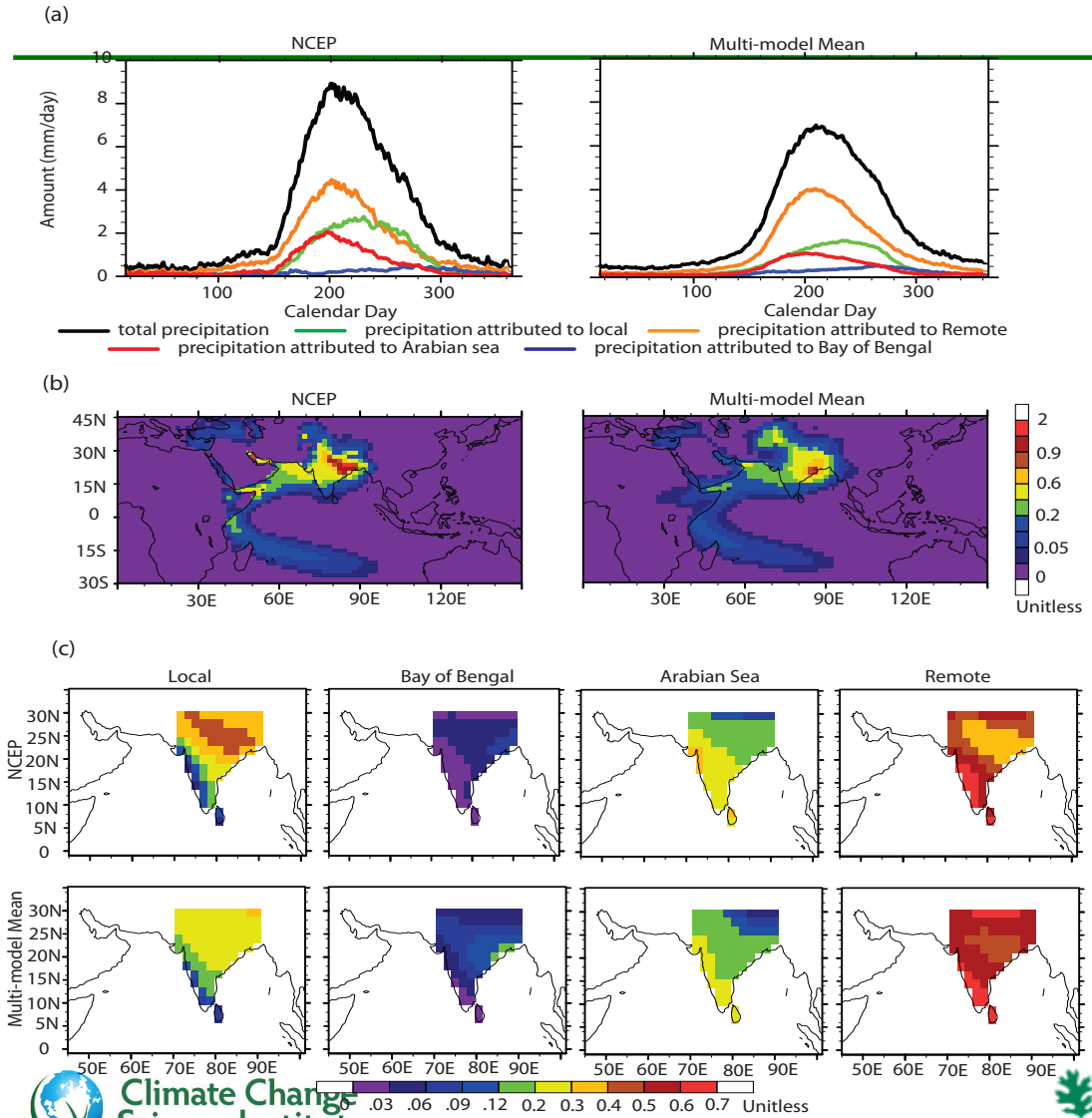



Late 21st century future period 2070-2099 e.g.,

Weakening of monsoon circulation accompanied by an increase in the atmospheric moisture

“apparent” moisture supply indicates moisture convergence determines precipitation response

# Moisture source attribution

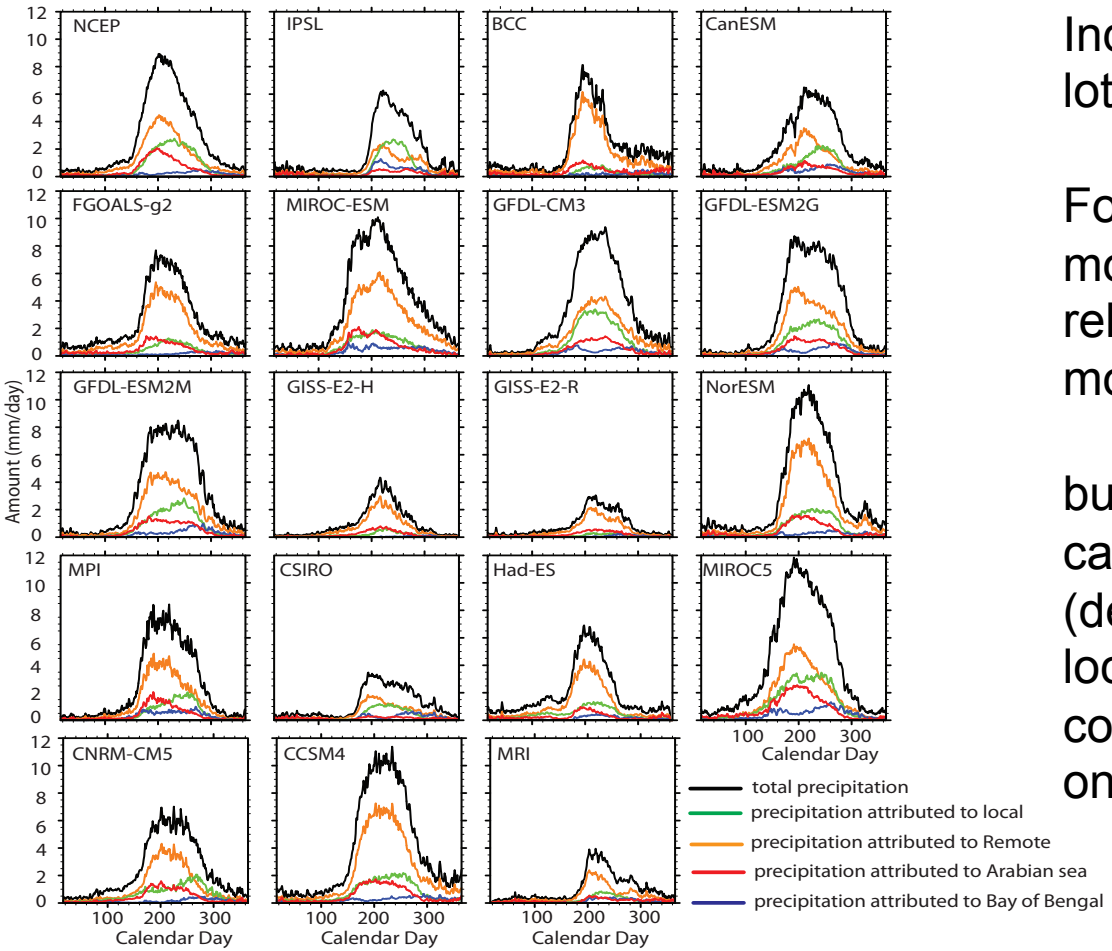



The four defined moisture sources contribution to summer monsoon precipitation in NCEP R1 (GCMs):

remote:46% (55%);
local recycling: 30.4% (23%);
Arabian Sea: 19.6% (15%);
Bay of Bengal: 4% (7%)

Multi-model mean generally captures NCEP R1.

# Moisture source attribution

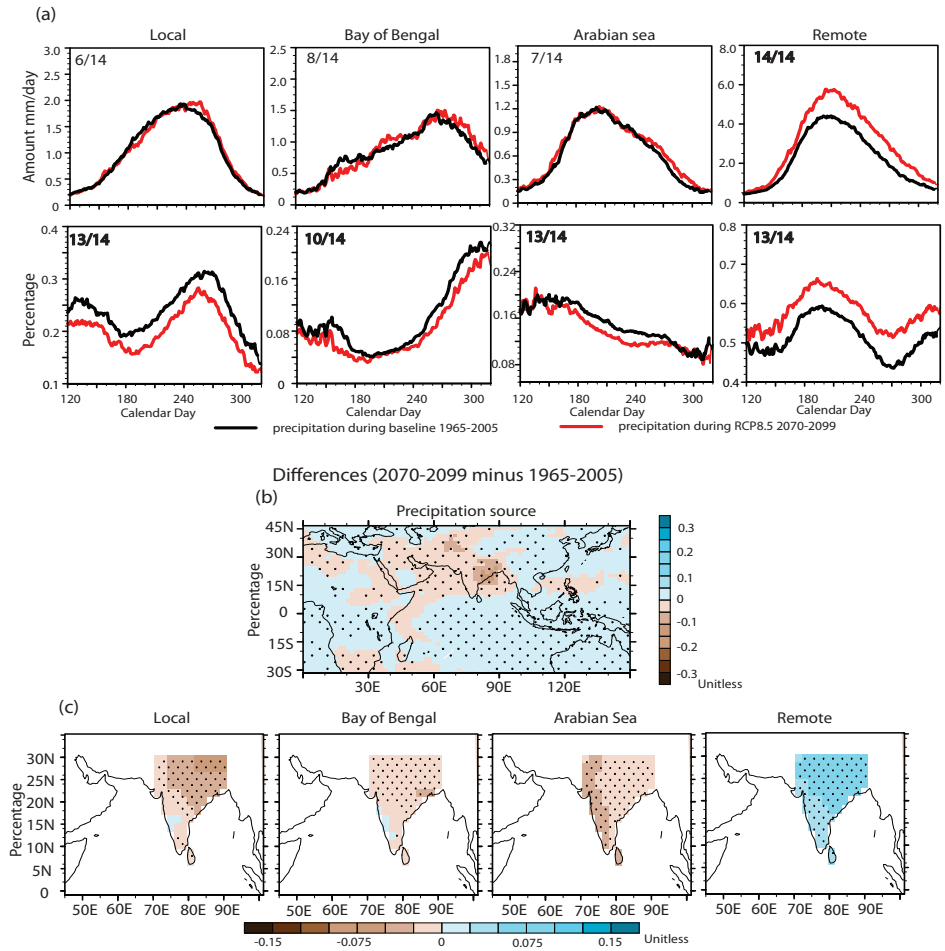



Individual GCM skill varies a lot:

For example, 12 out of 18 models can capture the relative contribution of each moisture source

but only 7 out of 18 models can capture the increasing (decreasing) dominance of local (remote and Arabian sea) contribution from monsoon onset to retreat.

# Moisture source response




Overall robust temporal and spatial changes include:

an increase in the absolute and percentage contribution from the remote

and a decrease in the percentage contribution from all other relatively regional sources (local, Bay of Bengal and Arabian Sea).

# Summary

**Consistent with majority of previous studies:**

A robust increase in summer monsoon precipitation in South Asia through 21st century in CMIP5

Weakening of the monsoon dynamics (through MTG, U-shear, and V-shear) is compensated by the increase in atmospheric precipitable water due to atmospheric warming.

**New insights gained:**

Reveal the relative contribution of four exclusive but complementary moisture sources: remote, local recycling, Arabian Sea, Bay of Bengal.

Unveil intrinsic characteristics of precipitation from different moisture sources such as their spatial footprints over South Asia and temporal variability during the summer monsoon period.

Infer that summer monsoon precipitation increase is mostly sustained by the increase in moisture supply from remote sources instead of regional sources (local, Arabian Sea and Bay of Bengal), facilitated through increases in atmospheric moisture content and moisture convergence over South Asian monsoon region.

