Regional Climate Downscaling Tutorial

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- Model Design (Traps and Good Practices)
  8:00 – 8:50 (Cindy Bruyère)
- Assessing Uncertainty and Evaluation of Data
  8:50 – 9:40 (James Done)
- Break (9:40 – 10:00)
- Bias Correction
  10:00 – 10:20 (Cindy Bruyère)
- Statistical Downscaling
  10:20 – 11:00 (Greg Holland)
- Applications and Use of Model Data
  11:00 – 12:00 (Heather Lazrus; Tom Galarneau; Erin Towler; Deb PaiMazumder; Gabi Pfister)

Useful References

Done, J.M., Holland, G.J., Bruyère, C.L., Leung, L.R., and Suzuki-Parker, A., 2012: Modeling high-impact weather and climate: Lessons from a tropical cyclone perspective. NCAR/TN-490+STR, 28pp. http://nldr.library.ucar.edu/repository/collections/TECH-NOTE-000-000-000-854

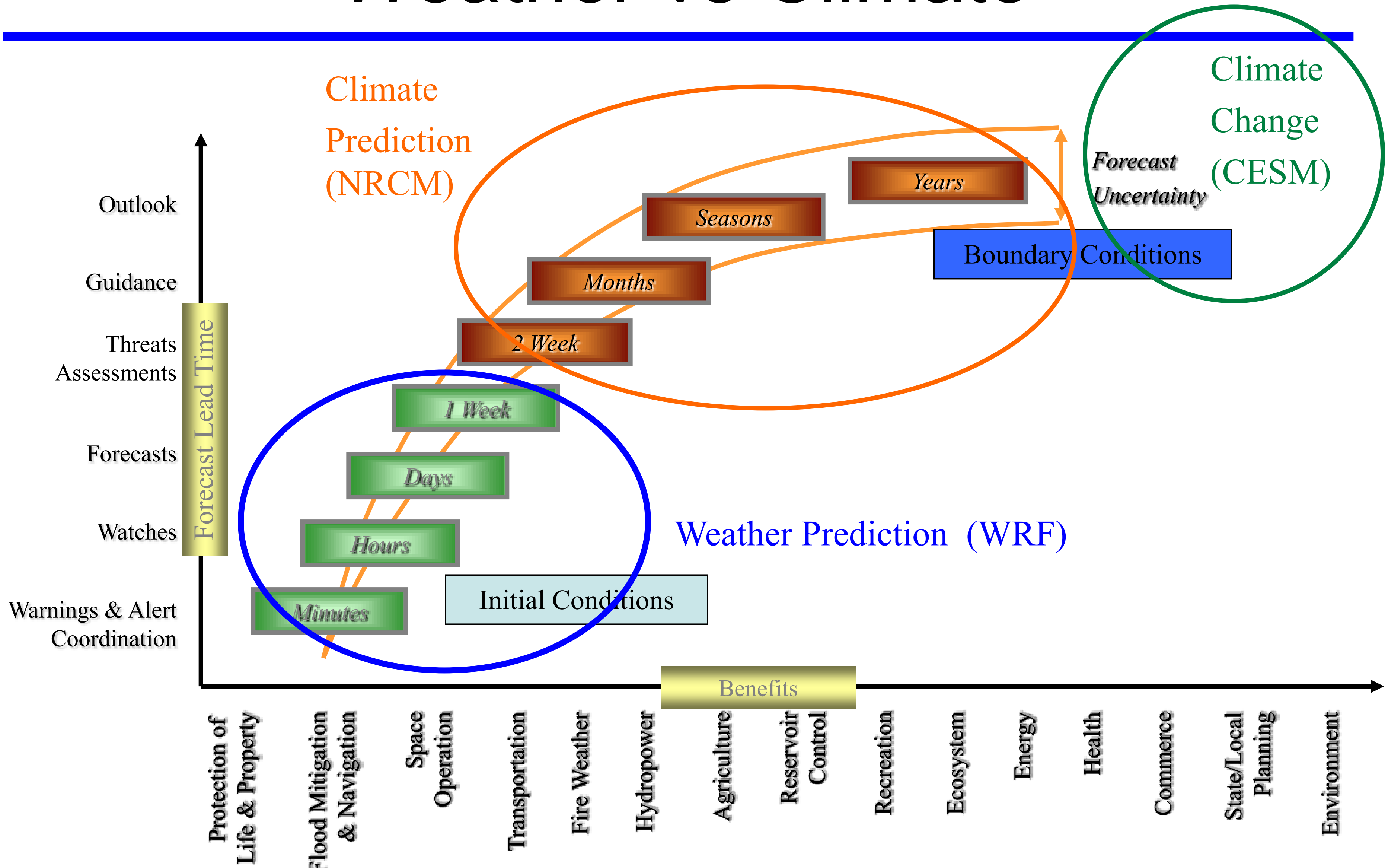
Warner, Thomas T., 2011: Quality Assurance in Atmospheric Modeling. *Bull. Amer. Meteor. Soc., 92, 1601-1610.doi:* *http://dx.doi.org/10.1175/BAMS-D-11-00054.1*

