NSF Expeditions in Computing

Understanding Climate Change: A Data Driven Approach

Vipin Kumar

University of Minnesota

kumar@cs.umn.edu

http://climatechange.cs.umn.edu

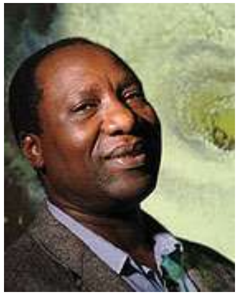
Expeditions Team

Vipin Kumar, UM

Auroop Ganguly, NEU

Nagiza Samatova, NCSU

Arindam Banerjee, UM


Fred Semazzi, NCSU

Joe Knight, UM

Shashi Shekhar, UM

Peter Snyder, UM

Jon Foley, UM

Alok Choudhary, NW

Ankit Agrawal, NW

Abdollah Homiafar
NCA&T

Michael Steinbach
UM

Singdhansu Chatterjee
UM

Karsten Steinhaeuser
UM

Stefan Liess
UM

Shyam Boriah
UM

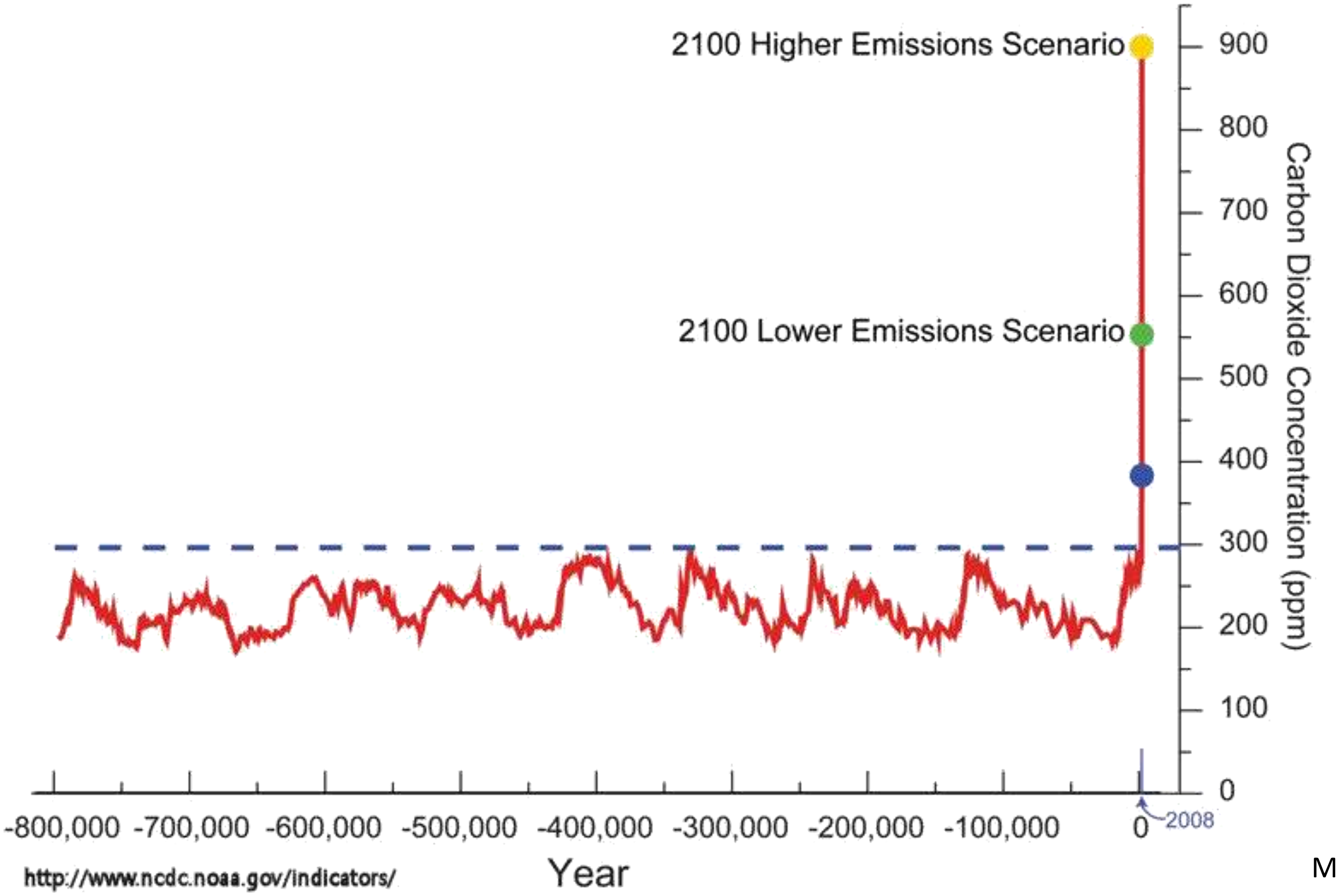
Understanding Climate Change - Motivation

CO2 levels hit new peak at key observatory

CNN U.S.

NOAA Satellite and Information Service
National Environmental Satellite, Data, and Information Service (NESDIS)

National Climatic Data Center
U.S. Department of Commerce



http://www.ncdc.noaa.gov/indicators/

Understanding Climate Change – Physics-Based Approach

General Circulation Models: Mathematical models with physical equations based on fluid dynamics

Parameterization and non-linearity of differential equations are sources for uncertainty!