# Using Graphics Processing Units for Climate Simulation

Matt Norman

Scientific Computing Group
National Center for Computational Sciences

ORNL is managed by UT-Battelle
for the US Department of Energy

Climate Change Science Institute
Oak Ridge National Laboratory

# Why Bother with GPUs?

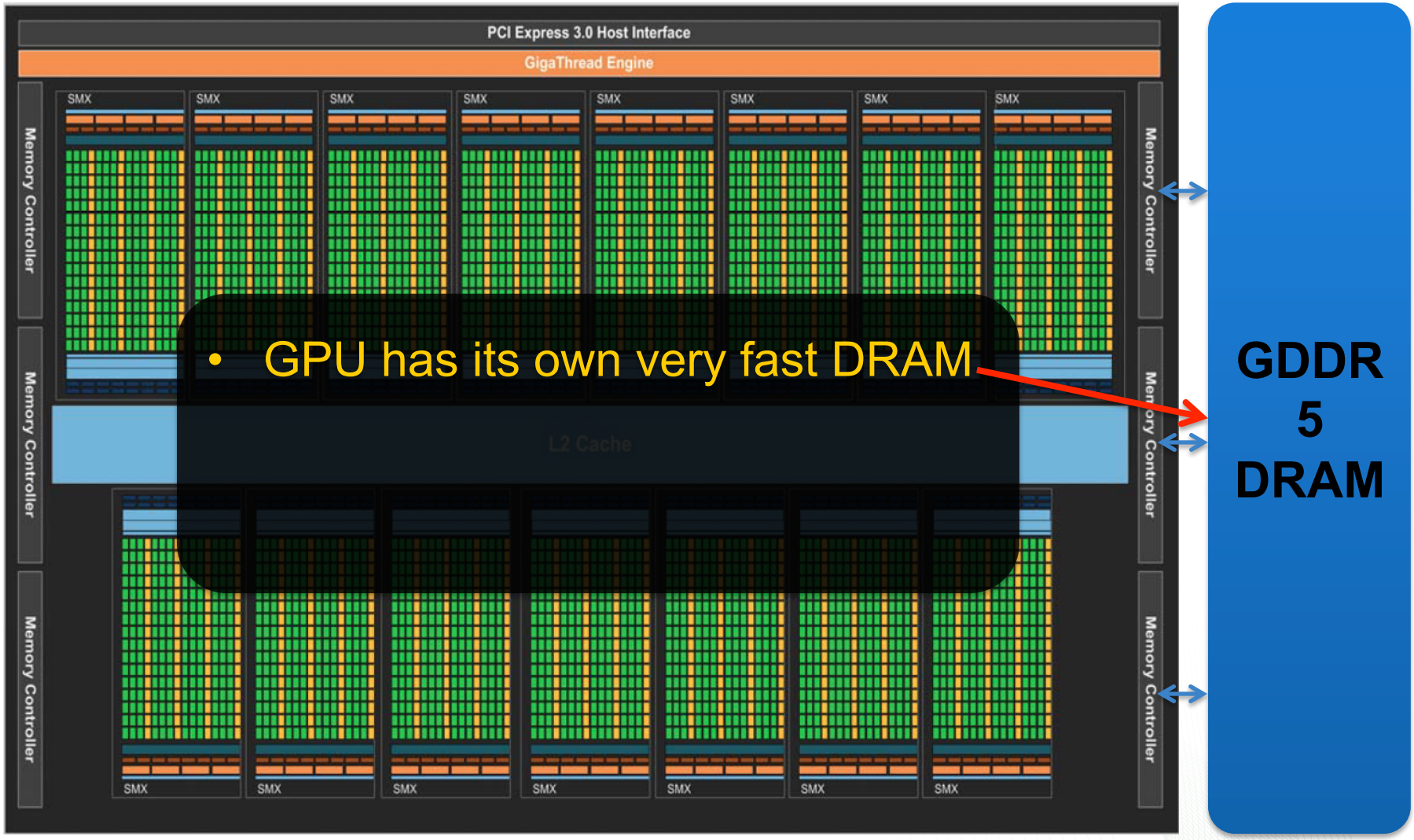
- Nov. 2011 Top 500 – Dense Linear Algebra Bench.
  - OLCF's Jaguar (#3): 1.8 Petaflops, 7 MegaWatts
  - That's **5,600** average U.S. households of power
  - Tennessee costs 9.98 cents per KiloWattHour
  - Power bill runs about $500,000 / month
  - **$300,000/month** per Petaflop
- Nov. 2012 Top 500
  - OLCF's Titan (#1): 17.6 Petaflops, 8.2 Megawatts
  - **$34,000/month** per Petaflop
- No other way to give advances in computational science

**Only matters if real science can access this performance**

# What Is a GPU?

Image Source: http://www.nvidia.com/content/PDF/kepler/NVIDIA-Kepler-GK110-Architecture-Whitepaper.pdf

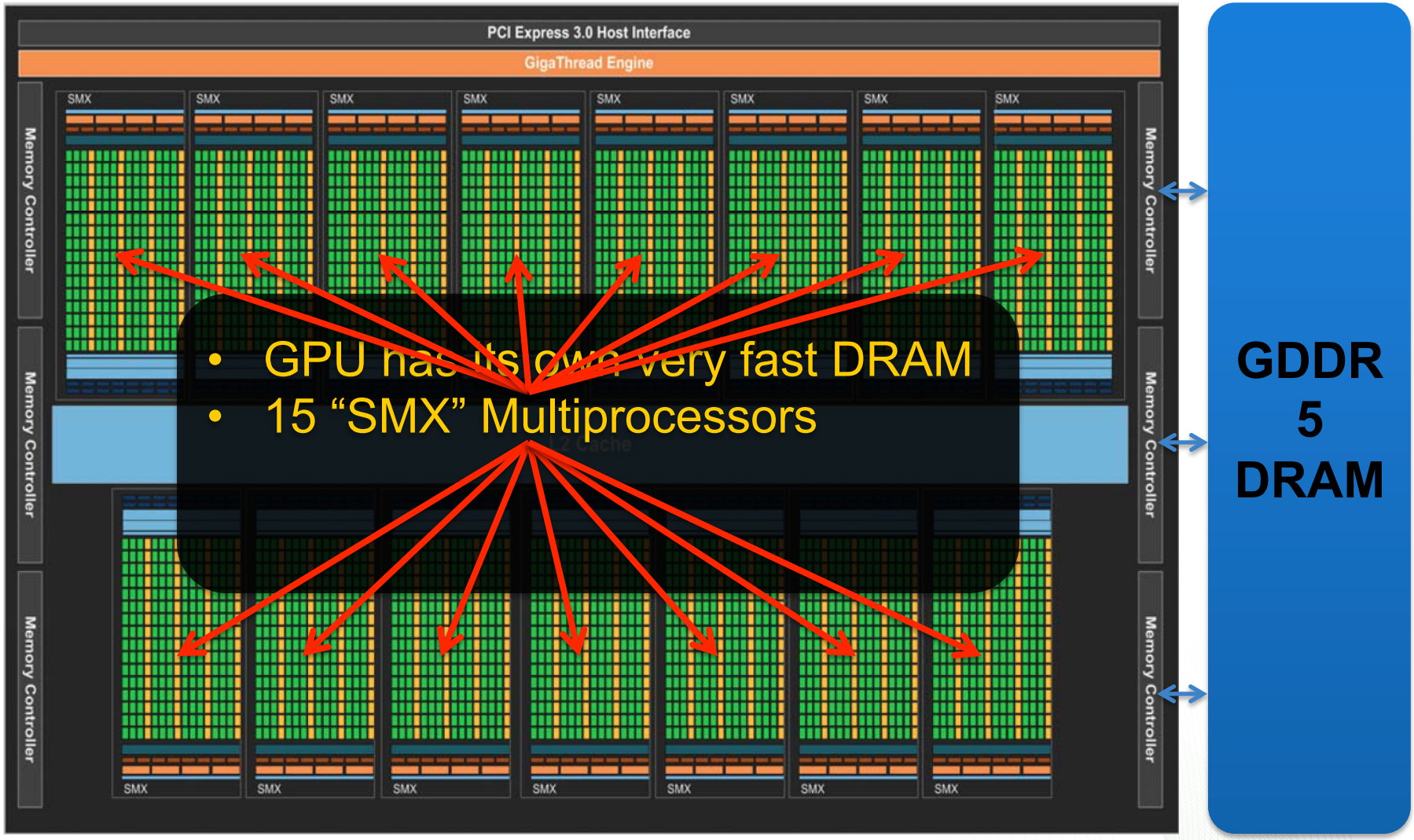
# What Is a GPU?




- GPU has its own very fast DRAM

**Image Source: http://www.nvidia.com/content/PDF/kepler/NVIDIA-Kepler-GK110-Architecture-Whitepaper.pdf**

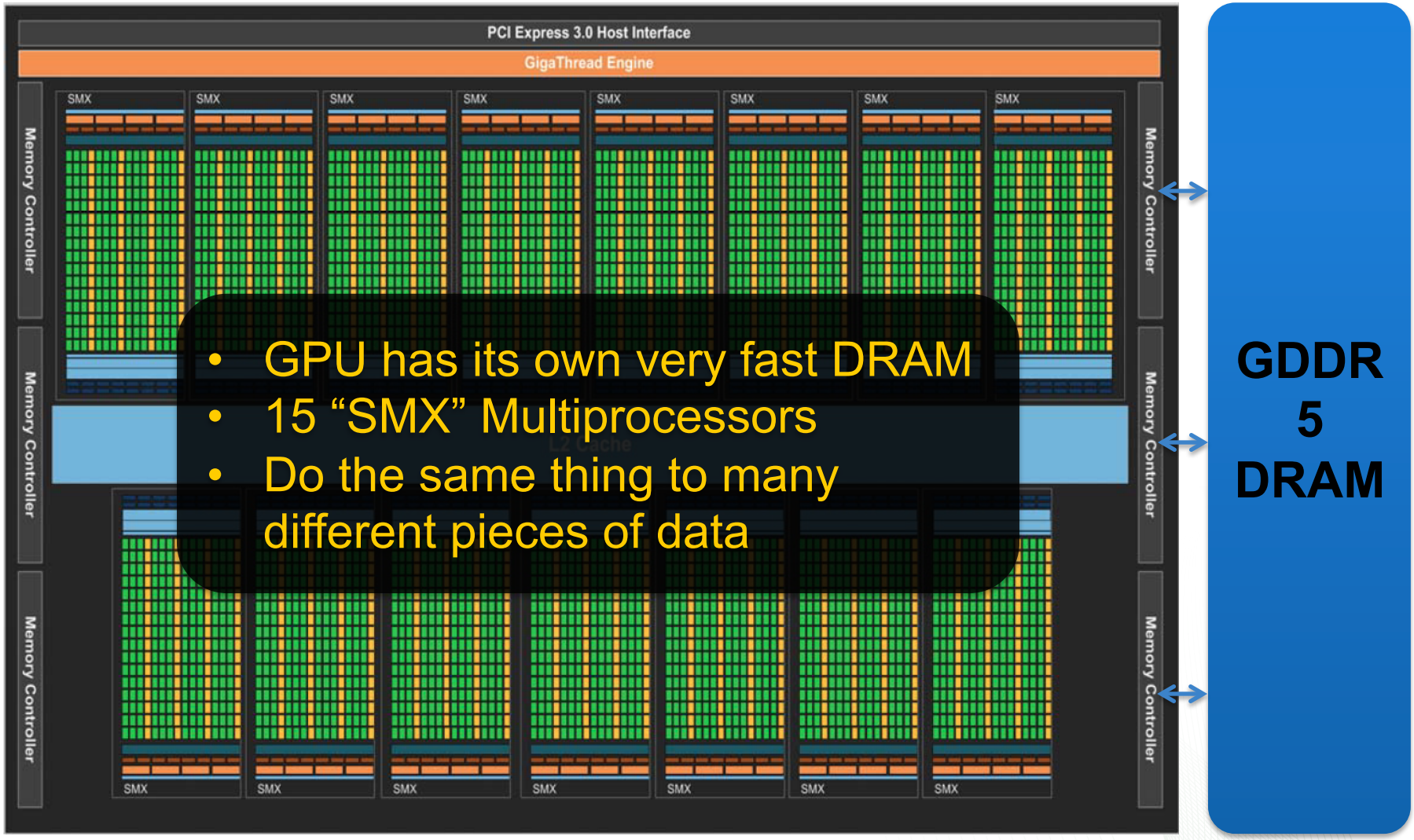
# What Is a GPU?