Model Design

Traps and Good Practices

Cindy Bruyère

Weather vs Climate



Considerations for Model Design

Input data

- Format ; Bias ; SST

Domain size

- Area of interest
- Inflow areas

Model runs

- Long runs vs time slices
- Statistical–dynamical

Choice of physics

Namelist options

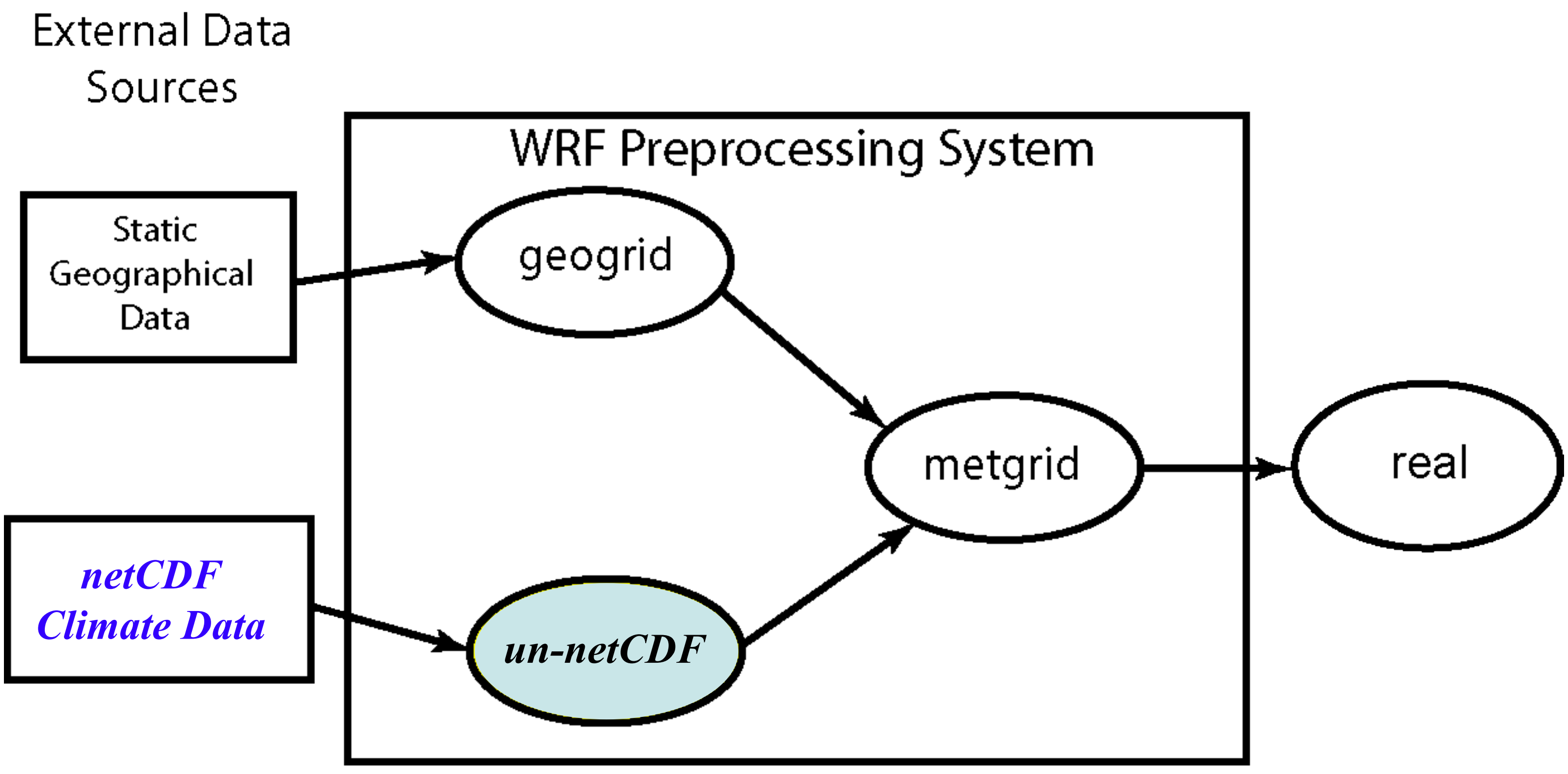
Resolution

Nudging

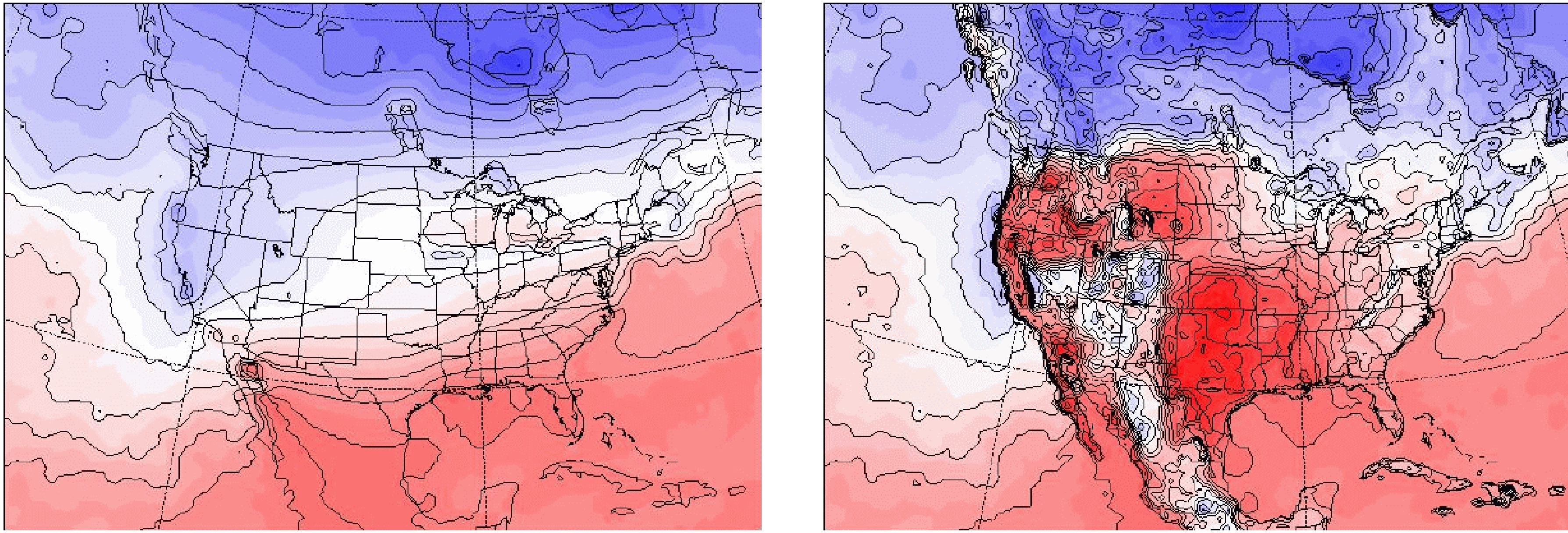
Input data

Input data from climate models are typically in netCDF format

You still need high temporal resolution data *(6 hourly)*



SST vs SKINTEMP



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`auxinput4_interval` = 360, 360, 360,

and in *&physics*

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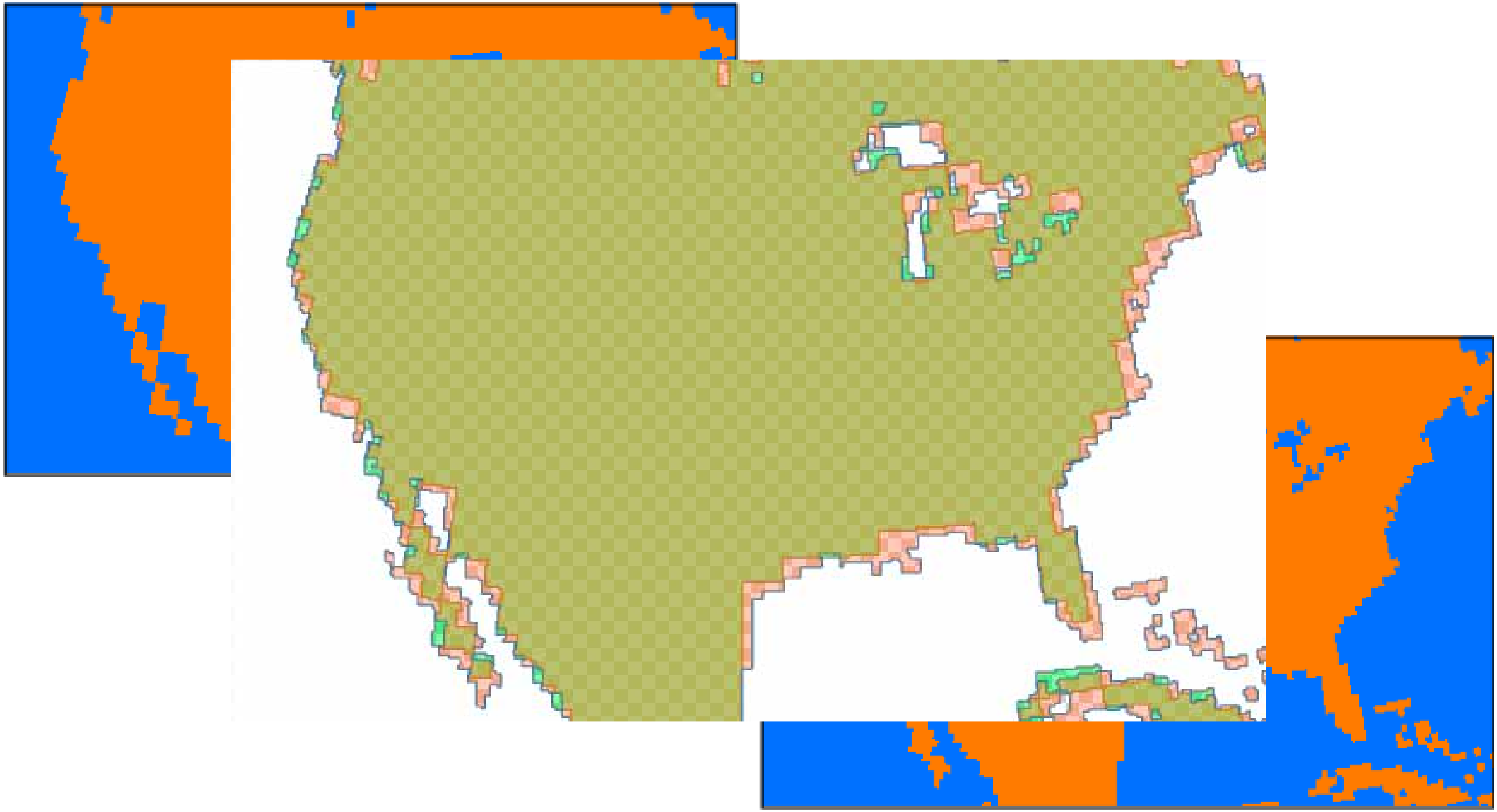
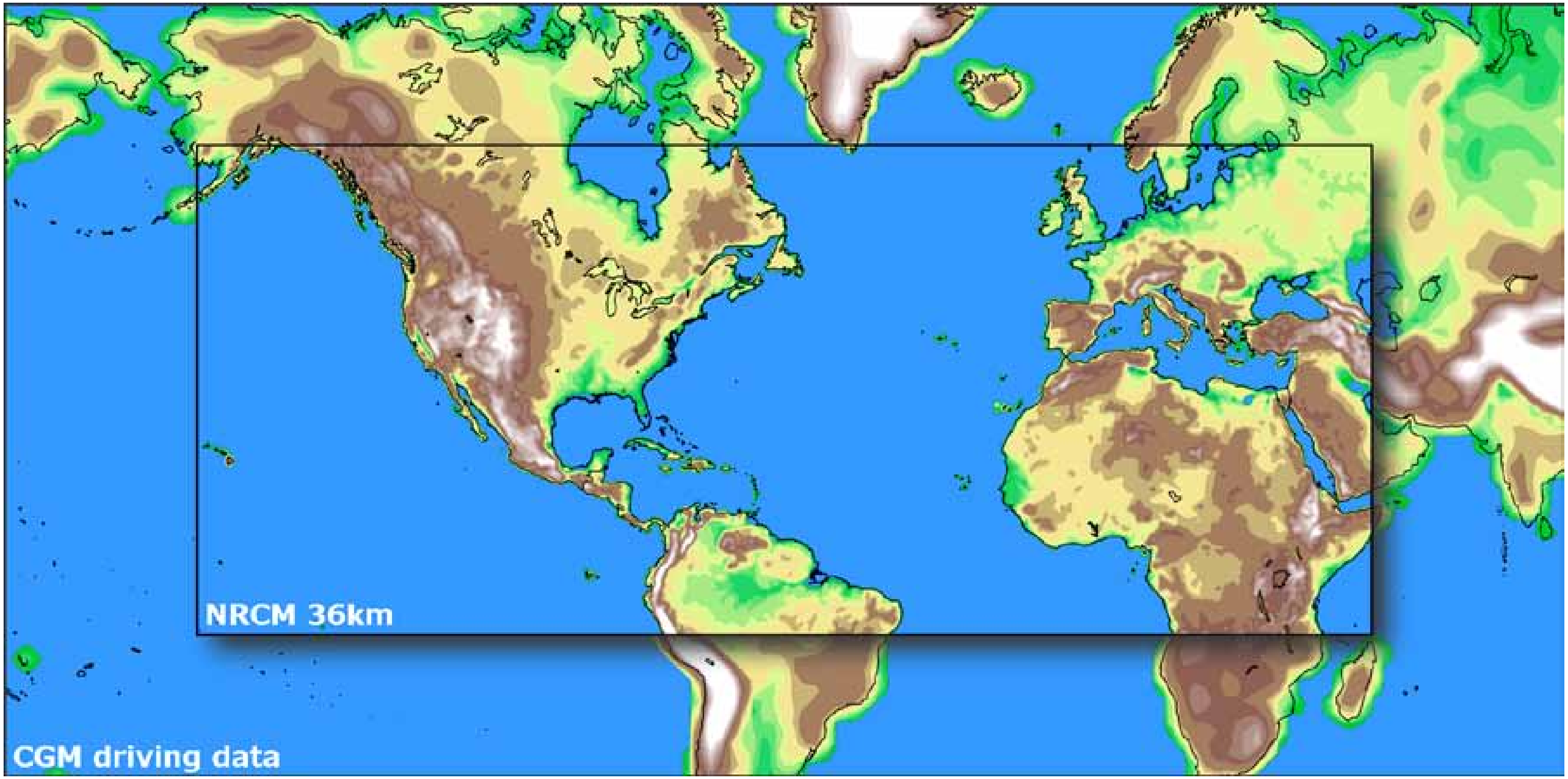
SST vs SKINTEMP