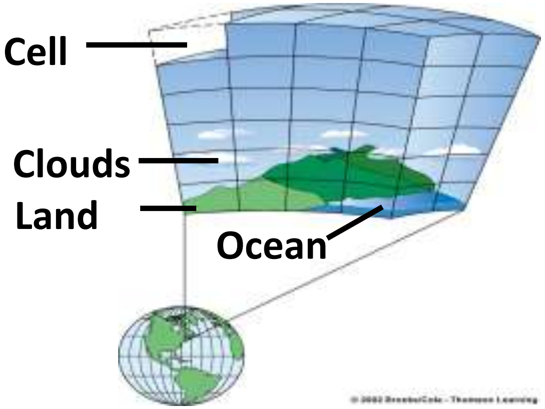
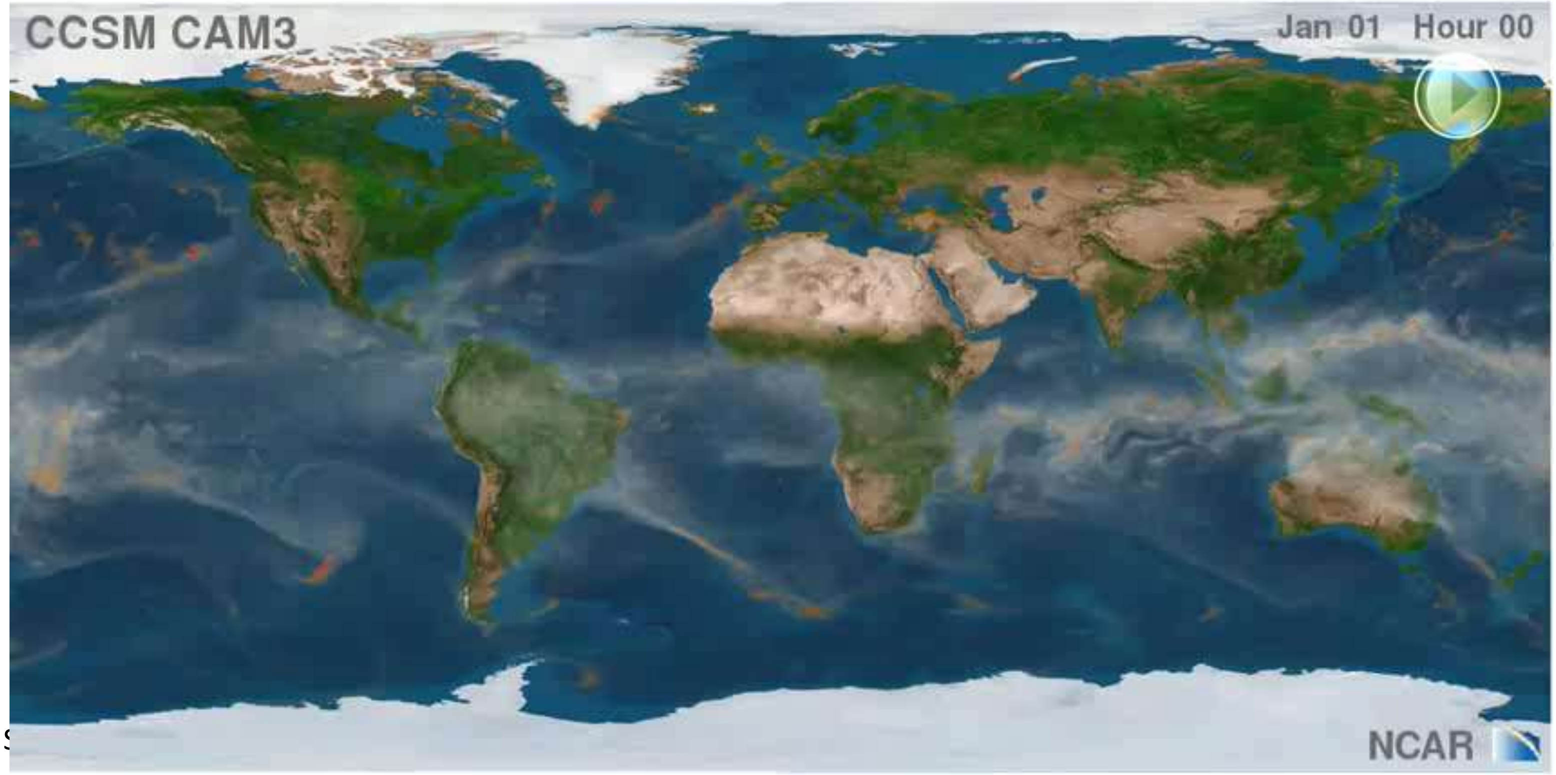
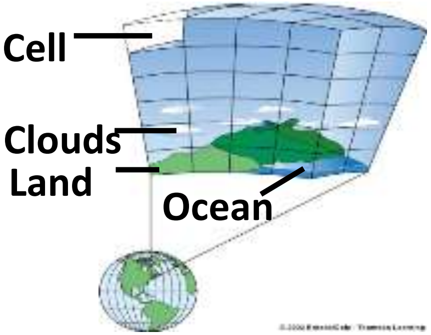


Figure Courtesy: NCAR



Understanding Climate Change - Physics Based Approach

General Circulation Models: Mathematical models with physical equations based on fluid dynamics