- GPU has its own very fast DRAM
- 15 “SMX” Multiprocessors

**Image Source: http://www.nvidia.com/content/PDF/kepler/NVIDIA-Kepler-GK110-Architecture-Whitepaper.pdf**

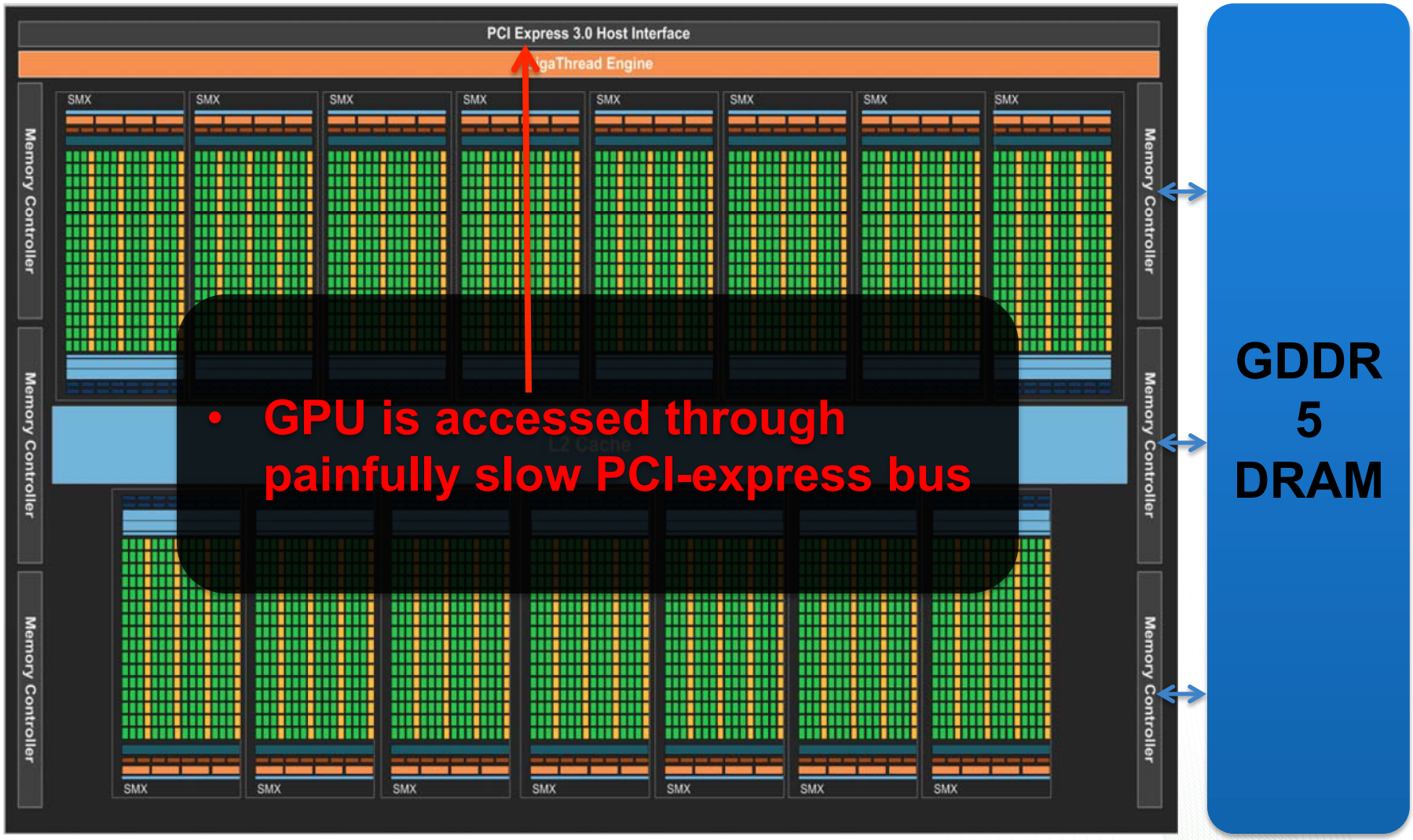
# What Is a GPU?




- GPU has its own very fast DRAM
- 15 “SMX” Multiprocessors
- Do the same thing to many different pieces of data

**Image Source: http://www.nvidia.com/content/PDF/kepler/NVIDIA-Kepler-GK110-Architecture-Whitepaper.pdf**

# What Is a GPU?




- GPU is accessed through painfully slow PCI-express bus

Image Source: http://www.nvidia.com/content/PDF/kepler/NVIDIA-Kepler-GK110-Architecture-Whitepaper.pdf

# Challenges for Climate on GPUs

- MPI Waiting: Cannot be accelerated
  - Must minimize or overlap MPI Waiting
- PCI-express Bus: Going away soon!
- Software Engineering: CUDA, OpenACC
  - CUDA requires too much code rewriting; unreadable code
  - OpenACC requires significant code restructuring
    - But we might have to do this restructuring anyway
  - OpenMP for Intel MICs looks quite similar to OpenACC
- Compiler bugs common due to immature OpenACC implementations
- Ensure code is portable & performant on other machines

# Opportunities for Climate on GPUs

- Current atmospheric grid: 28km
- Grid refinement impossible: $\Delta t$ refines with $\Delta x$
  - Therefore, 2x smaller grid spacing → 2x less data per node!
  - MPI dominates when there is too little data per node
- We must reduce cost per DOF for more DOFs / node
  - GPUs & accelerators give us the ability to do this
  - Future machines give multiple accelerators per node
- Ensembles become much cheaper to compute
  - The more data per node, the faster the GPUs perform
  - Incentive to run <u>more ensembles</u> to understand uncertainties
- Future computers remove biggest performance bottlenecks

# OLCF Center for Accelerated Application Readiness (CAAR)

- ACME received a CAAR award for 2015-2018
- Porting to OLCF's coming Summit computer in advance
- Order 10x more powerful than Titan
- ACME currently utilized Titans' GPUs poorly
  - Thus, >> 10x improvement is successfully using Summit
- Two main scientific tracks
  1. Port costliest portions of ACME to GPUs with OpenACC
  2. Use "super-parametrizations" of clouds to keep GPUs busy
- Early science runs will be groundbreaking climate simulations infeasible on current computers

# Time Integration for Earth Simulation Models

Rick Archibald
Oak Ridge National Laboratory

**ESM Workshop**
**ORNL**
**June 9nd, 2015**

# Challenge: Computational Time-step Barrier

- Without development in time-stepping, climate simulation will hit the time-step barrier
  - Little benefit from higher scales of computing
  - Must choose between higher resolution or tolerable throughput
- Dramatically improve accuracy of highly-coupled models

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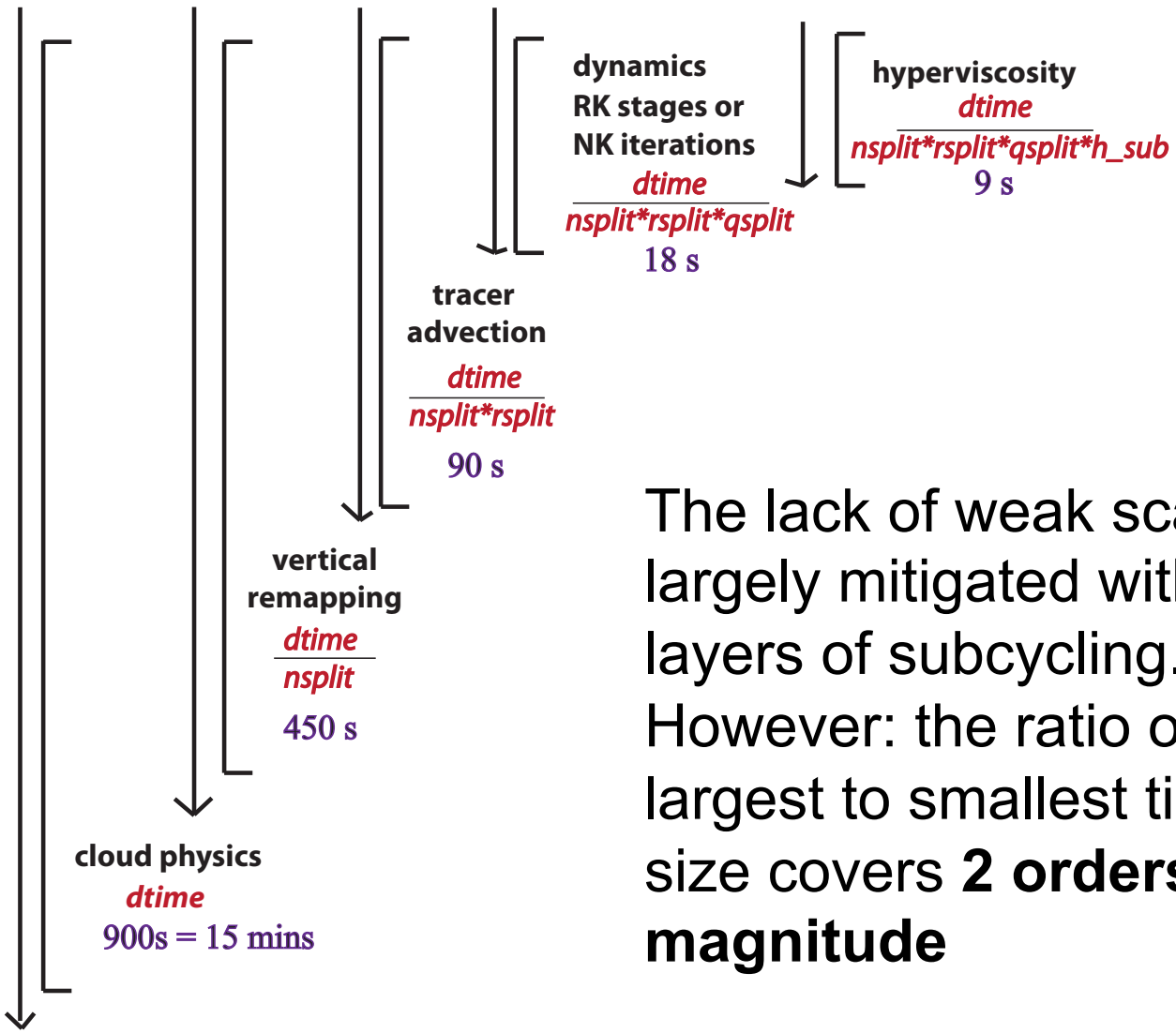
- Dramatically improve accuracy of highly-coupled models
- Dramatically accelerate spin-up of new simulations
- Potentially revolutionize climate simulation and other application areas with long time integration
- *Crucial for climate simulation, promising for other fields*

# Anatomy of a Time Step: ¼° CAM-SE dycore




The lack of weak scaling is largely mitigated with many layers of subcycling. However: the ratio of the largest to smallest time step size covers **2 orders of magnitude**

# Climate Time-step solvers

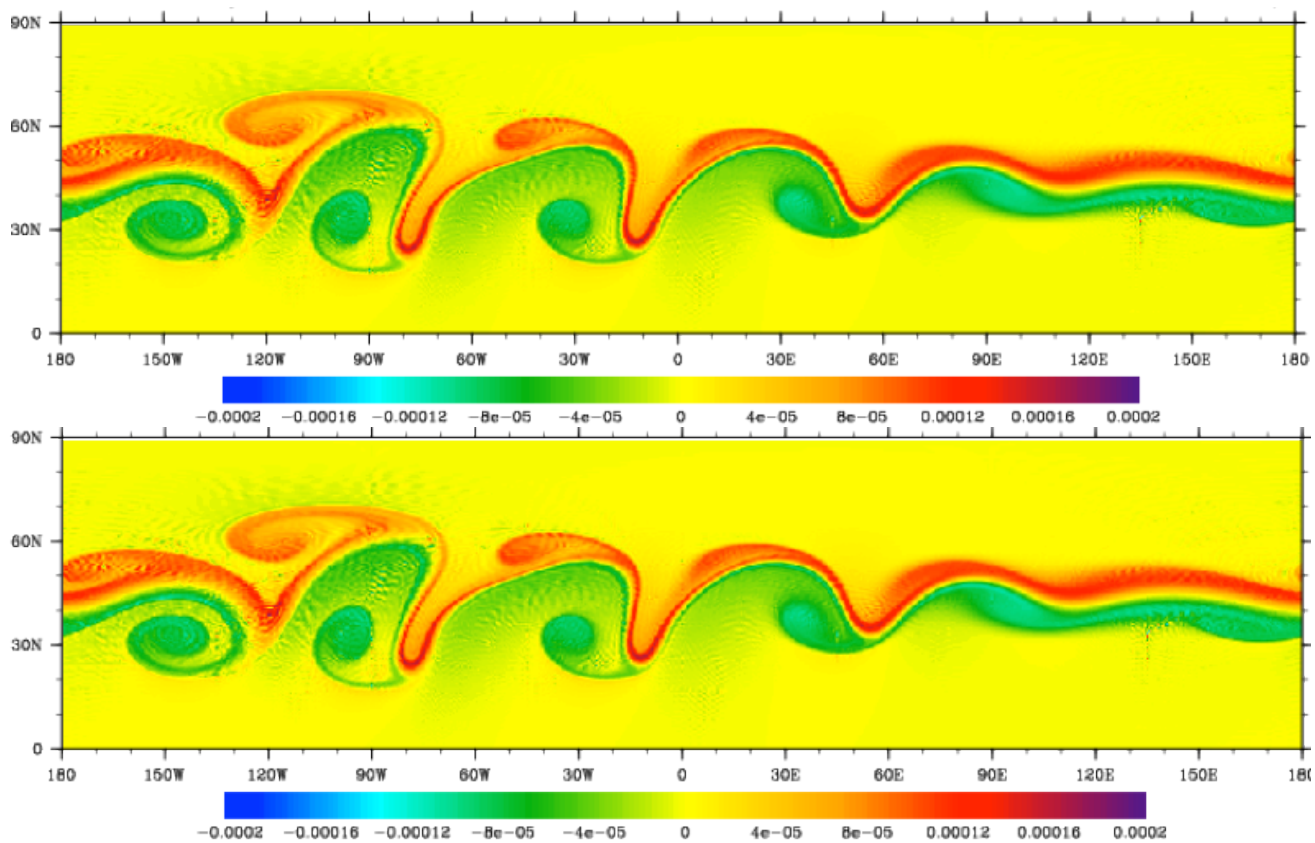
- Fully implicit methods
  - Require non-linear solvers and preconditioning.
- Exponential Operators
  - Equations split into non-linear and linear pieces.
- Asynchronous Multirate
  - Depended upon slow and fast time scale split.
- Arbitrary Derivative Riemann (ADER)
  - Higher order time derivatives swap out for spatial derivatives.
- Differed correction
  - Uses integral equations to iteratively minimize residual.