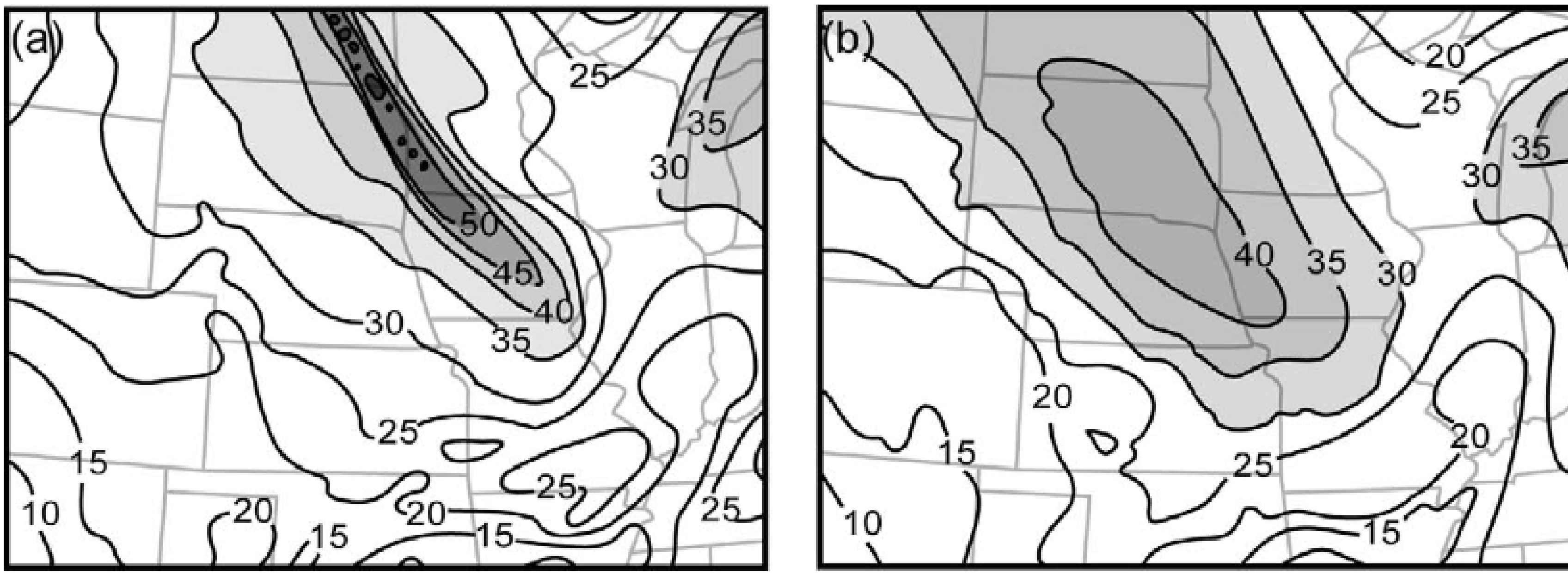


Domain Size / Boundary



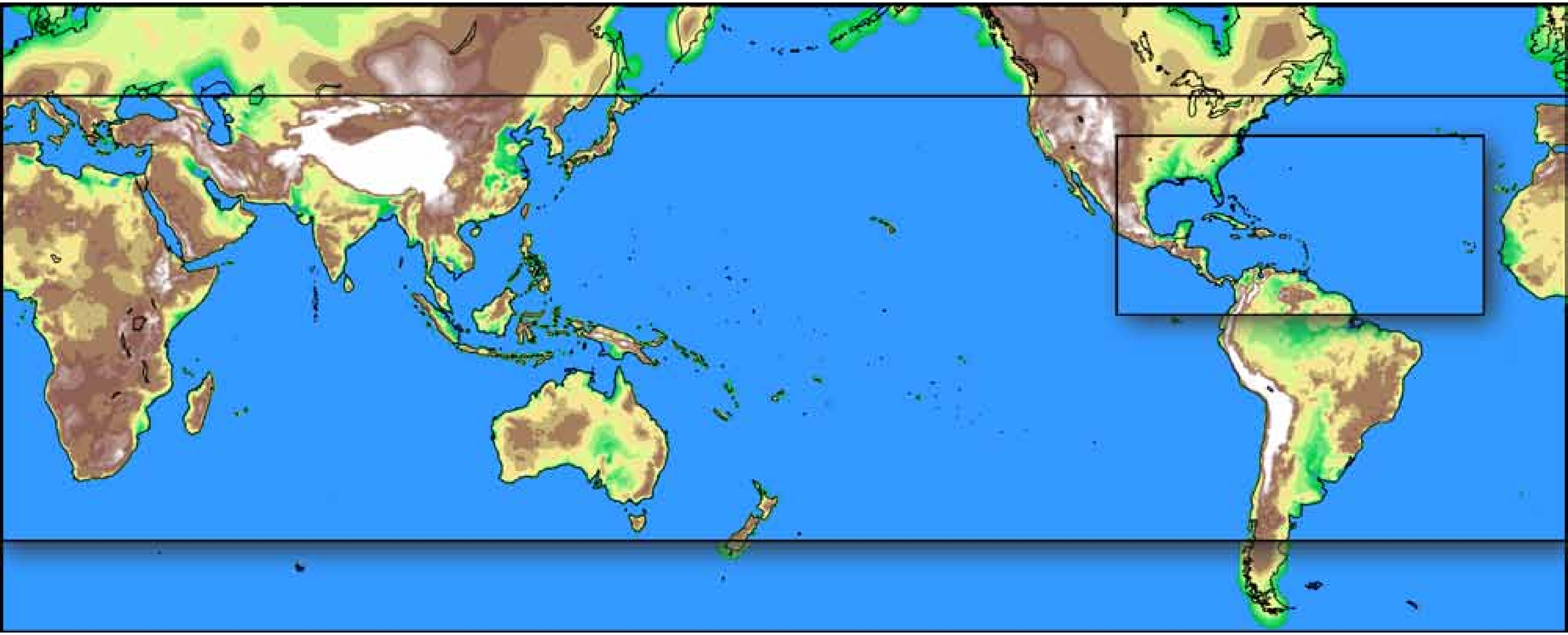
Domain Size

250mb Pressure

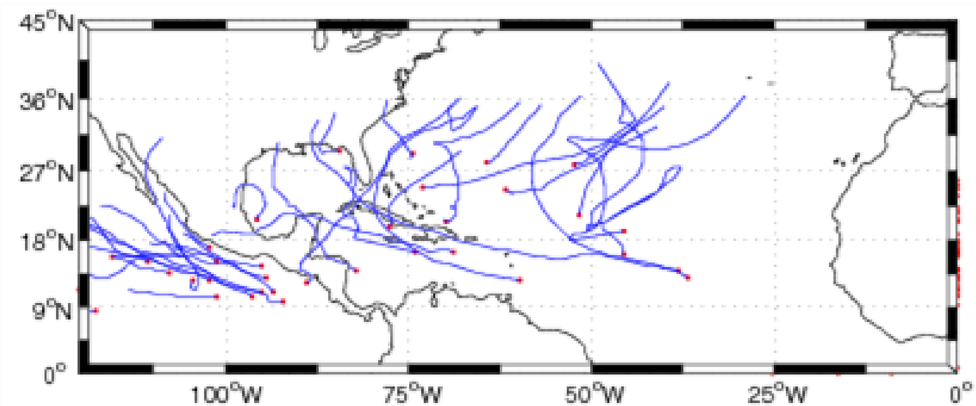


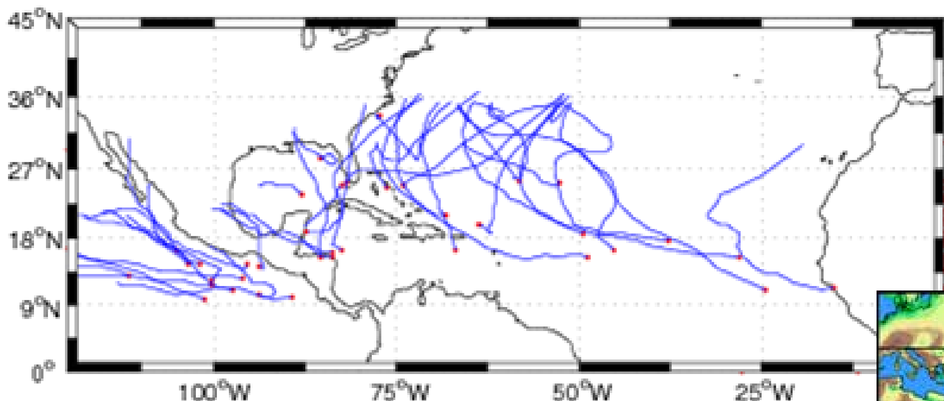
Warner, 2011

Domain Size / Boundary / Nests



Domain Size / Boundary / Nests

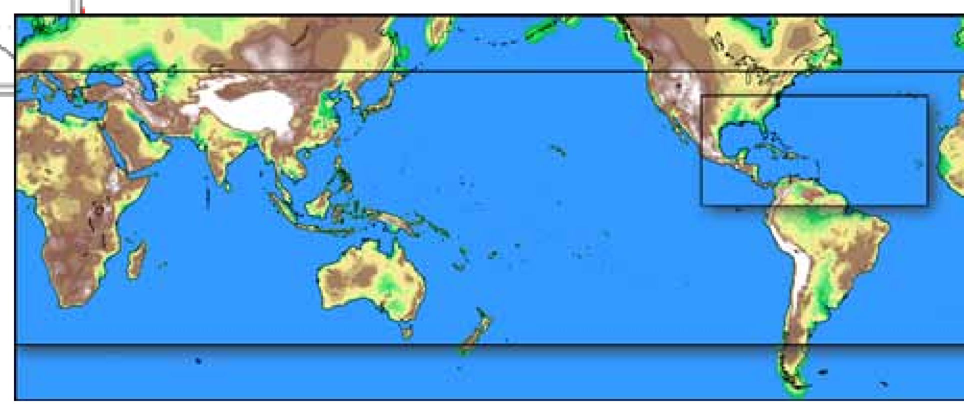




2005 N. Atlantic
27 storms actual

Non-nested 36km
18 storms

Nested 36km
25 storms



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radt                                = 30,
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bldt                                = 0,
cu_physics                          = 1,
cudt                                = 5,
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tmn_update                          = 1,
sst_skin                            = 1,
bucket_mm                           = 100.0,
bucket_J                            = 1.e9,
ptop_requested                      = 1000,
e_vert                              = 51,