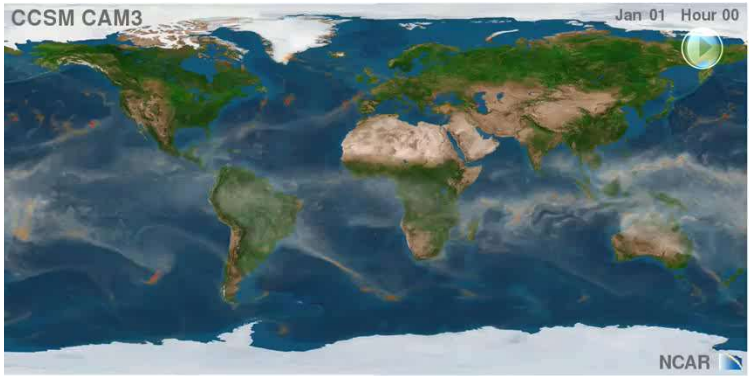
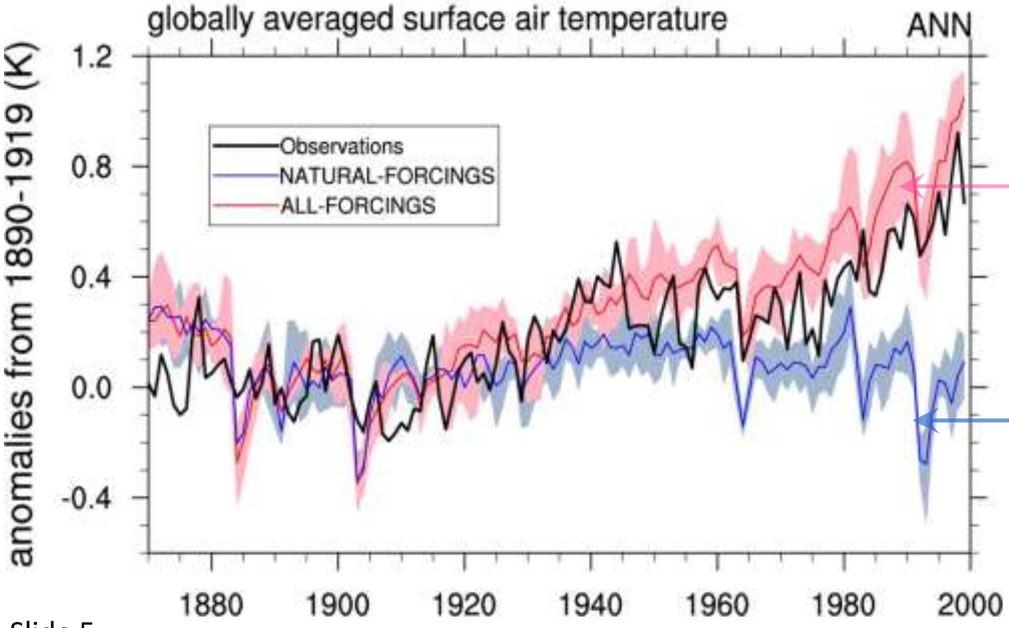