# Implicit Solver within CAM-SE

- Time step limitations grow with spatial resolution
- Regionally refined configurations are subject to the same limitations
- Goal: efficiency with acceptable accuracy for production runs
- Goal: use hybrid architectures (we are already being charged for them!)
- Use dynamics solver as a base for easier extension to physics and coupling to other components
- Challenge: scalable preconditioners require a lot of development and interaction with algorithmic experts
- Challenge: porting to GPUs is like jumping onto a moving vehicle

# Galewsky TC: initial flow perturbation within an unstable mid-latitude jet.

Challenges: Fast divergent gravity waves and longer term flow instabilities over 6 days




Explicit 2nd Order RK 5 stage 10s ts

Implicit 2nd Order BDF2 1200s ts

# 2D Baroclinic Instability Test Case ~1/2 degree 12 days long

| Method | Time Step Size | Sim Time | N | L/N |
|---|---|---|---|---|
| Exp RK | 10 | 4m 16s | N/A | N/A |
| Imp BDF2 | 1200 | 3m 42s | ~7 | 30 |
| Imp BDF2 | 1800 | 3m 30s | ~8 | 30* |

Higher order discretization within each element Good candidate case for GPU (not preconditioned)

# Gains possible using GPU: merge the data structure framework

**Implicit Framework**

```
do ie,q,k,j,i
     xstate(:) = elem(ie)%state%var(i,j,k,q)
end

call nxsolve(xstate,..)

do ie,q,k,j,i
       elem(ie)%state%var(i,j,k,q)=xstate(:)
end
```

**GPU Framework**

```
do ie,q,k,j,i
     gpu_array(:) = elem(ie)%state%var(i,j,k,q)
end

call GPU_Kernel(gpu_array,..)

do ie,q,k,j,i
       elem(ie)%state%var(i,j,k,q)=gpu_array(:)
end
```

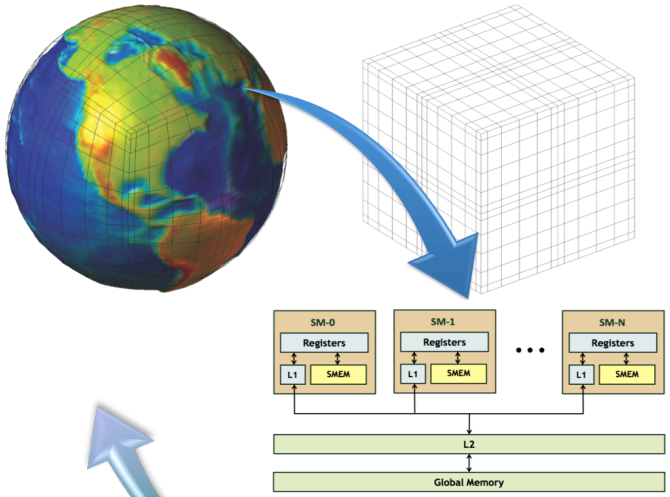
**Implicit-GPU Framework**

```
do ie,q,k,j,i
    xstate(:) = elem(ie)%state%var(i,j,k,q)
end

call nxsolve(xstate,..) ➔ call GPU_Kernel(xstate,..)

do ie,q,k,j,i
     elem(ie)%state%var(i,j,k,q)=xstate(:)
end
```

# Framework to compute implicit time-stepping on TITAN

Trilinos

Enabled:
Common build system that links Trilinos to CAM-SE **and** the GPU kernel development




Active:
Development of CAM-SE kernels providing GPU acceleration on green-power effective next generation architecture

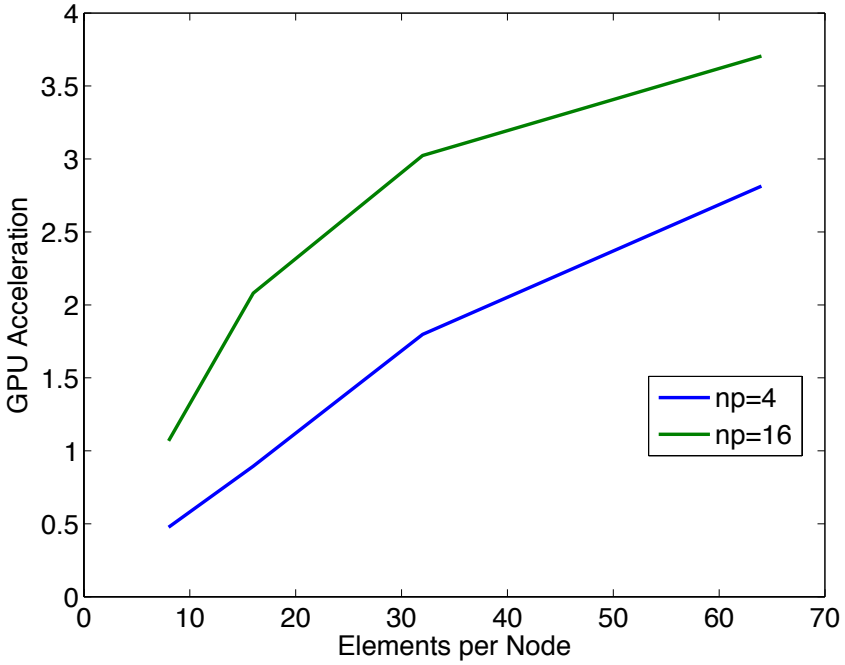
GPUs show 2x speedup on TITAN acceptance problem with 110 tracers

Enabled:
Build system that incorporates latest GPU development

CAM-SE

# Early results of speedup calculating the residual on the GPU

- Illustrates the use of hybrid architectures: Titan
- Assigning more work to the GPU produces more speed-up relative to CPU only
- Mountain test case: 4° and 1°, # vertical levels=26, ts=580s, 1 simulation day



# The benefits of ensemble simulation for testing: more confidence and efficiency

ESM Workshop

June 9, 2015

ORNL is managed by UT-Battelle
for the US Department of Energy

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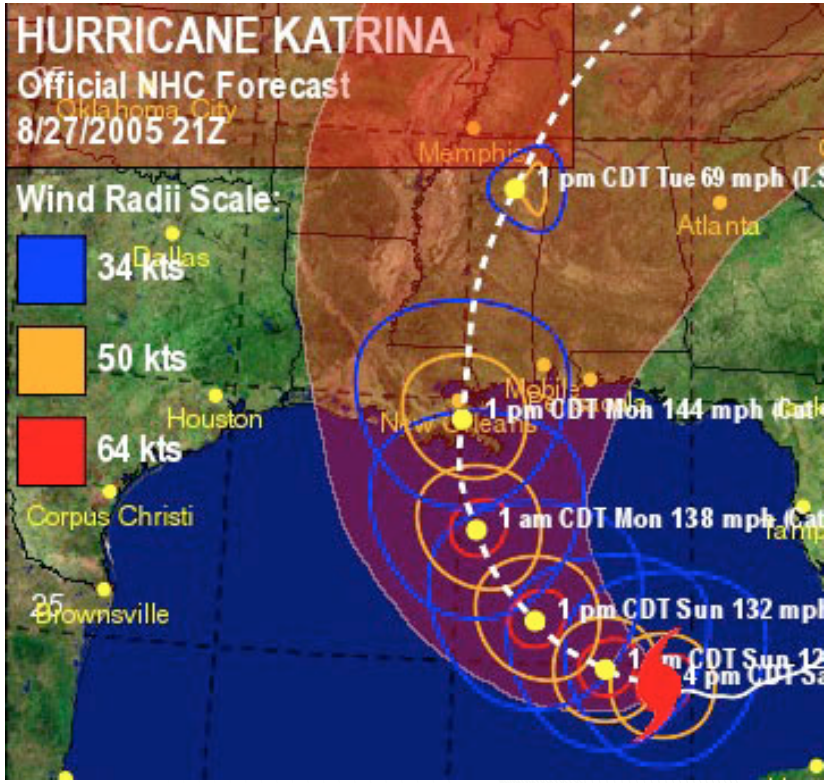
# Why Ensembles?

- Edward Lorenz and the "butterfly effect"
  - Physical equations governing weather and climate are non-linear
  - Small changes in initial conditions result in considerably different states of the system
- Ensemble: set of simulations with slightly perturbed initial conditions (different sizes of butterfly)
- We need ensembles to give us an idea of the range of possible system states



# Evaluating ACME Ensemble Scalability Performance

- How does a 100-year global climate simulation, or 5 20-year simulations, differ from 100 1-year simulations run in parallel?
  - Scientifically: How do model variables differ statistically? How and where do these simulations differ?
  - Computationally: What performance improvements do we get?

# Computational Improvements

- 1-year 100 member ensemble:
  - 5x more elements per node than the 20-year and 100-year runs
  - 60% of the core hours (1.1M versus 1.8M for 20 year 5 member)
  - 4400 nodes total: 1/4 of Titan (classified as a "capability-scale" job)
  - Aggregate throughput: 280 SYPD. 100 year: ~2 SYPD
- We use the computer architecture and our own time much more efficiently with parallel ensembles

# Are these sets of simulations the same?

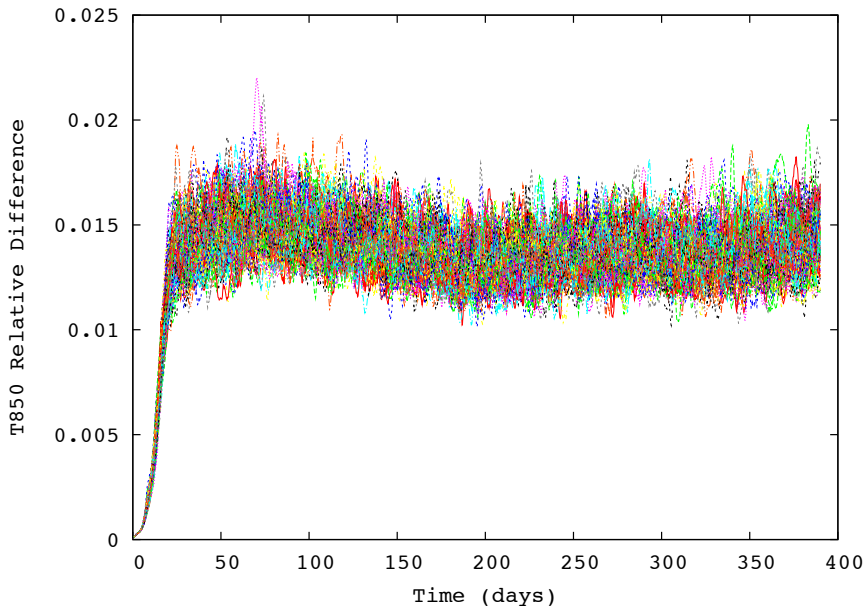
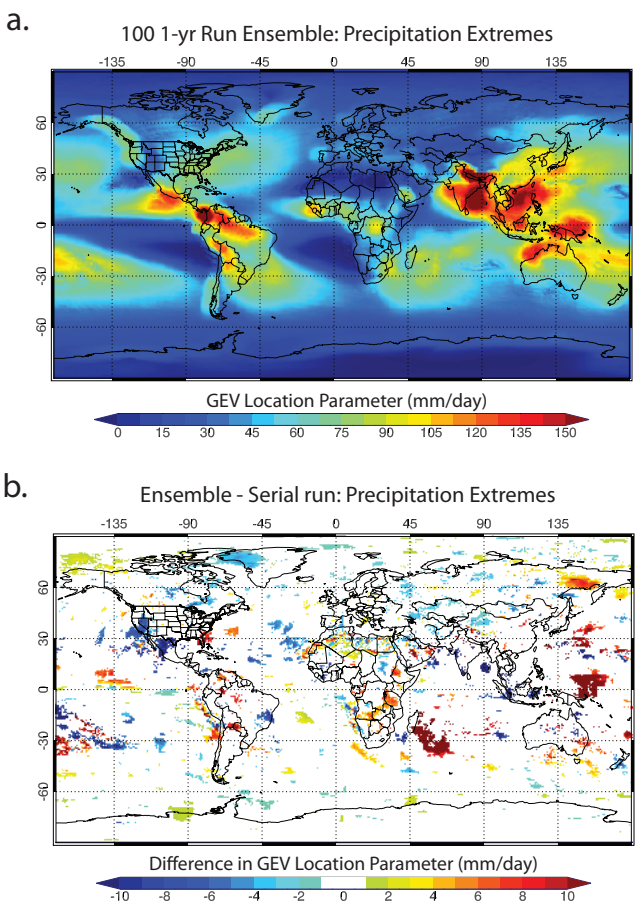


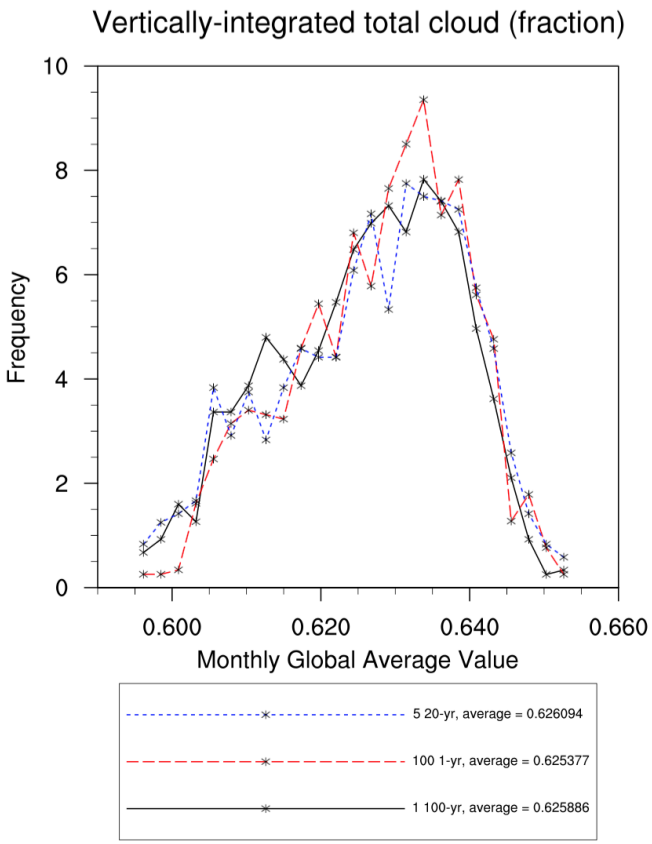

Figure 1: L1 norm of relative difference in 850mb temperature between each of the 100 ensemble members over time. Members are distinct after roughly 23 days.