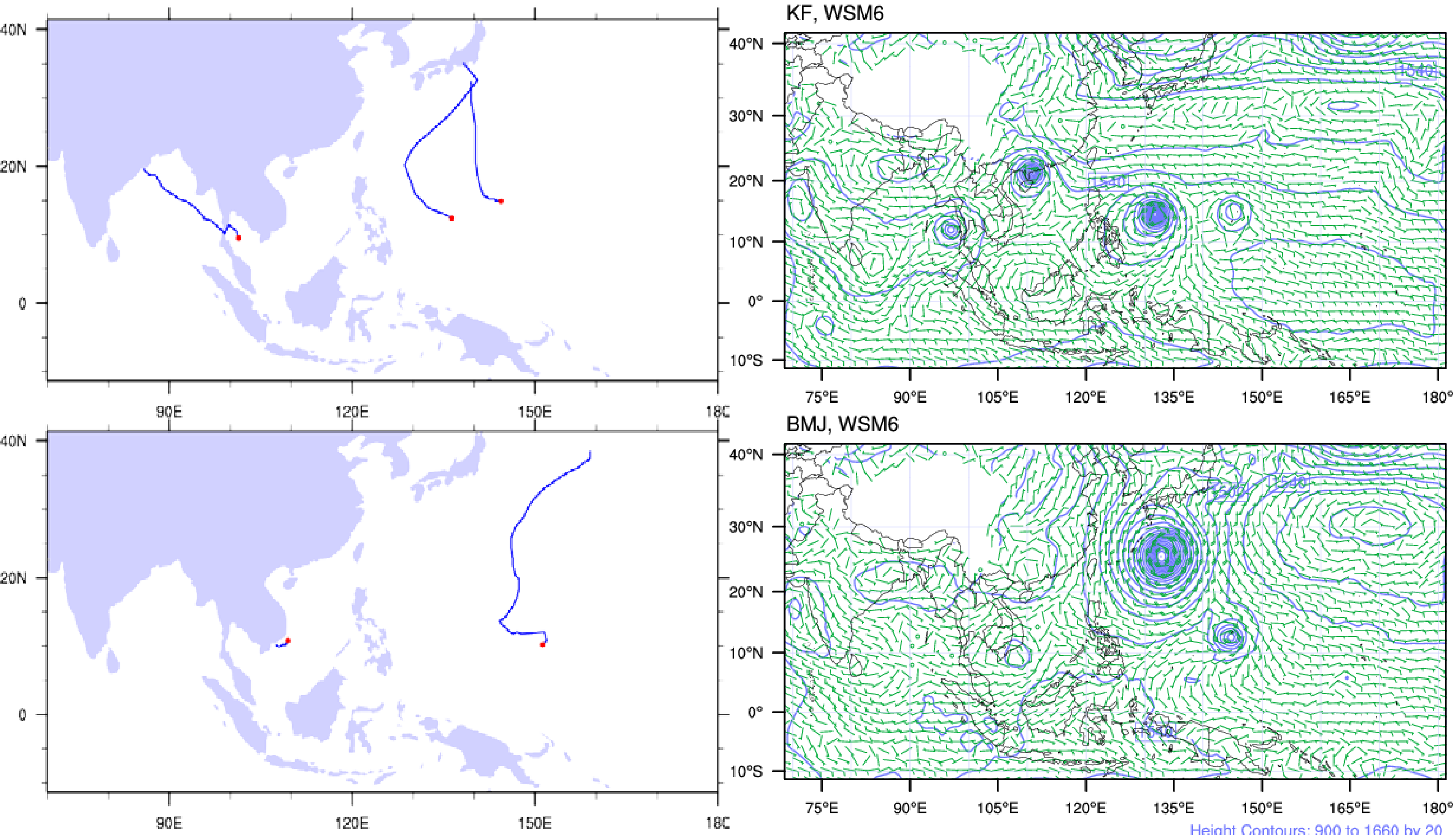
spec_bdy_width                      = 10,
spec_zone                           = 1,
relax_zone                          = 9,
spec_exp                            = 0.33,
```

WSM6; CAM; Noah; YSU; KF

Output_diagnostics
36 arrays
min/max/mean/std

Physics Considerations

Physics Considerations



Physics Considerations

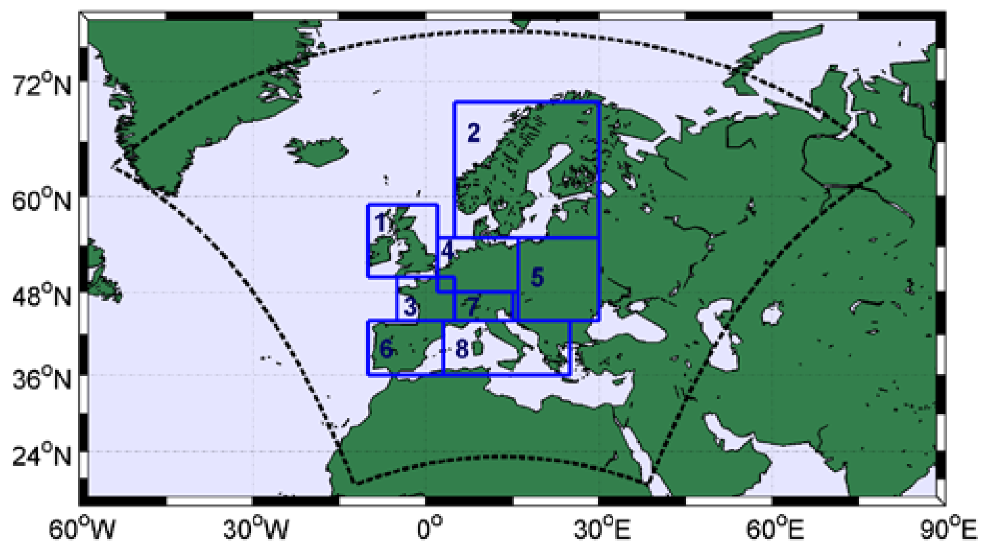
Driving data: ERA-Interim

Period: 1990-1995

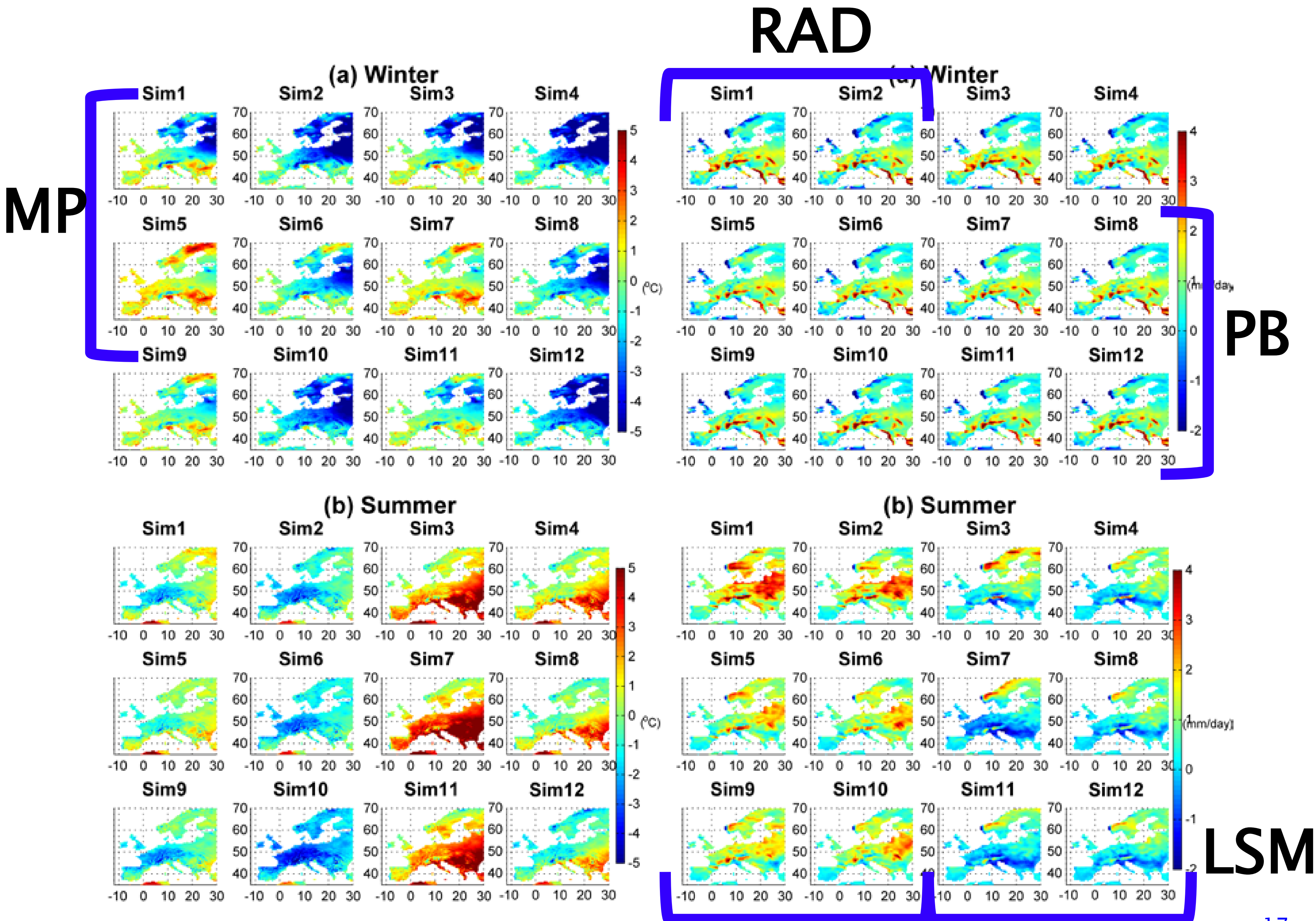
Grid Spacing: 0.44deg

WRF Version 3.1

Euro-CORDEX domain



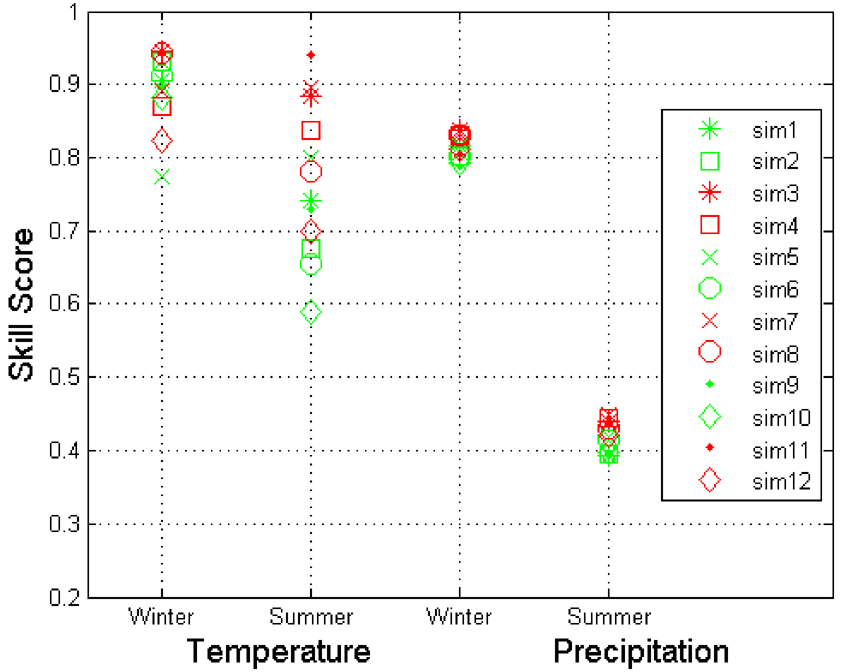
Mooney et al. (JClim)



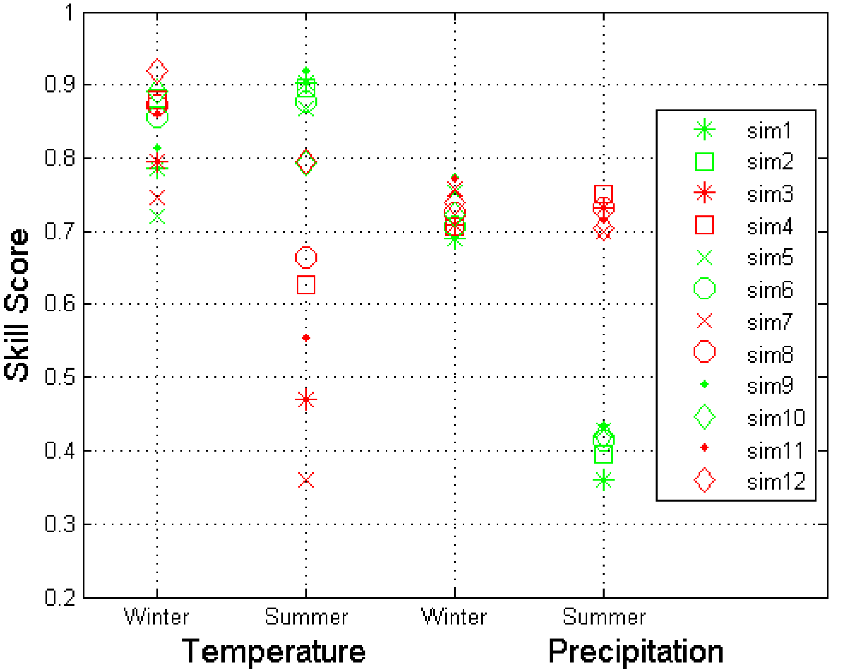
Mooney et al. (JClim)

Physics Considerations

British Isles

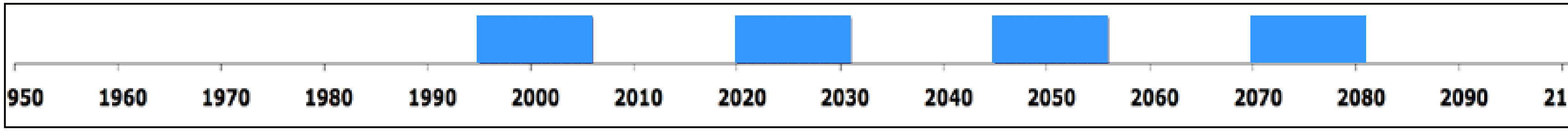


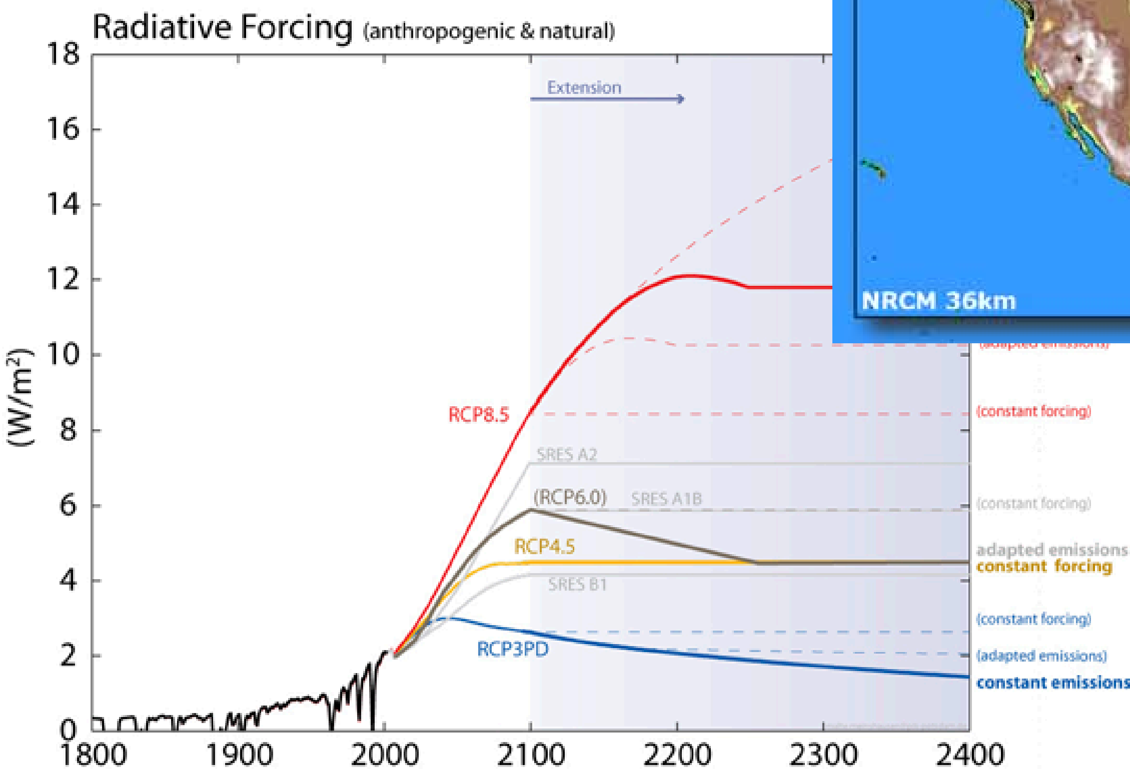
Mediterranean