Figure Courtesy: NCAR

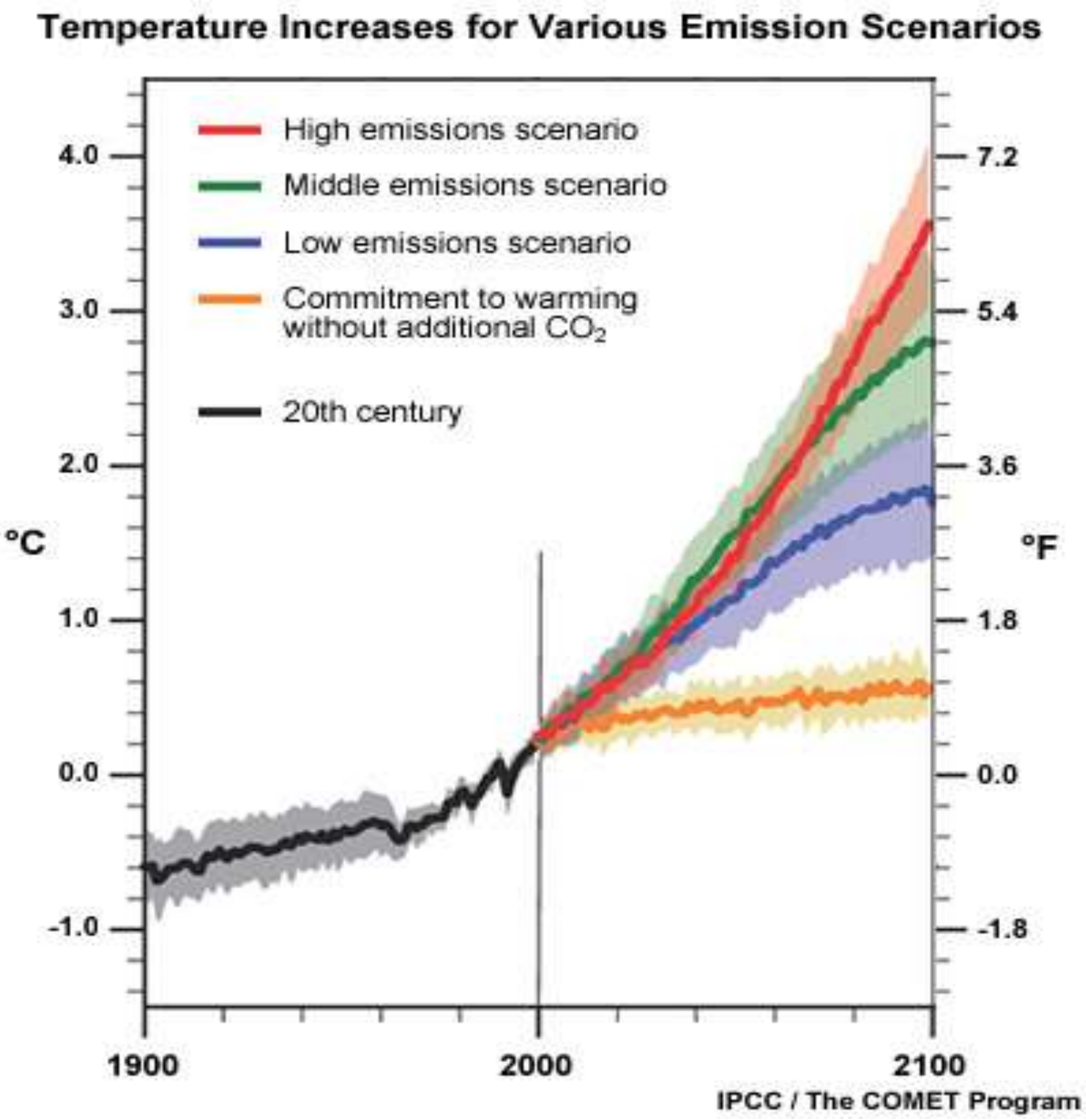


Ensemble average with observed greenhouse gas concentrations

Ensemble average with pre-industrial greenhouse gas concentrations

Figure Courtesy: ORNL

Understanding Climate Change - Physics Based Approach

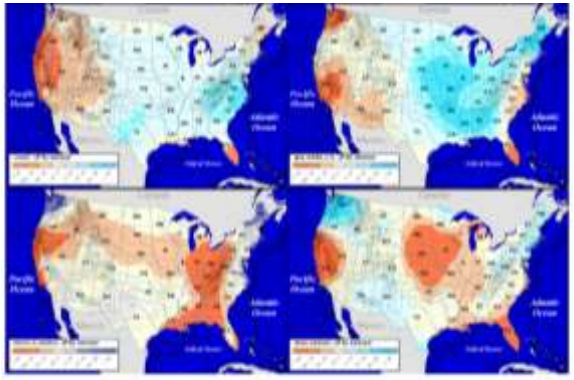


Projection of temperature increase under different **Special Report on Emissions Scenarios** (SRES) by 24 different GCM configurations from 16 research centers used in the **Intergovernmental Panel on Climate Change** (IPCC) 4^{th} Assessment Report.

Physics based models are essential but insufficient

- Relatively reliable predictions at global scale for ancillary variables such as temperature
- Least reliable predictions for variables that are crucial for impact assessment such as regional precipitation

Disagreement between IPCC models



Regional hydrology exhibits large variations among major IPCC model projections

"The sad truth of climate science is that the most crucial information is the least reliable"

(Nature, 2010)

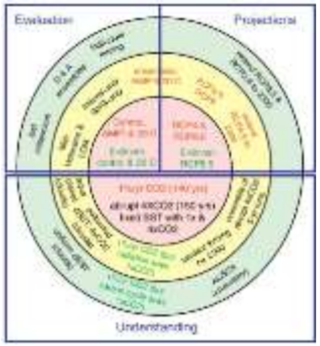
Physics based models

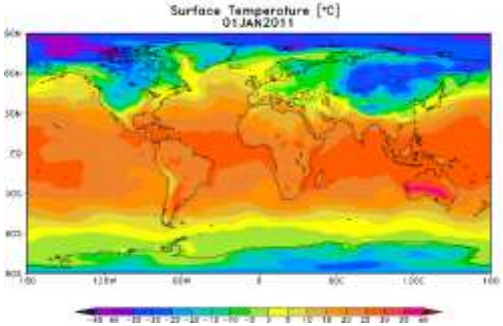
Low uncertainty	High uncertainty	Out of scope
Temperature	Hurricanes	Fires
Pressure	Extremes	Malaria outbreaks
Large-scale wind	Precipitation	Landslides

Data-Driven Knowledge Discovery in Climate Science

Transformation from Data-Poor to Data-Rich

- Sensor Observations
- Reanalysis Data
- Model Simulations





A new and transformative data-driven approach that:

- Makes use of wealth of observational and simulation data
- Advances understanding of climate processes
- Informs climate change impacts and adaptation

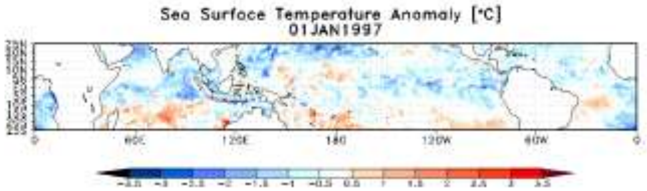
"Climate change research is now 'big science,' comparable in its magnitude, complexity, and societal importance to human genomics and bioinformatics."
(Nature Climate Change, Oct 2012)

Need for data driven discovery

Physics based models

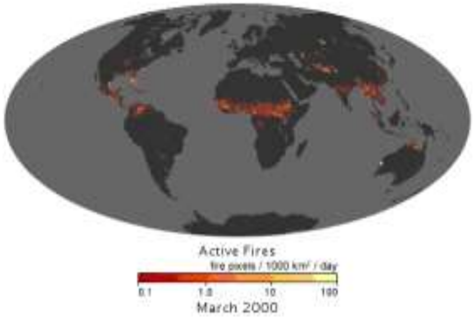
Low uncertainty	High uncertainty	Out of scope
Temperature	Hurricanes	Fires
Pressure	Extremes	Malaria outbreaks
Large-scale wind	Precipitation	Landslides

Global sea surface temperatures



Atlantic hurricanes

Global fires



Need for data driven discovery

Physics based models

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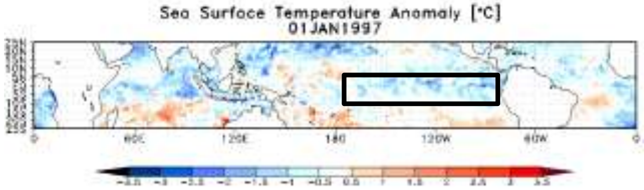
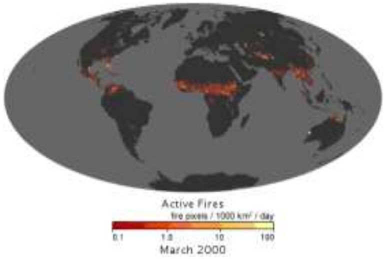
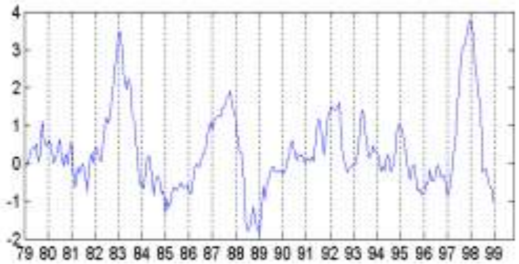