- Analysis underway:
  - RMS error and error growth
  - Probability distribution function comparisons and tests
  - Statistical evaluation of extremes

# Further analysis




(a) Precipitation extremes for the 100 member ensemble
(b) Statistically significant difference in precipitation extremes between 100 year simulation and 100 member ensemble




Histogram of total cloud fraction vertically integrated and globally averaged monthly values for all three sets of simulations

# ***Ultra high-resolution*** *ensemble projections of the near-term climate change over the* ***United States***

Deeksha Rastogi

June 09, 2015

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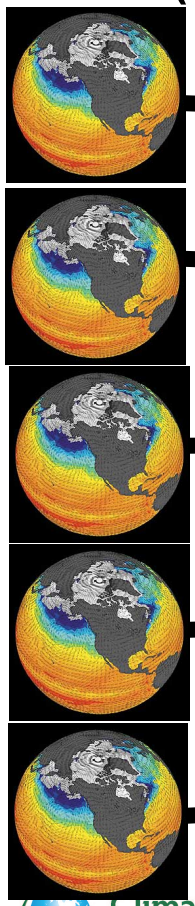
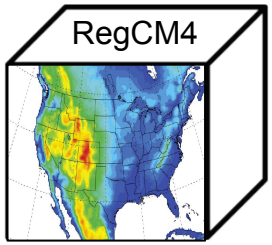
# Modeling Framework

**Global Climate Models (12)**



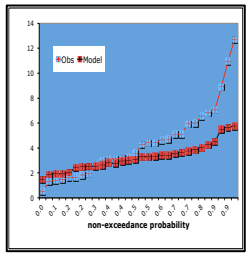
**(RegCM4) Regional Climate Model (18km)**

(Diffenbaugh and Ashfaq, 2010)



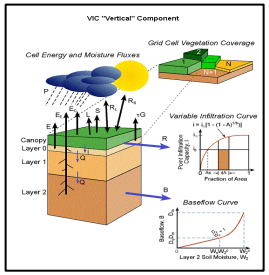

**Statistical Correction**

(Ashfaq et al, 2010, 2013)




**VIC Hydrological Model (4km)**

(Oubeidillah et al, 2014)




Baseline period 1965-2005
Future (RCP8.5) 2010-2050
Number of ensemble members **TWELVE**

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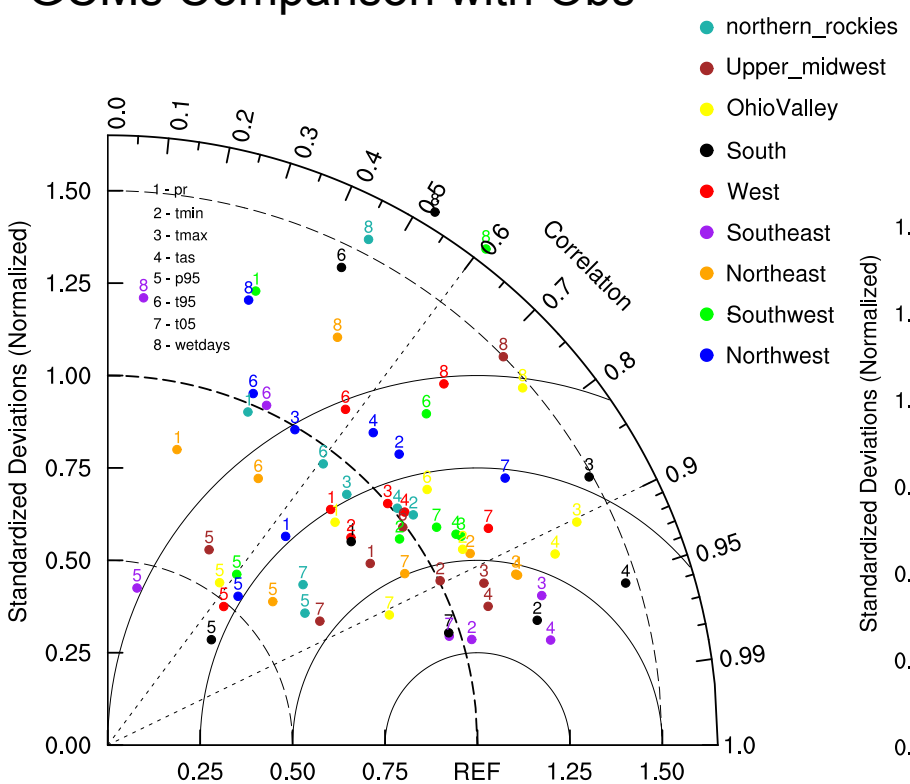
# Computational expense and data needs

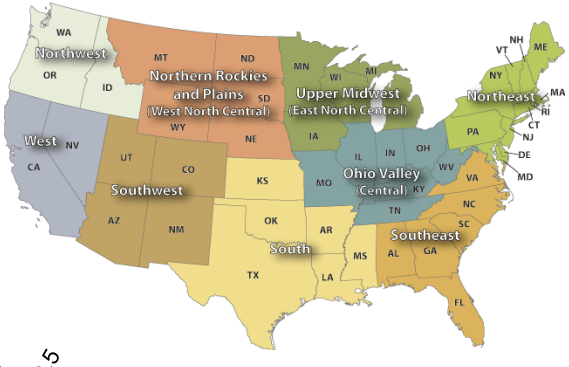
| Task Name | Processor hours per GCM<br>1965-2005 (baseline)<br>2010-2050 (future) | Data I/O |
|---|---|---|
| GCMs 6 hourly input data | - | ~40 TB |
| RegCM4 runs | 0.7M (8.5M for 12 GCMs) | ~8 TB per GCM (96 TB for 12 GCMs) |
| VIC runs | 0.2M (2.4 M for 12 RCMs) | ~4 TB per ensemble member (48 TB for 12 RCM ensemble members) |
| Pre and Post-processing of data | 3M | 5 TB |
| **Total** | **~15 Million Core hours** | **~200 Terabytes** |

# Baseline Comparisons (1966-2005)

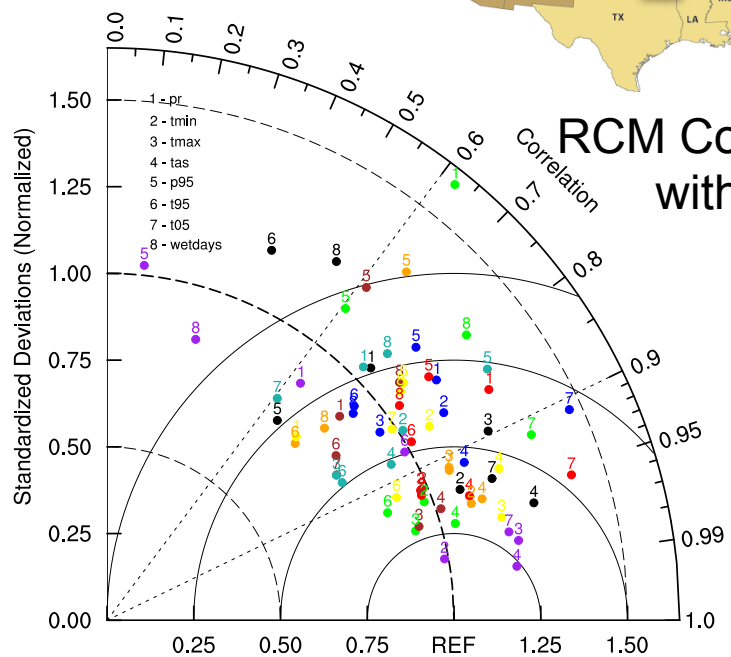
# Added Value in RCM simulations

GCMs Comparison with Obs



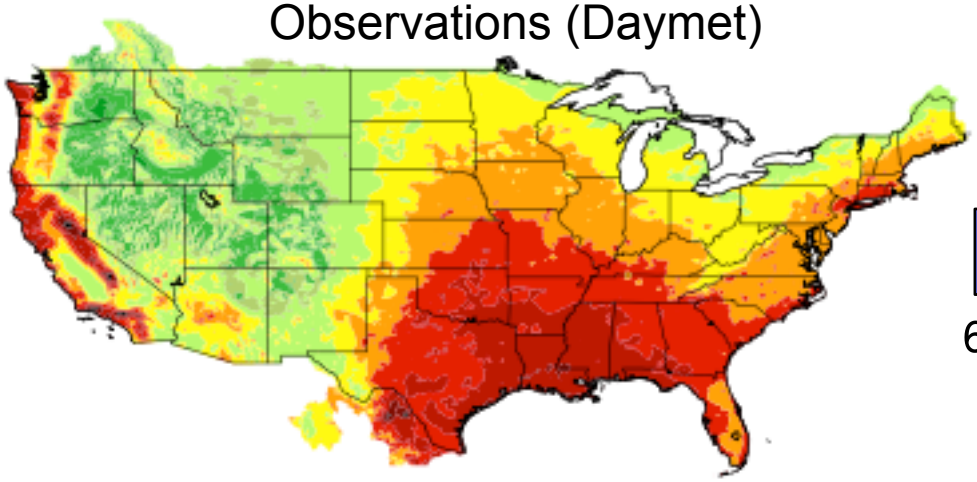




RCM Comparison with Obs

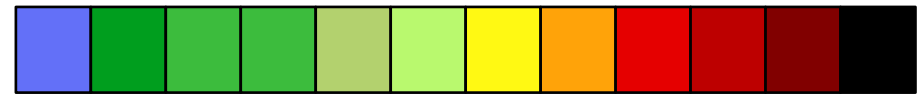


# Precipitation Extremes (95th Percentile)

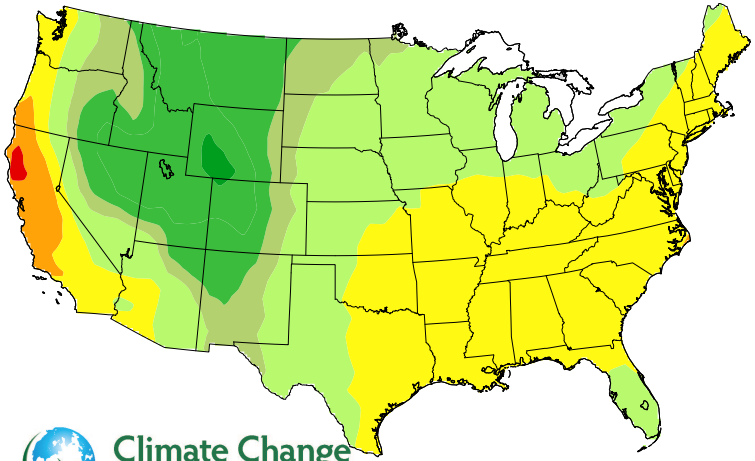
Observations (Daymet)