Mooney et al. (JClim)

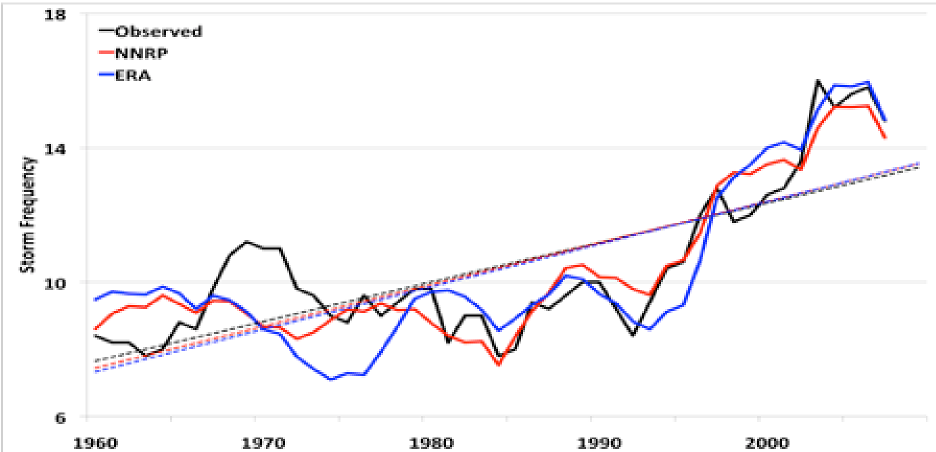
Model Runs *(Long vs Time Slices)*

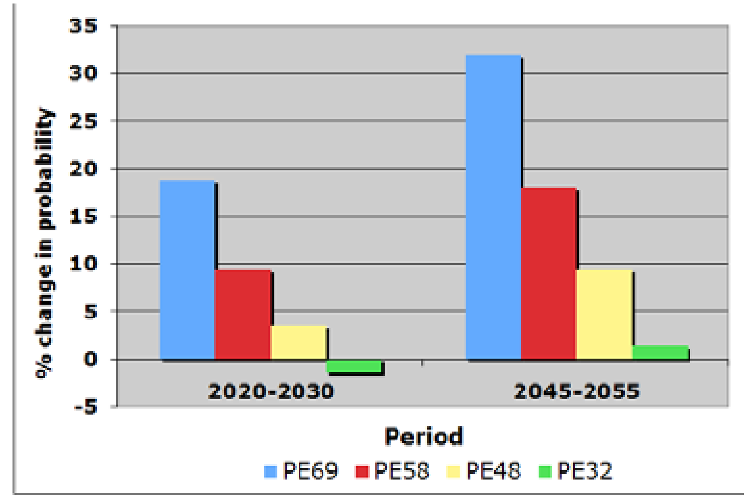


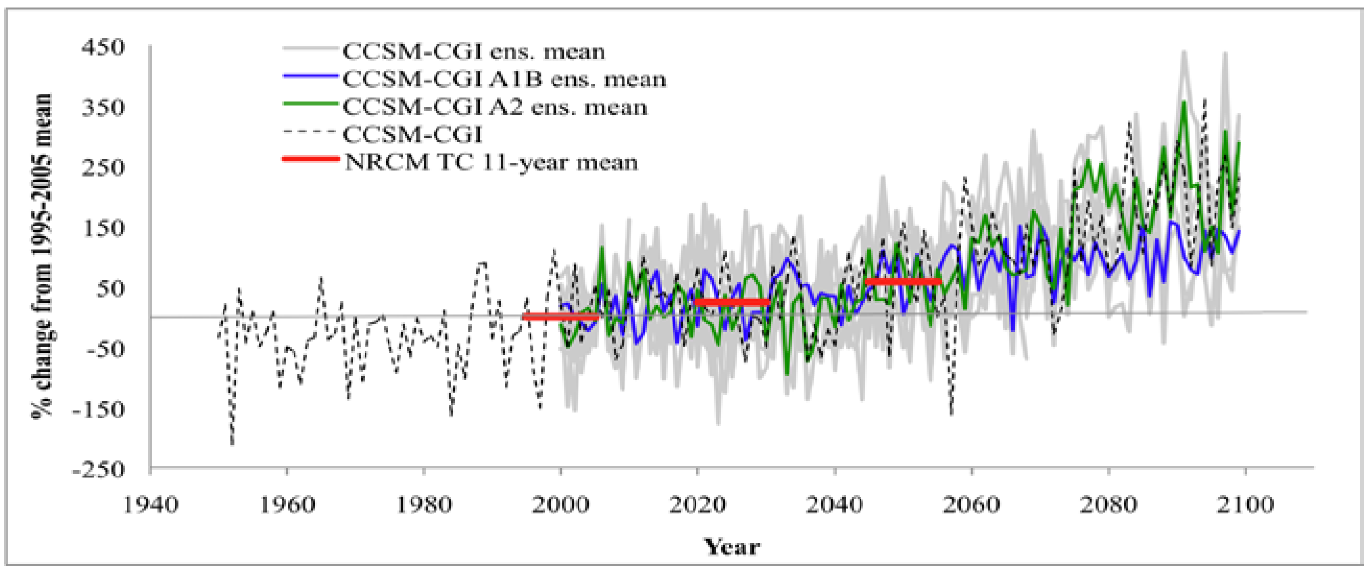


36km domain
≈ 1mil CPU hours
per 10 year
simulation

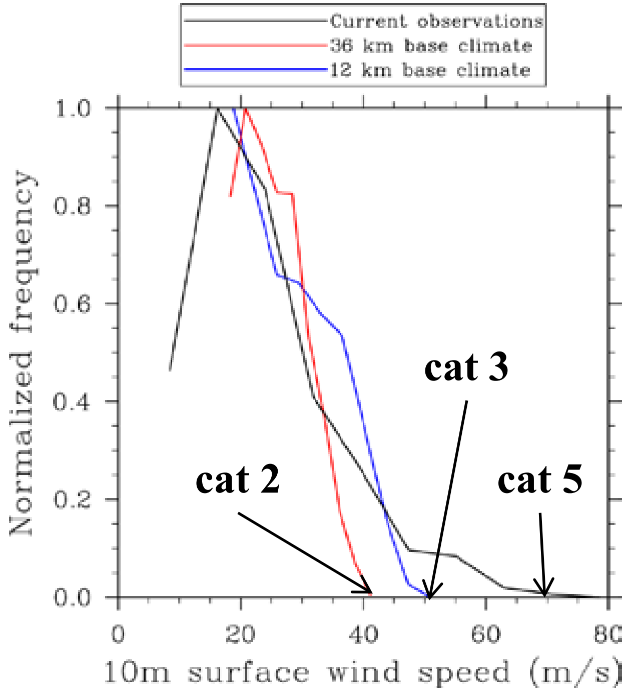
Statistical Downscaling

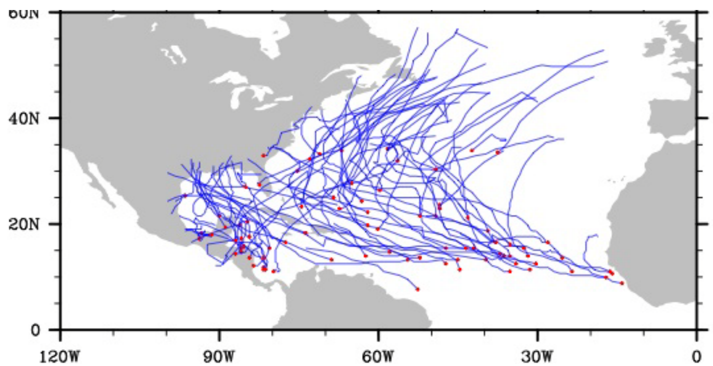


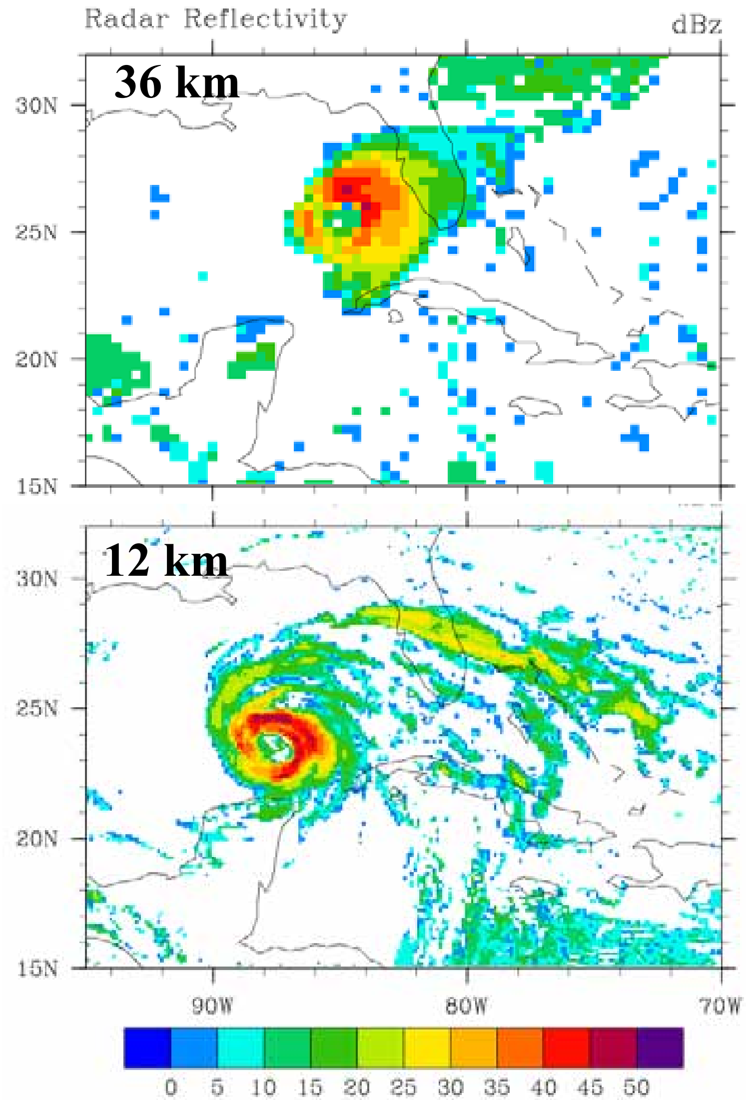




Resolution


Current observations
36 km base climate
12 km base climate
Normalized frequency
10m surface wind speed (m/s)
cat 2
cat 3
cat 5




Radar Reflectivity
dBz
36 km
12 km

Nudging - Motivation

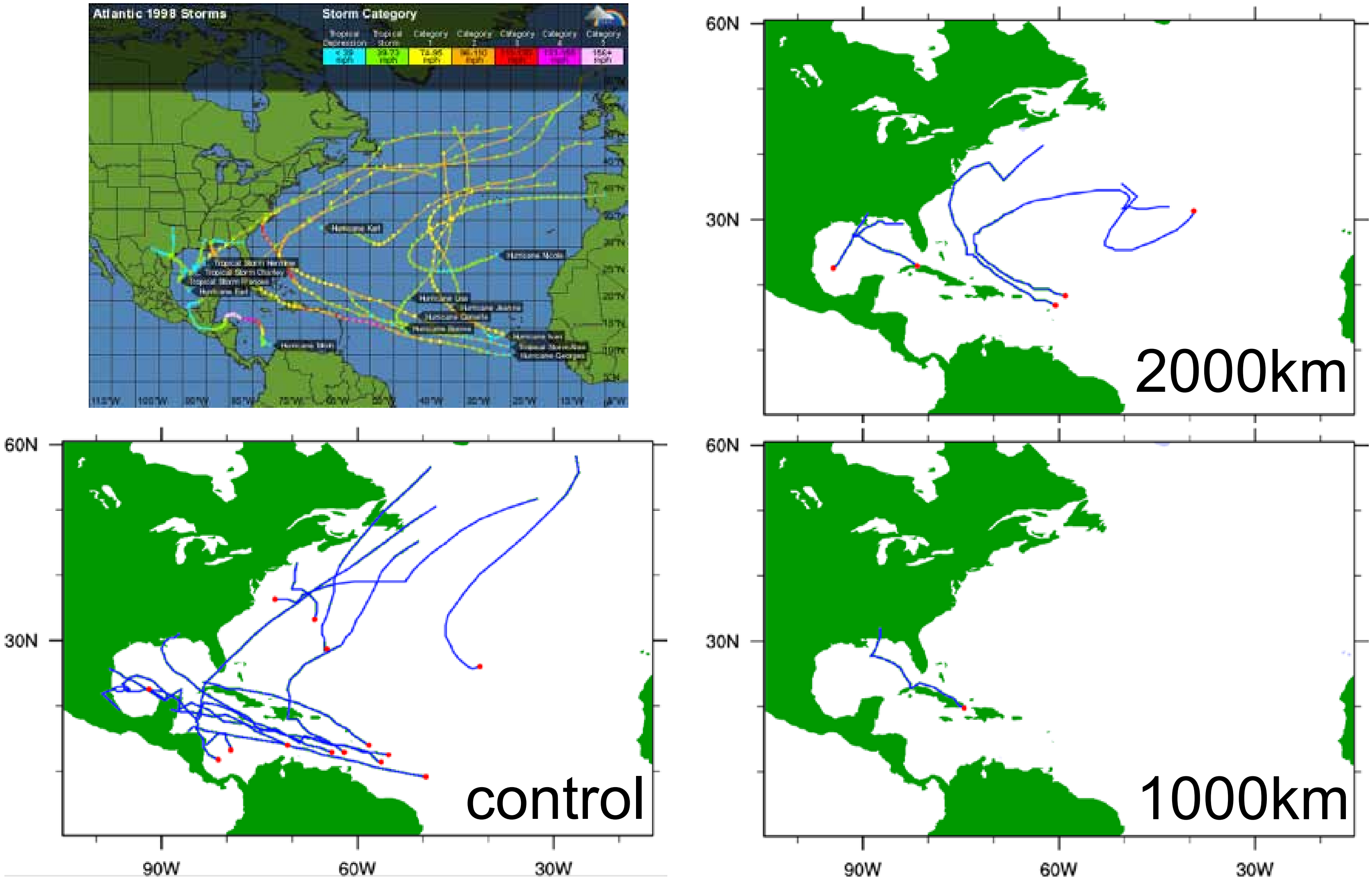
Climatologist often use nudging when downscaling global climate data to keep the model "on-track" and provide better climate statistics.

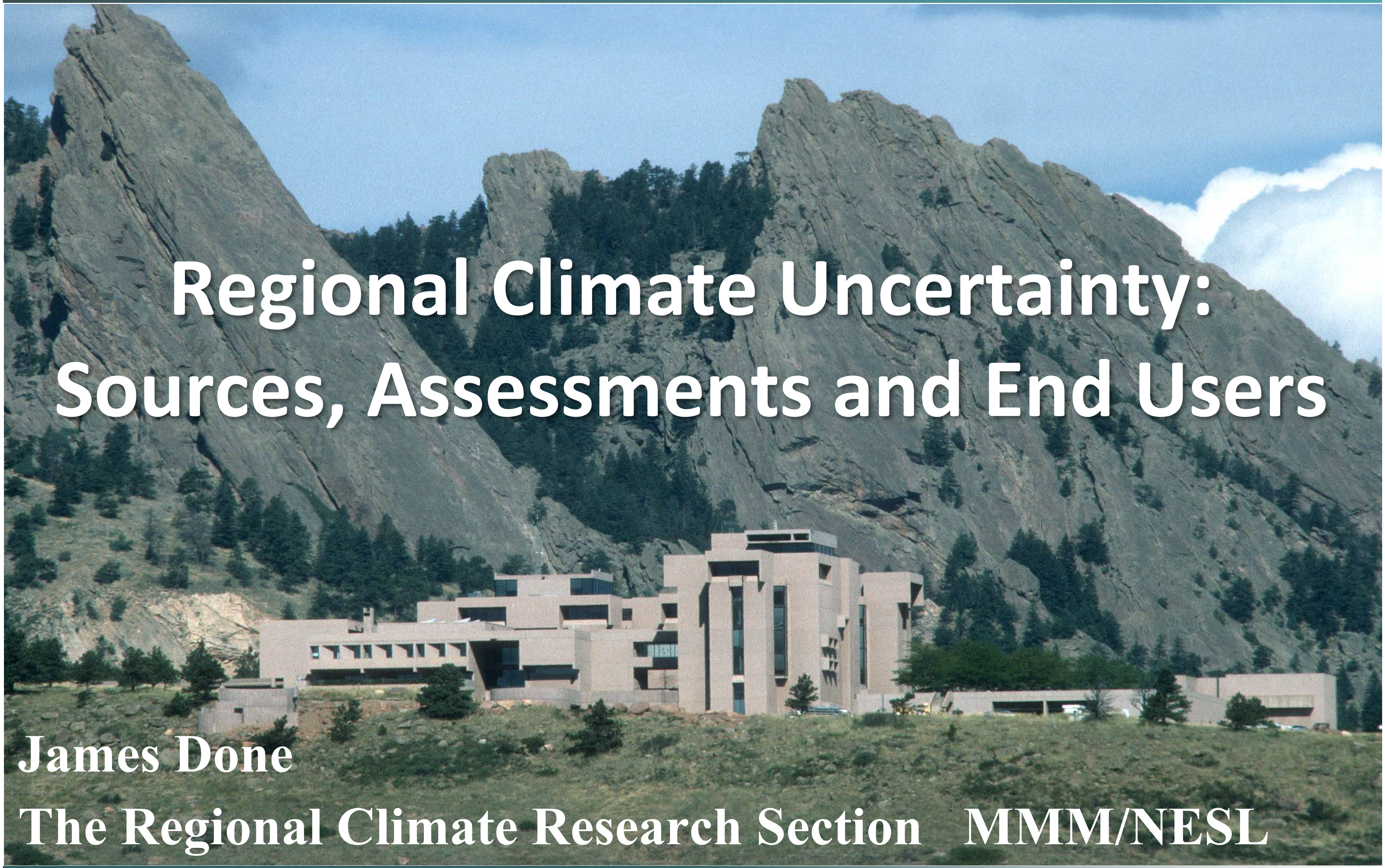