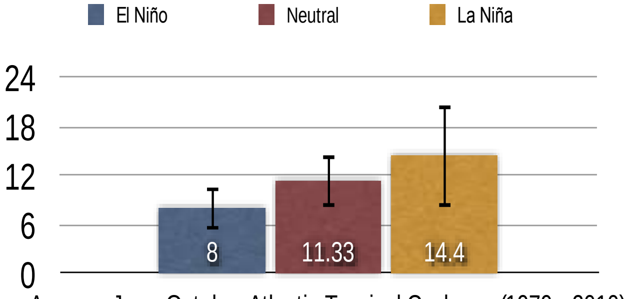
Atlantic hurricanes

Global fires

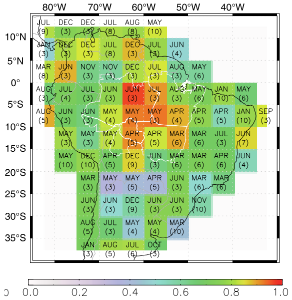




SST Anomaly Time Series in the ENSO region



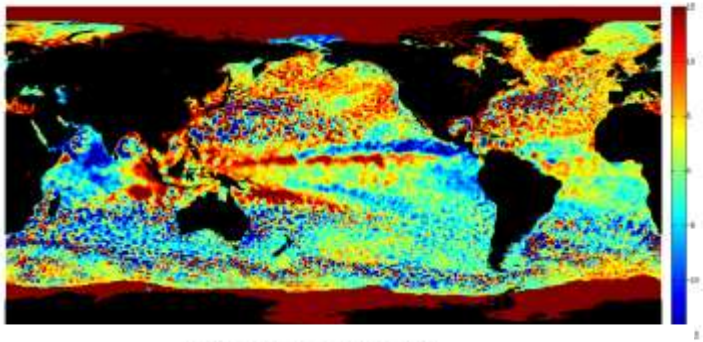
Average June-October Atlantic Tropical Cyclones (1979 - 2010)

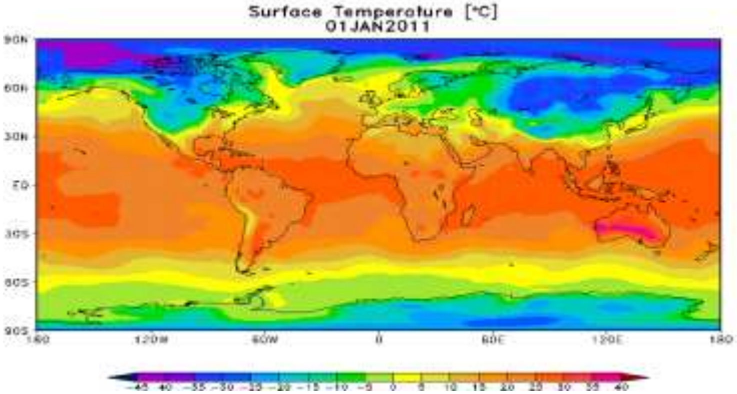


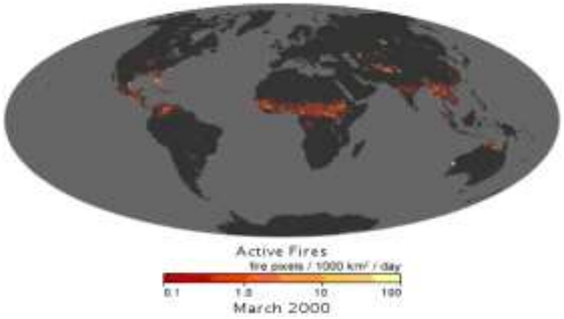
Correlation with fires in Amazon

Chen et al., Science, 2011

Challenges in data driven analysis







- Complex dependence
  - Non-IID
  - Spatio-temporal correlation
  - Long memory in time
  - Long range dependence in space
  - Nonlinear relationships
- Data characteristics
  - Heterogeneous, Multivariate
  - Heavy Tailed Distributions
  - Noisy, incl. low frequency variability
  - Paucity of training data
- Complex processes
  - Evolutionary
  - Multi-scale in space and time
  - Non-stationary

Project vision and scope

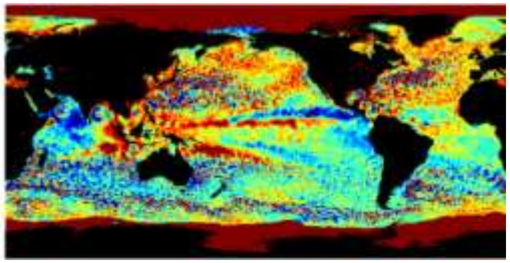
Transformative Computer Science Research
Advancing Climate Change Science

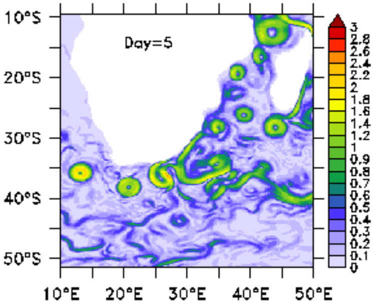
Process Understanding	Extreme Events - Heat Waves - Rainfall Extremes - Droughts - Hurricanes Model Evaluation Downscaling - Statistical - Dynamical Ocean-Atm.-Land Interactions	Change Detection - Abrupt vs. Gradual - Point vs. Regions/Intervals - Change in Extremes Spatio-Temporal Classification Sparse/High-Dim. Methods Causal Relationships Networks/Graphs HPC	Computational Innovations
Understanding Climate Change			