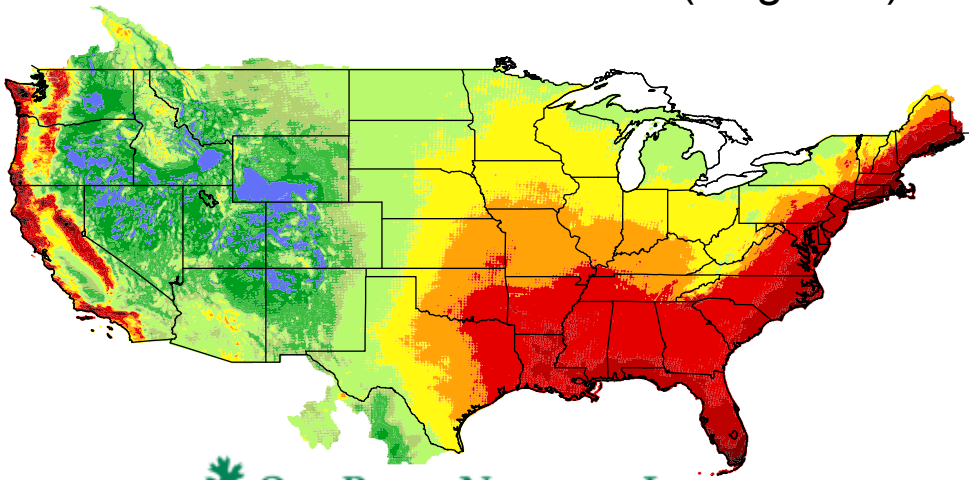
mm per day




Simulated Ensemble Mean (GCMs)



Simulated Ensemble Mean (RegCM4)



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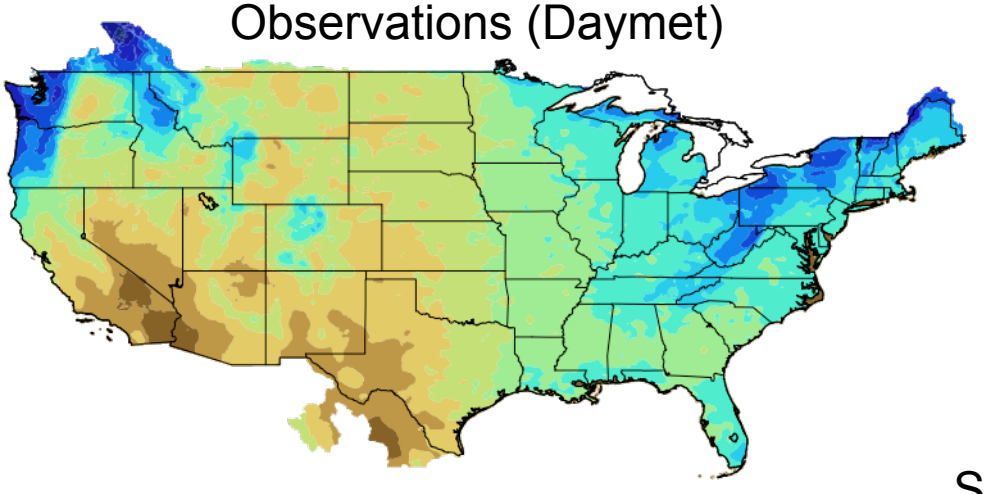
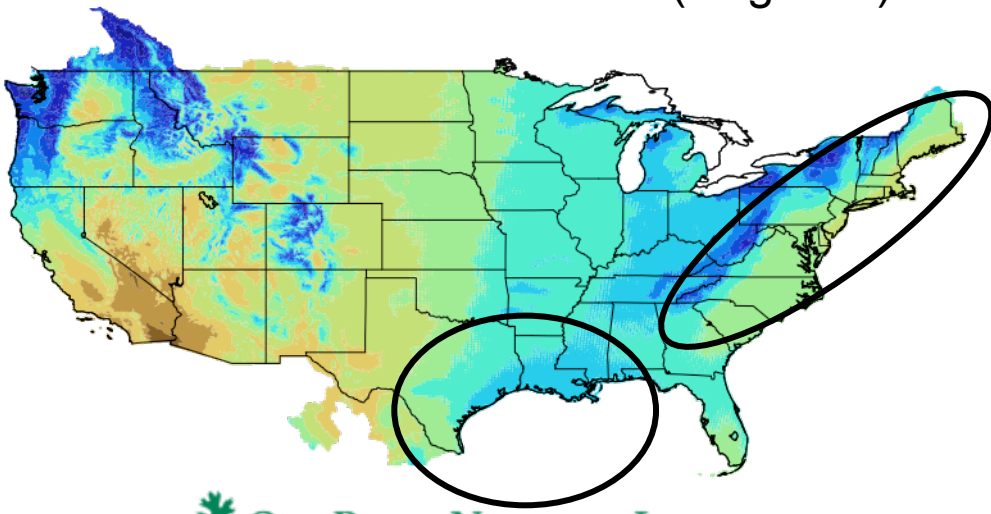
# Wet Days (at least 1 mm precipitation)

Observations (Daymet)



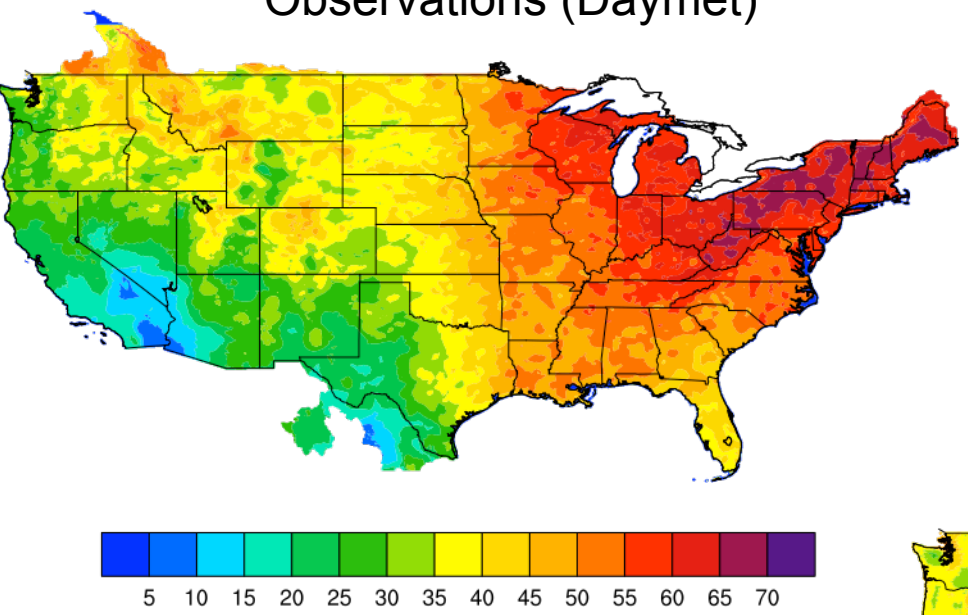
Days in a calendar year

Simulated Ensemble Mean (RegCM4)



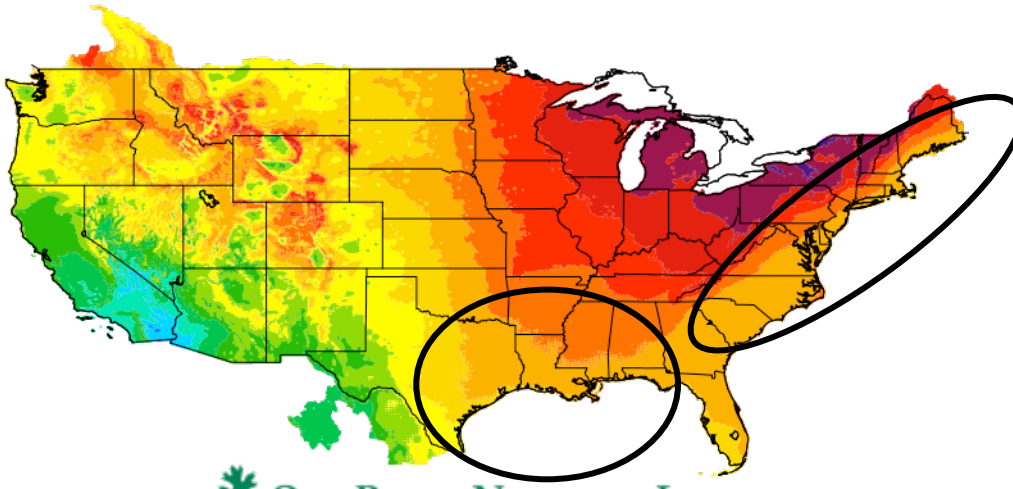
# Precipitation spells ( 5 days and shorter)

Observations (Daymet)




events per year

Simulated Ensemble Mean (RegCM4)



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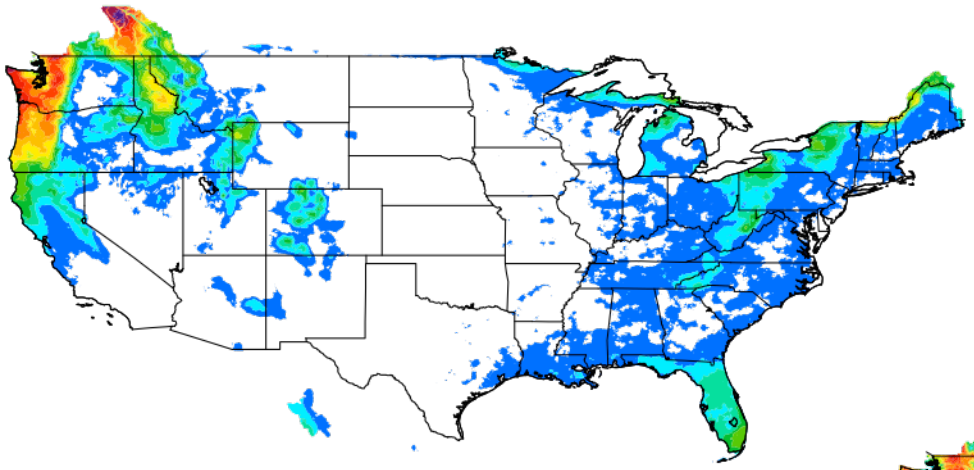
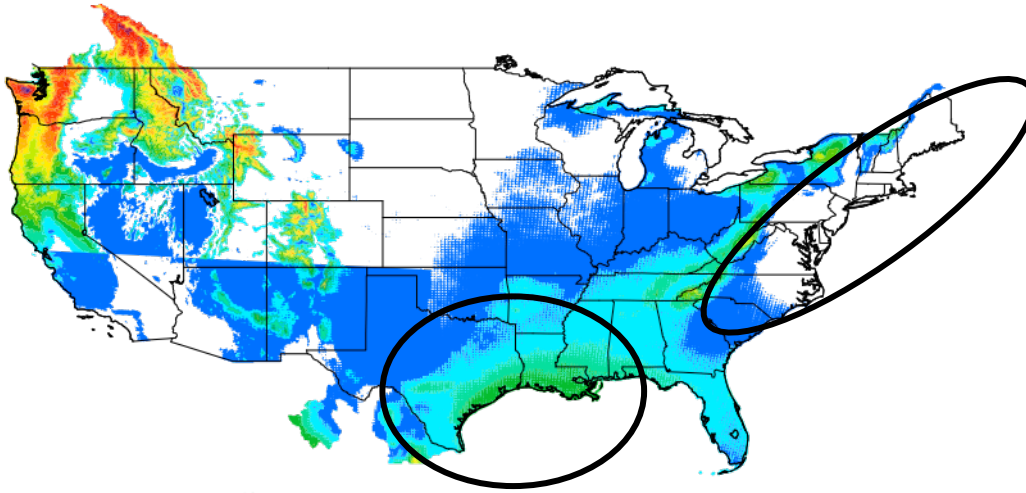
# Precipitation spells (longer than 5 days)

Observations (Daymet)



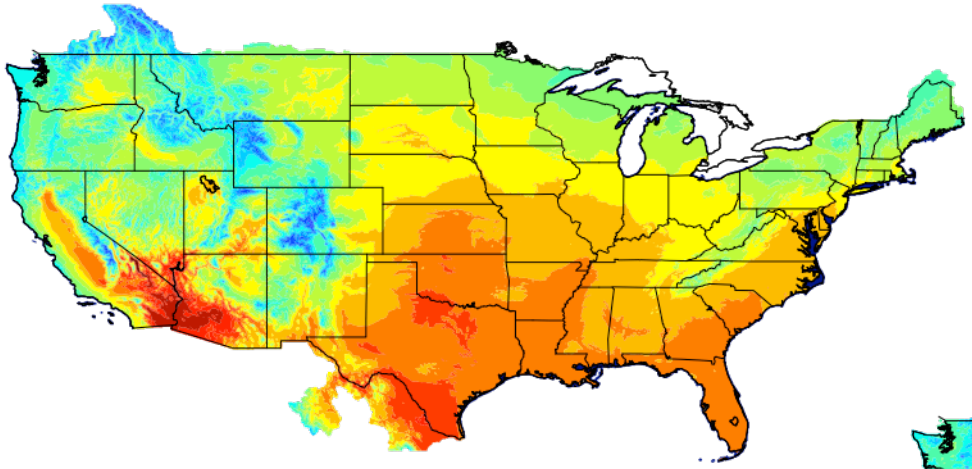
events per year

Simulated Ensemble Mean (RegCM4)