- "One-to-one hurricane climate statistics"

This could potentially impair results

- Global data does not correctly represent waves
- Model not able to spin up own climate
- Model not able to spin up small scale features

Nudging – An Example



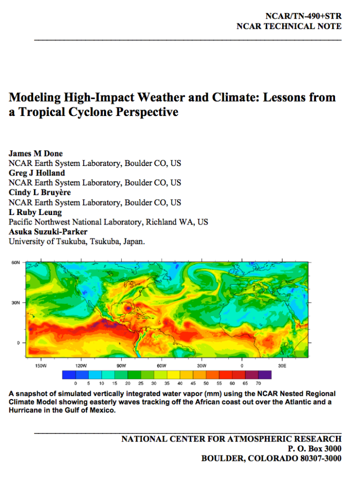


Regional Climate Uncertainty: Sources, Assessments and End Users

James Done
The Regional Climate Research Section   MMM/NESL

Take Home Messages

- The value of regional climate simulation and prediction is limited without an assessment of uncertainty.
- Many sources of regional climate uncertainty.
- The statistical-dynamical modeling approach can provide information on uncertainty, yet remains largely unexplored.


NCAR/TN-490+STR
NCAR TECHNICAL NOTE

Modeling High-Impact Weather and Climate: Lessons from a Tropical Cyclone Perspective

James M Done