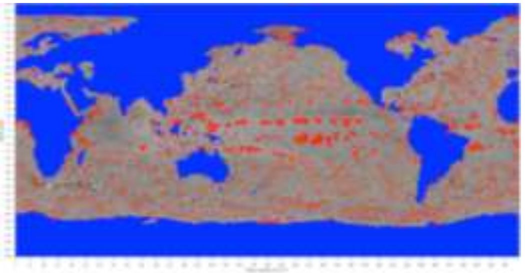
Pattern Mining: Ocean Eddies Monitoring

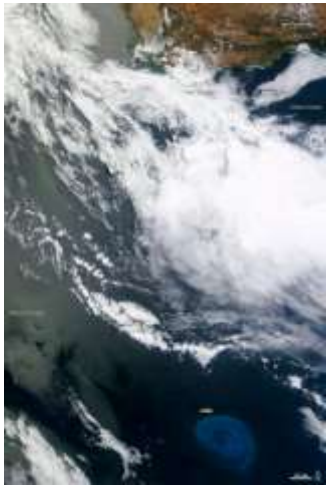
- Scalable spatio-temporal pattern mining algorithms for noisy and continuous data
- Novel multiple object tracking for uncertain features

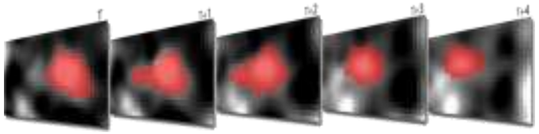
- Detect more accurate features and tracks for improved ocean dynamics monitoring
- Open source data base of 20+ years of eddies and eddy tracks available for scientific applications









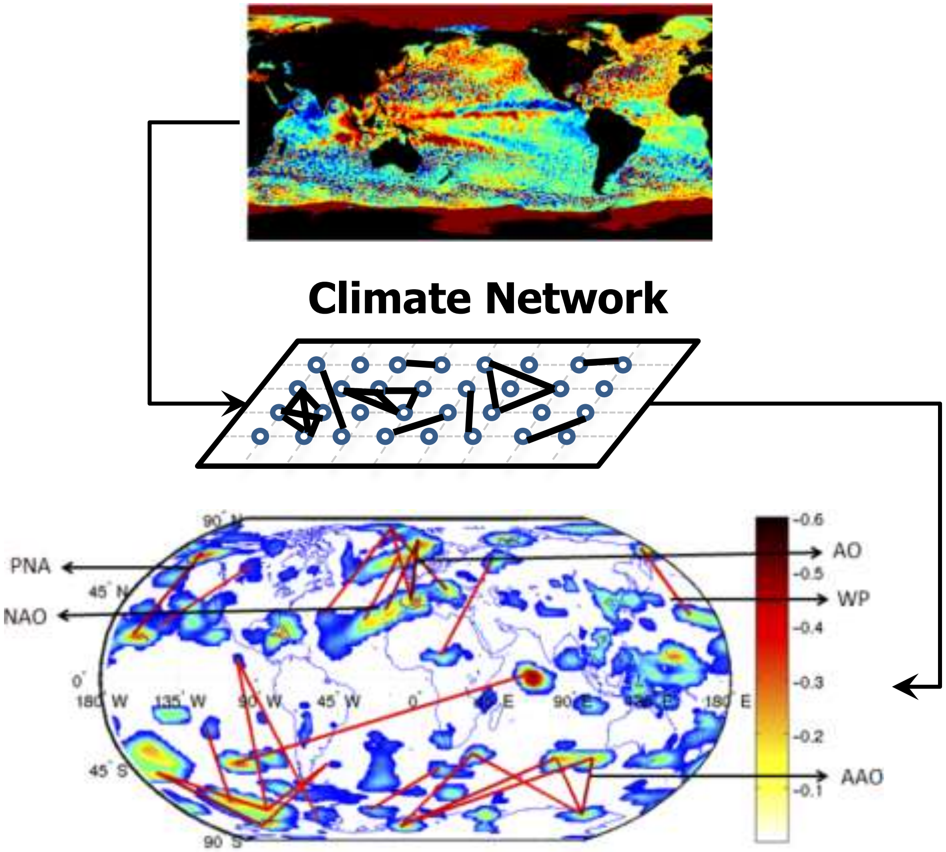


Faghmous et al. *AAAI* (2012a)
Faghmous et al. *CIDU* (2012b) **Best student paper award**
Faghmous et al. *AAAI* (2013)
NSF Nordic Research Opportunity Grant to conduct research at the Bjerknes Centre for Climate Research in Norway

Network analysis: Climate teleconnections

- Scalable method for discovering anti-correlated graph regions
- Novel dynamic graph clustering for dense directed graphs
- Significance testing for spatio-temporal patterns

- Discovered previously unknown climate teleconnection
- Analyzed climate network properties to better understand global climate dynamics
- Method used to compare climate models



Kawale et al. *SDM*(2011a)
Kawaleet al. *CIDU* (2011b) **Best student paper award**
Kawale et al. *ACM SIGKDD* (2012)
Steinhaeuser et al. *Climate Dynamics* (2012).
SC’11: Exploration in Science through Computation Award
Grace Hopper ‘12: Best Poster Award (Winner of the ACM Student Research Competition)

Predictive Modeling: Regression, Ensembles, Inference

- Hierarchical sparse regression: rates of convergence with low samples
- Multi-task learning with spatial smoothing
- Primal decomposition based LP solver for max-cut type problems (~10 million+ node graphs)

- Regional land-climate predictions from observations over oceans
- Combining multiple GCM outputs more accurately than state-of-art
- Mega-drought detection, trends over past 100-1000 years