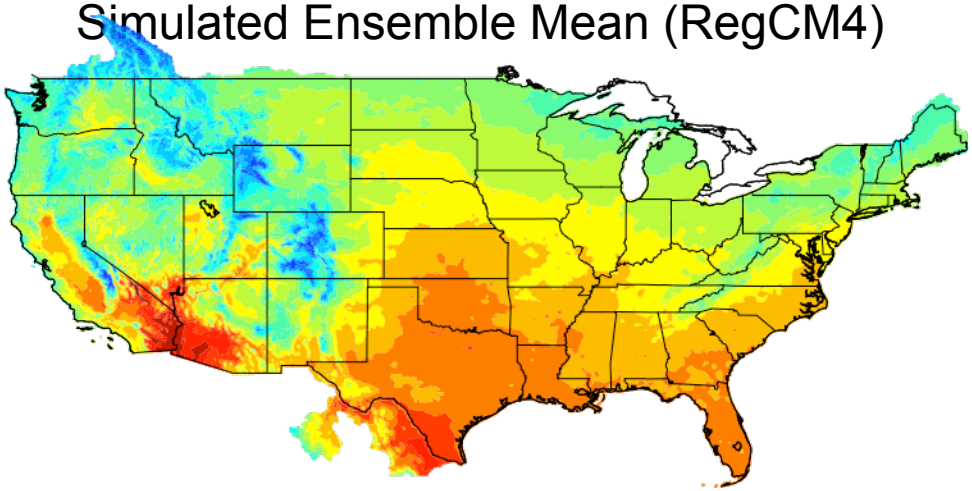
# Extreme Hot Temperature (95th Percentile of max daily Temperature)

Observations (Daymet)



Degree C

Simulated Ensemble Mean (RegCM4)



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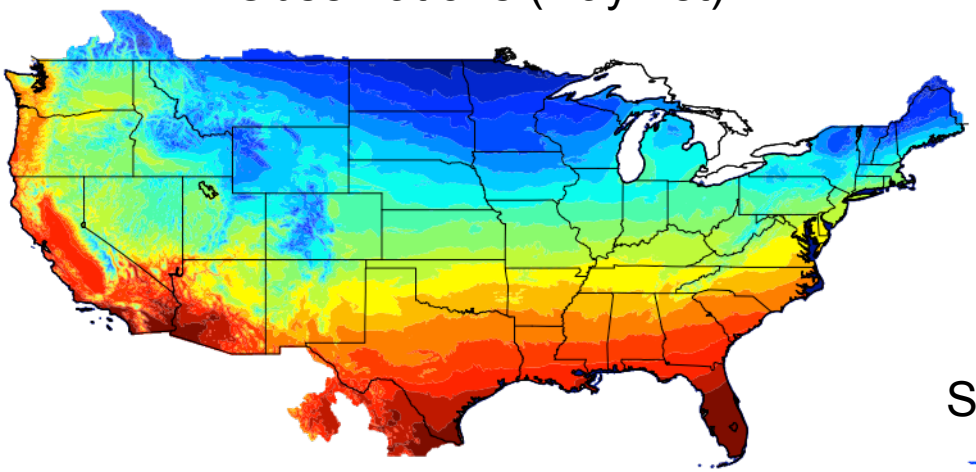
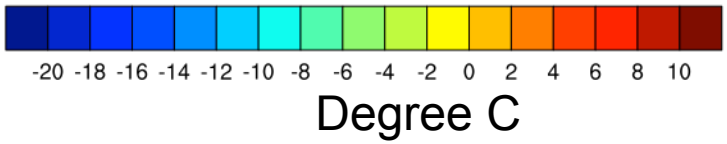
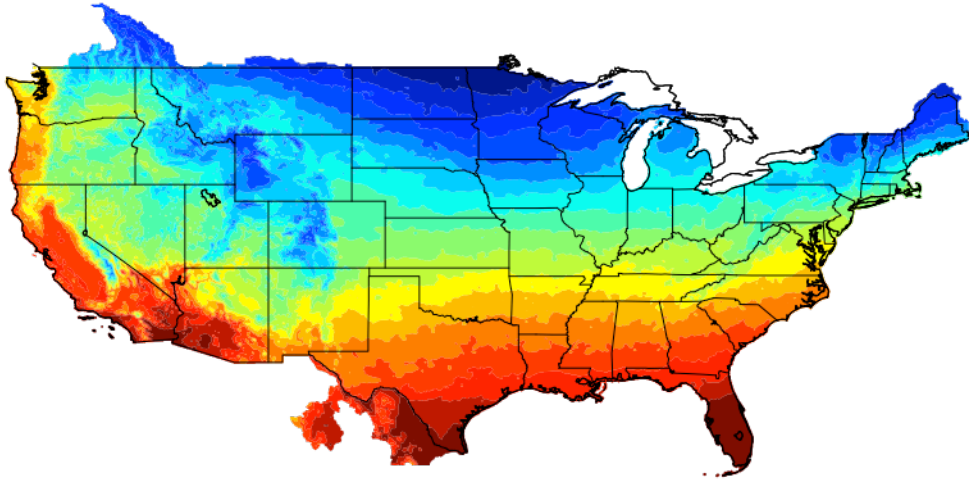
# Extreme Cold Temperature (5th Percentile of min daily Temperature)

Observations (Daymet)





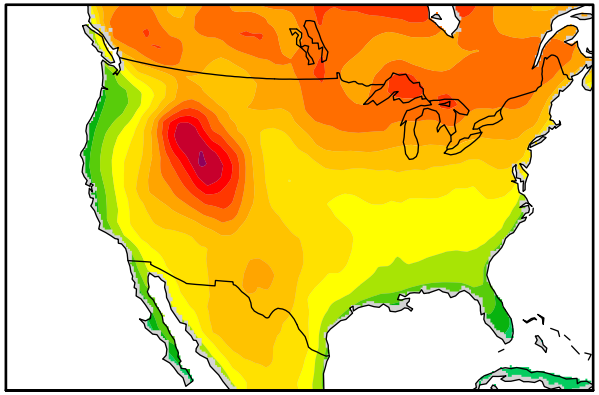

Simulated Ensemble Mean (RegCM4)

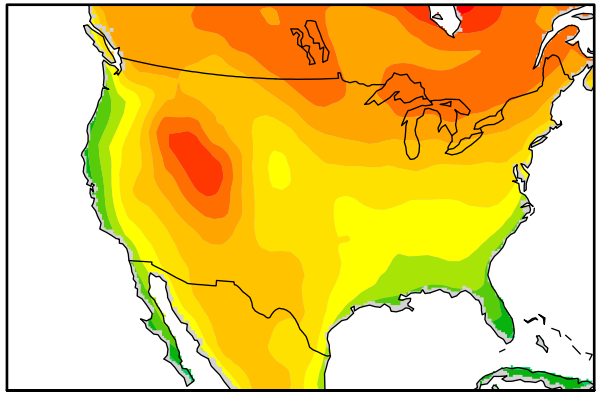


# Future Changes (2011-2050)

# Temperature Change (2011-2050 minus 1966-2005)

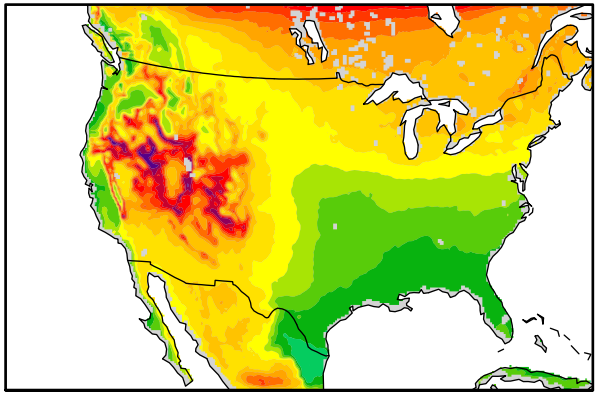
**10** CMIP5 Global Climate Models ensemble

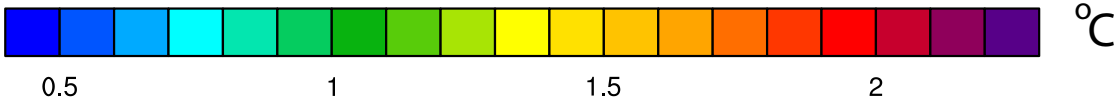




**30** CMIP5 Global Climate Models ensemble

**10** Dynamically Downscaled Regional Climate Model Ensemble



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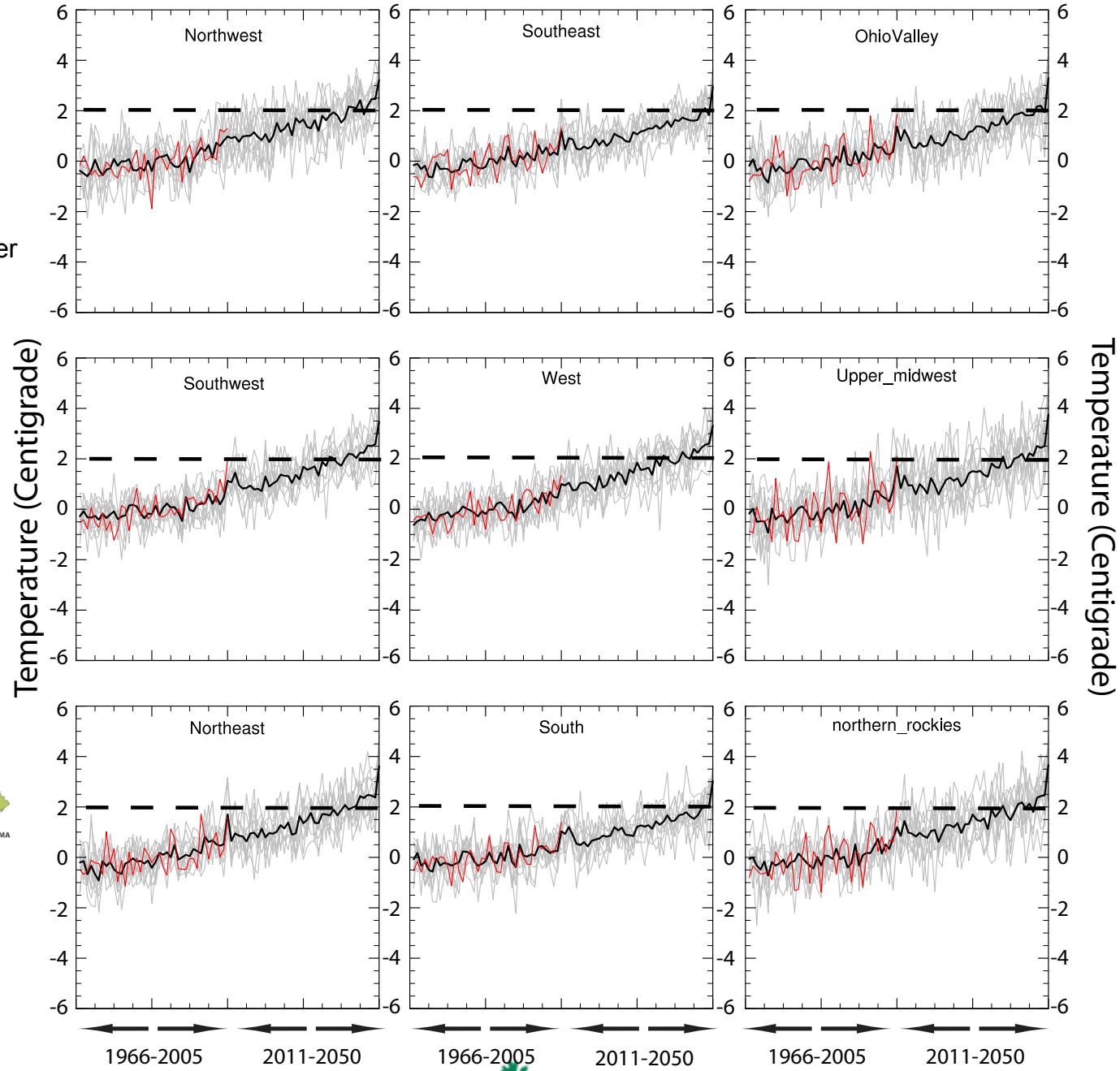
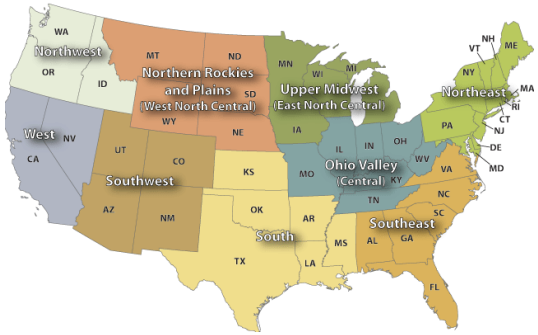
**Red**= PRISM Observations
**Black** = Multi Model Mean
**Grey** = Individual Ensemble Member

# Temperature Change w.r.t 1966-2005 Average

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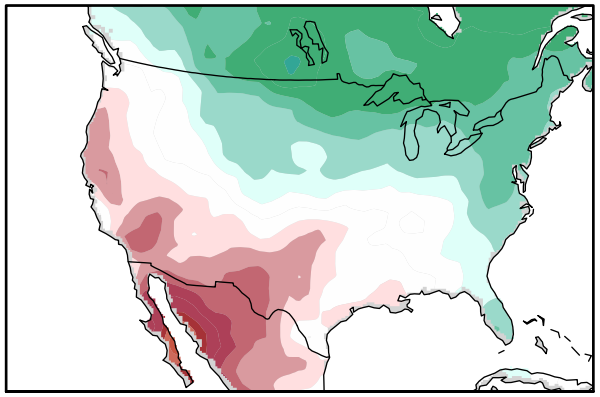
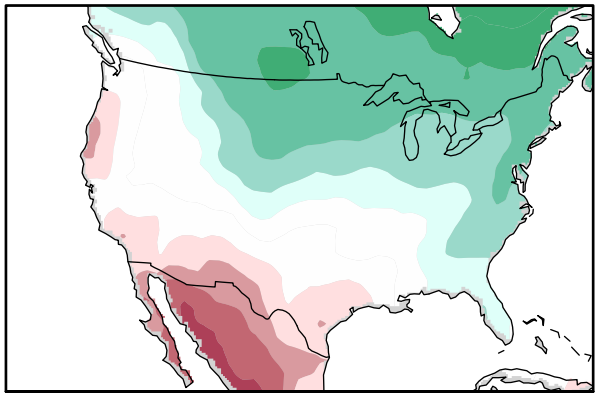
# Precipitation Change (2011-2050 minus 1966-2005)

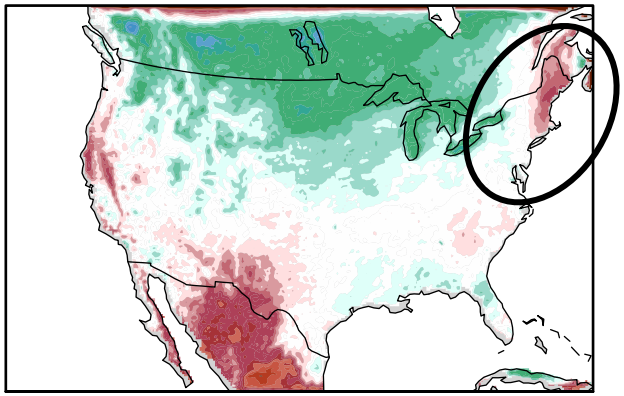
**10** CMIP5 Global Climate Models ensemble

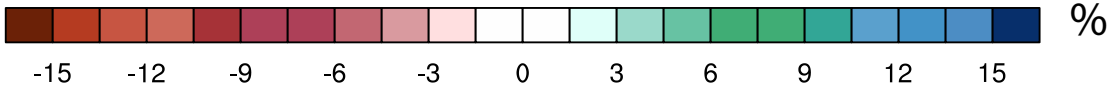




**30** CMIP5 Global Climate Models ensemble

**10** Dynamically Downscaled Regional Climate Model Ensemble



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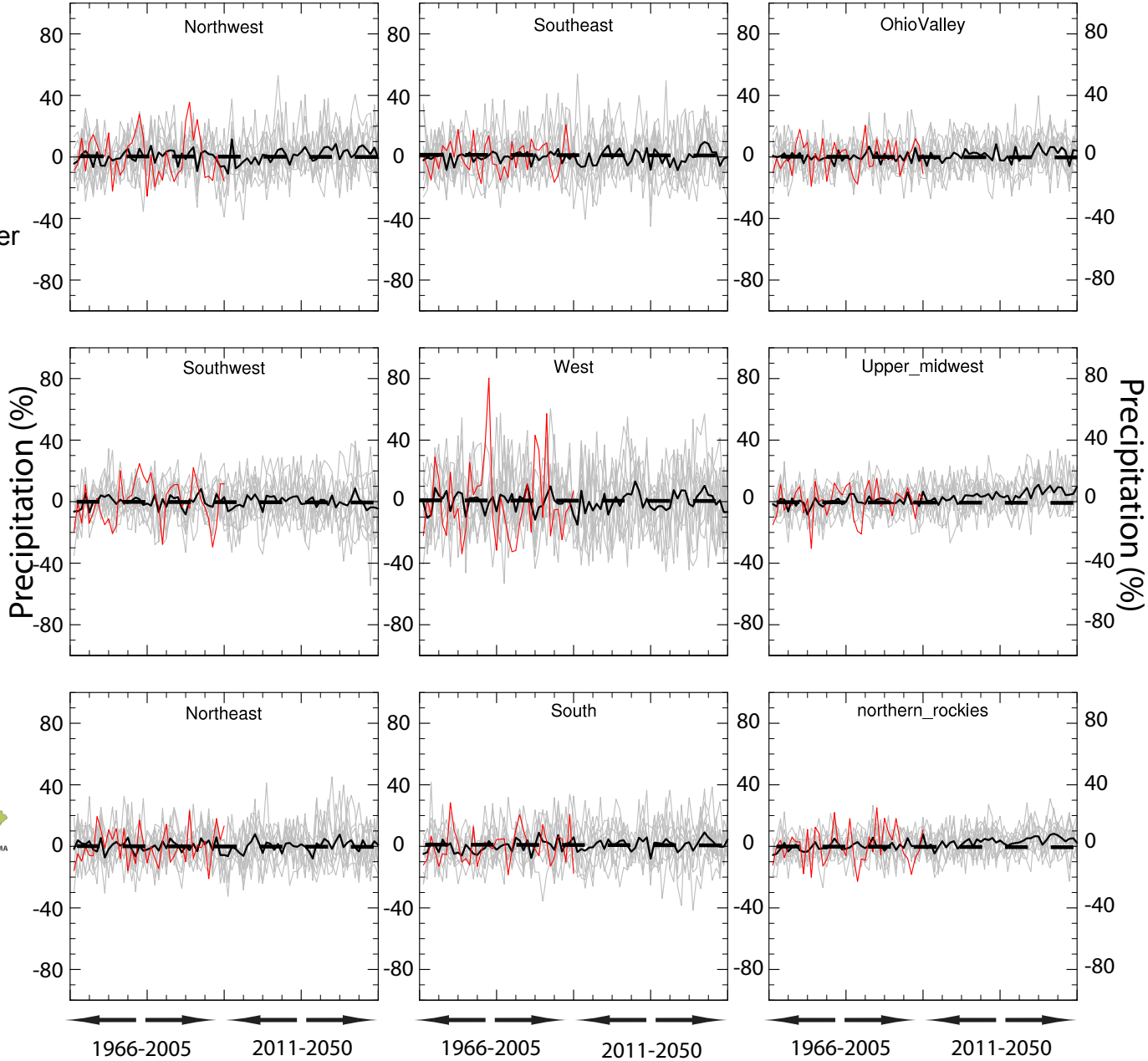
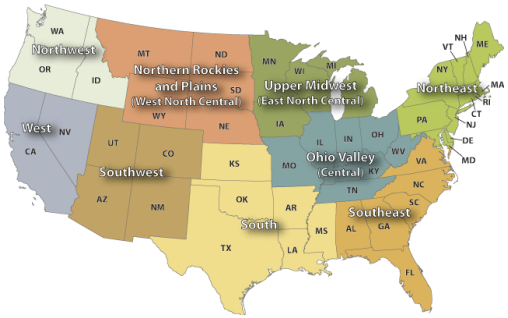
**Red**= PRISM Observations
**Black** = Multi Model Mean
**Grey** = Individual Ensemble Member

# Precipitation Change w.r.t 1966-2005 Average

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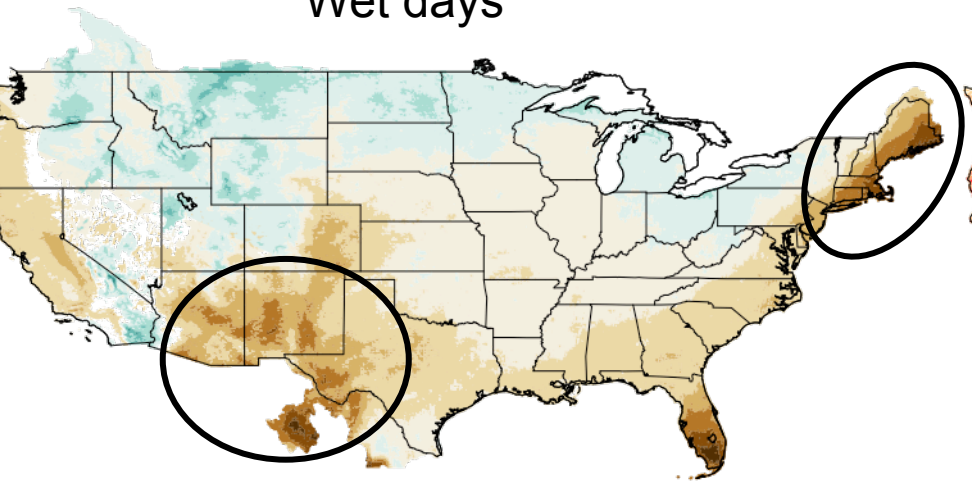
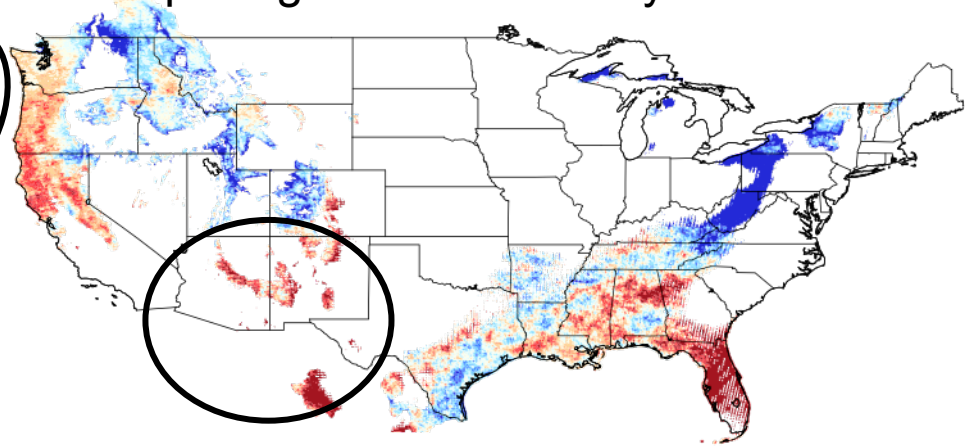
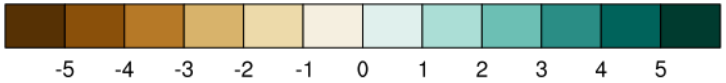
# Precipitation Change (2011-2050 minus 1966-2005)

Wet days



Spells greater than 5 days



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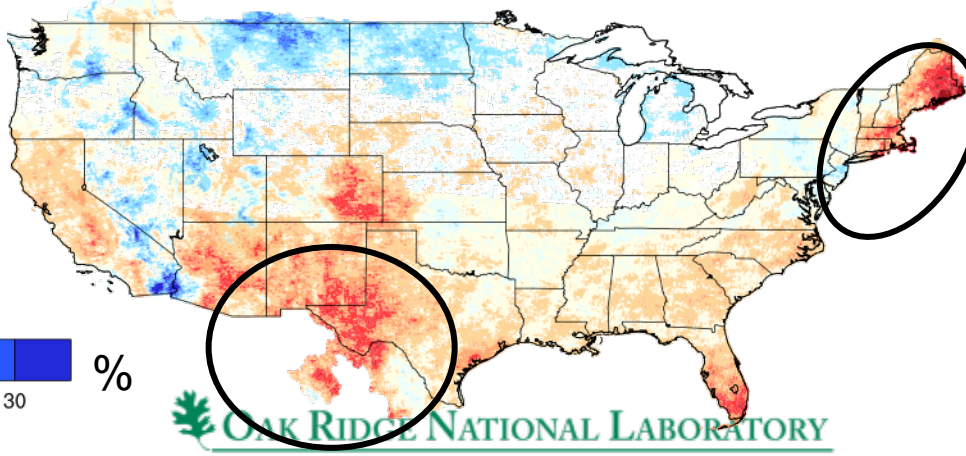
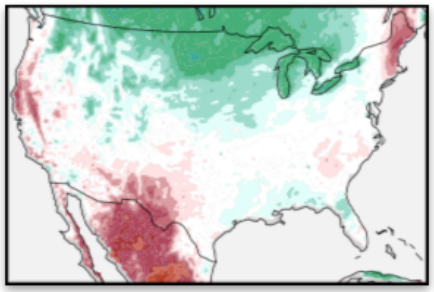
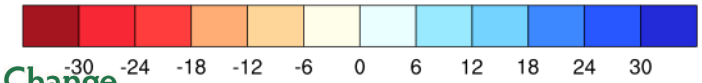
Spells up to 5 days long





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# Summary

*We* generate a *12 member ensemble of ultra high-resolution (4 km)* simulations ***that are the most detailed (to date)*** *over the continental U.S.*

*High-resolution ensemble exhibits* ***high degree of accuracy*** *in the simulation of mean and extreme historical climate.*

*Simulated future precipitation changes in means and extremes exhibit a* ***dipolar*** *(north-south)* ***response*** *in general.*