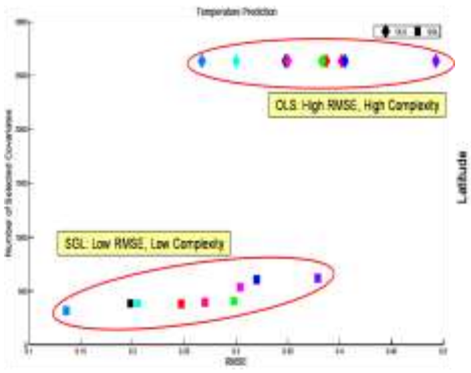
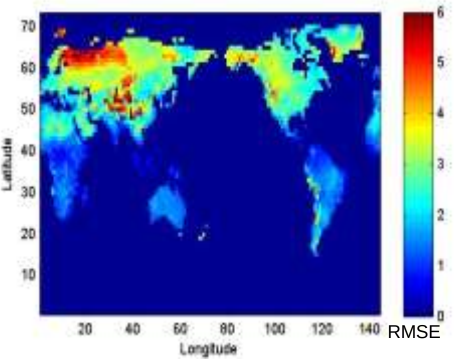
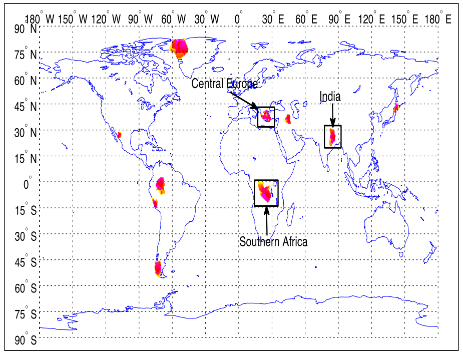


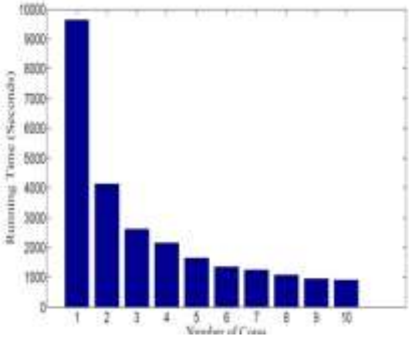
Fig. RMSE vs. Model Complexity of OLS and Sparse Regression Methods



Prediction RMSE from spatially smoothened Multi-model ensemble



Major droughts starting within the period 1981-1995.



Fu et al. *UAI(2013)*

Subbian et al. *SDM(2013)* **Best Application Paper Award**

Hsieh et al. *NIPS(2012)*

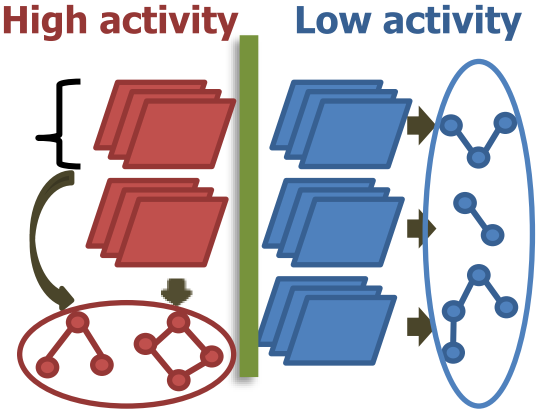
Wang et al. *ICML(2012)*

Chatterjee et al. *SDM(2012)* **Best Student Paper Award**

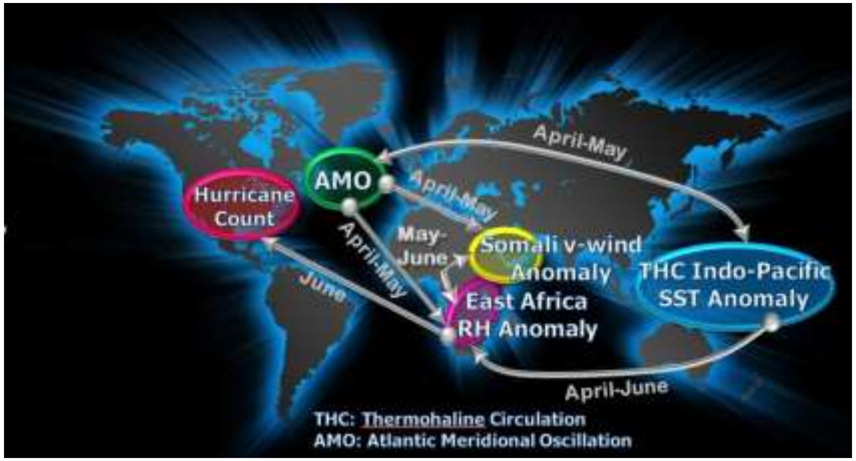
Fu et al. *SDM(2012)*

Relationship mining: Seasonal hurricane activity

- Contrast-based network mining for discriminatory signatures
- Novel dynamic graph clustering for dense directed graphs
- Statistically robust methodology for automatic inference of modulating networks



- Improved forecast skill for seasonal hurricane activity
- Discovered key factors and mechanisms modulating NA hurricane variability
- Discovered novel climate index with much improved correlation with NA hurricane variability: 0.69 vs 0.49



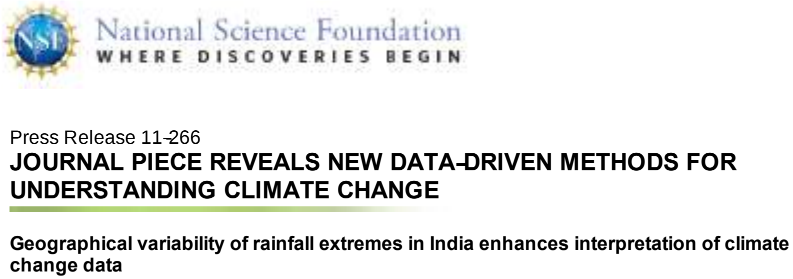
THC: Thermohaline Circulation
AMO: Atlantic Meridional Oscillation

NSF News, DOE Research News, Science360
Sencan et al. *IJCAI* (2011)
Pendse et al. *SIAM SDM* (2012)
Chen et al. *Data Mining & Knowledge Discovery* (2012)
Chen *et al. SIAM SDM* (2013)
Chen *et al. IJCAI* (2013)
Semazzi *et al.* in review at journal (2013)

Extremes and uncertainty: Heat waves, heavy rainfall, …

- Extreme value theory in space-time and dependence of extremes on covariates
- Mutual information and copula-methods for space-time extremes dependence
- Uncertainty quantification with Bayesian and resampling techniques
- Physics-guided data mining and quantification of uncertainty

- Spatiotemporal trends in heat waves, cold snaps, and heavy rain with climate change
- Climate model evaluation and physics-guided uncertainty quantification
- Covariate-based improvement of extremes projections under climate change
- Translation to adaptation and stakeholder relevant metrics

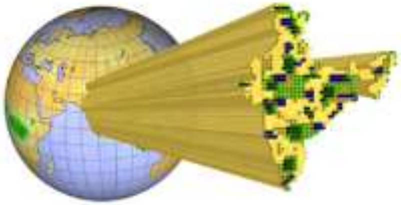


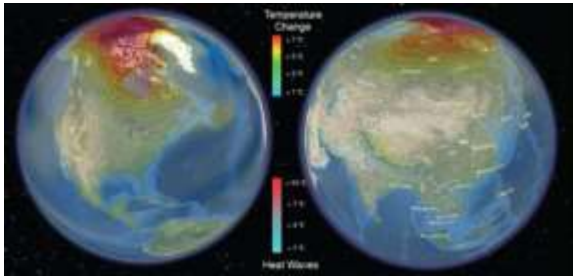
National Science Foundation
WHERE DISCOVERIES BEGIN

Press Release 11-266

JOURNAL PIECE REVEALS NEW DATA-DRIVEN METHODS FOR UNDERSTANDING CLIMATE CHANGE

Geographical variability of rainfall extremes in India enhances interpretation of climate change data



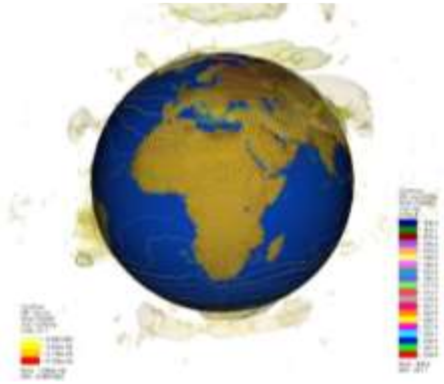


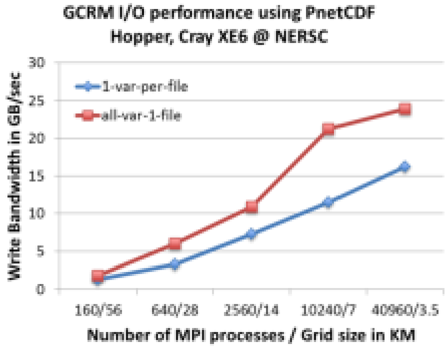
Ghosh *et al.* Nature Climate Change (2012)
Parish *et al.* Computers & Geosciences (2012)
Kodra *et al.* Environmental Research Letters (2012)
Ganguly *et al.* Climate Extremes & UQ: Book Ch. (2013)
Kodra *et al.* in revision at journal (2013)
Kumar *et al.* in review at journal (2013)

High Performance Tools and Methods

- Scalable library and software for
  - data mining / machine learning
  - Input-Output
  - Many algorithms have shown speedups of several orders of magnitude.
- HPC solutions for bootstrapping methods for extreme value prediction and Markov Random Field based abrupt change detection
- Enabled execution of a high-resolution cloud resolving model that is critical to operationalize the next generation of an IPCC GCM
  - Improved I/O throughput using PnetCDF optimizations, massive scalability
  - For 3.5 km grid resolution, grid size is 41.9M cells with 256 vertical layers

Improving I/O for the Global Cloud Resolving Model




GCRM I/O performance using PnetCDF
Hopper, Cray XE6 @ NERSC
Write Bandwidth in GB/sec
0
5
10
15
20
25
30
1-var-per-file
all-var-1-file
160/56
640/28
2560/14
10240/7
40960/3.5
Number of MPI processes / Grid size in KM

Jin *et al*. EuroMPI (2011)
Patwary *et al*. SC (2012)
Hentrix *et al*. HPC (2012)
Kumar *et al*. IPDPS (2011)
Rangel *et al.* in review (2013)
Jin *et al.* in review (2013)

Education/Outreach Activities

- Undergraduate and graduate courses/programs at the intersection of climate and data sciences
- Cross disciplinary training environment
- Extensive research opportunities for students from historically underrepresented groups
- Interdisciplinary workshops and sessions at climate and computer science venues
- Engagement with UNEP (United Nations Environmental Program) and IPCC

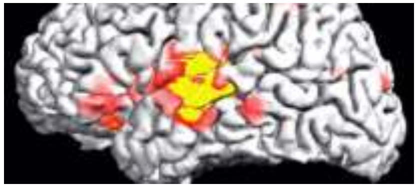
Annual workshop

Future of Water Inspires Scientist to Develop Data-driven Models
AGU FALL MEETING
San Francisco | 3–7 December 2012
Climate Change & Society
PSM
NC STATE UNIVERSITY
science360 News Service
News Home
About
Sections
Breaking Story
Researchers Devise More Accurate Method For Predicting Hurricane Activity
National Science Foundation
WHERE DISCOVERIES BEGIN
Journal Piece Reveals New Data-driv
Understanding Climate Change
African Meningitis Belt

Climate Prediction Community Interface

Future Directions and Goals

- Climate science problems provide transformative research opportunities
  - Complex dependence and noise structures
  - Nonlinear dynamical spatiotemporal systems
  - Data size from few petabytes 350 petabytes by 2030
  - Motivates the development of "physics-guided data mining"
- Transformative spatiotemporal methods can generalize to multiple domains
  - Brain science
  - Ecology and biodiversity
  - Social networks
  - Geospatial Intelligence



- Help establish the field of "climate informatics" over the next 5-10 years