NCAR Earth System Laboratory, Boulder CO, US
Greg J Holland
NCAR Earth System Laboratory, Boulder CO, US
Cindy L Bruyère
NCAR Earth System Laboratory, Boulder CO, US
L Ruby Leung
Pacific Northwest National Laboratory, Richland WA, US
Asuka Suzuki-Parker
University of Tsukuba, Tsukuba, Japan.

A snapshot of simulated vertically integrated water vapor (mm) using the NCAR Nested Regional Climate Model showing easterly waves tracking off the African coast out over the Atlantic and a Hurricane in the Gulf of Mexico.

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH
P. O. Box 3000
BOULDER, COLORADO 80307-3000

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NCAR Tech Note:
http://nldr.library.ucar.edu/repository/assets/technotes/TECH-NOTE-000-000-000-854.pdf

Data Needs

Society requires assessment of *weather statistics*, particularly of *extreme weather events*, and their *impacts* with *regional clarity.*

Data Needs

Society requires assessment of *weather statistics*, particularly of *extreme weather events*, and their *impacts* with *regional clarity.*

Predictions

Uncertainty estimation

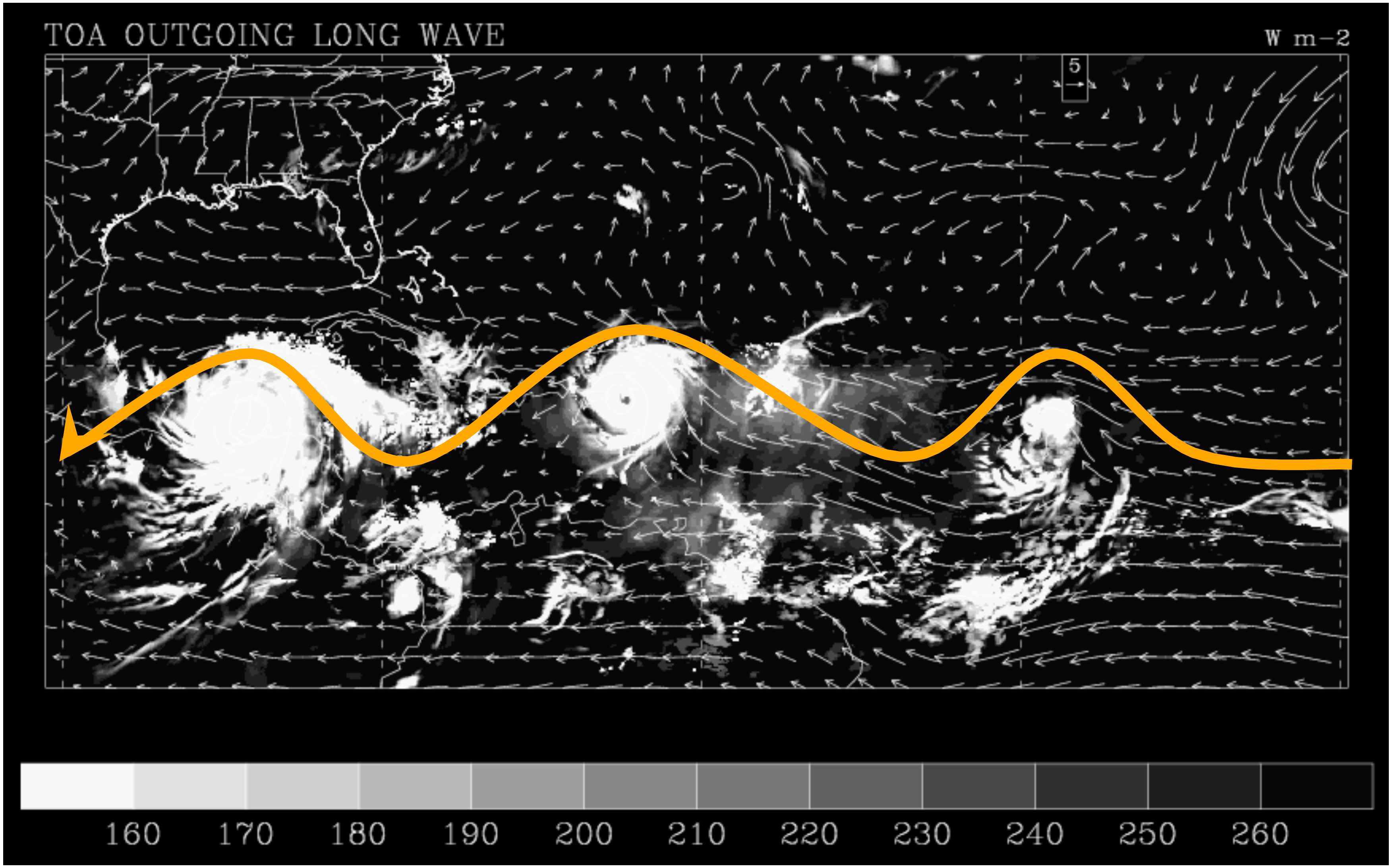
- A challenging problem
- Huge computational demands

Regional Climate Models Can Provide:

- Physical response to climate variability and change;
- Events outside the historical range;
- Consistent data – no artificial trends;
- Contain error but independent of errors in the historical archive:

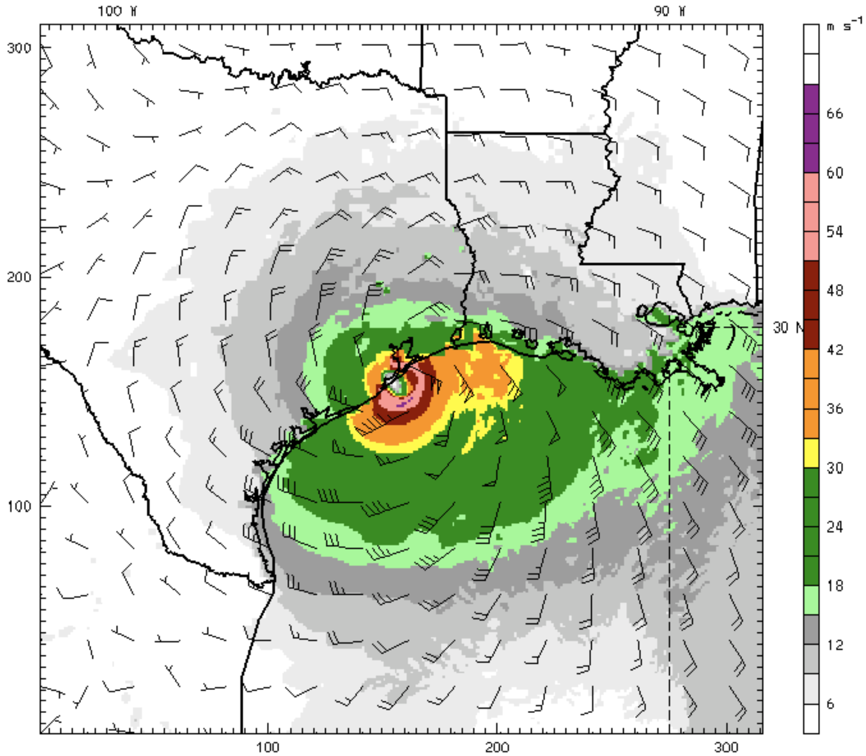
  - a complimentary view of regional climate.

Clustering of High-Impact Weather

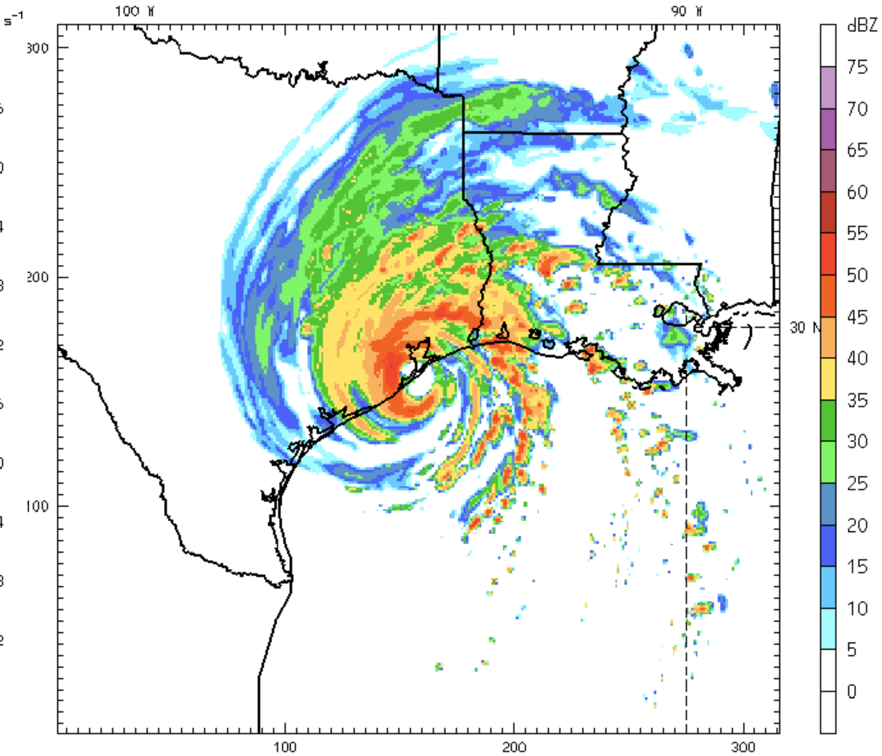


Information on Critical Parameters

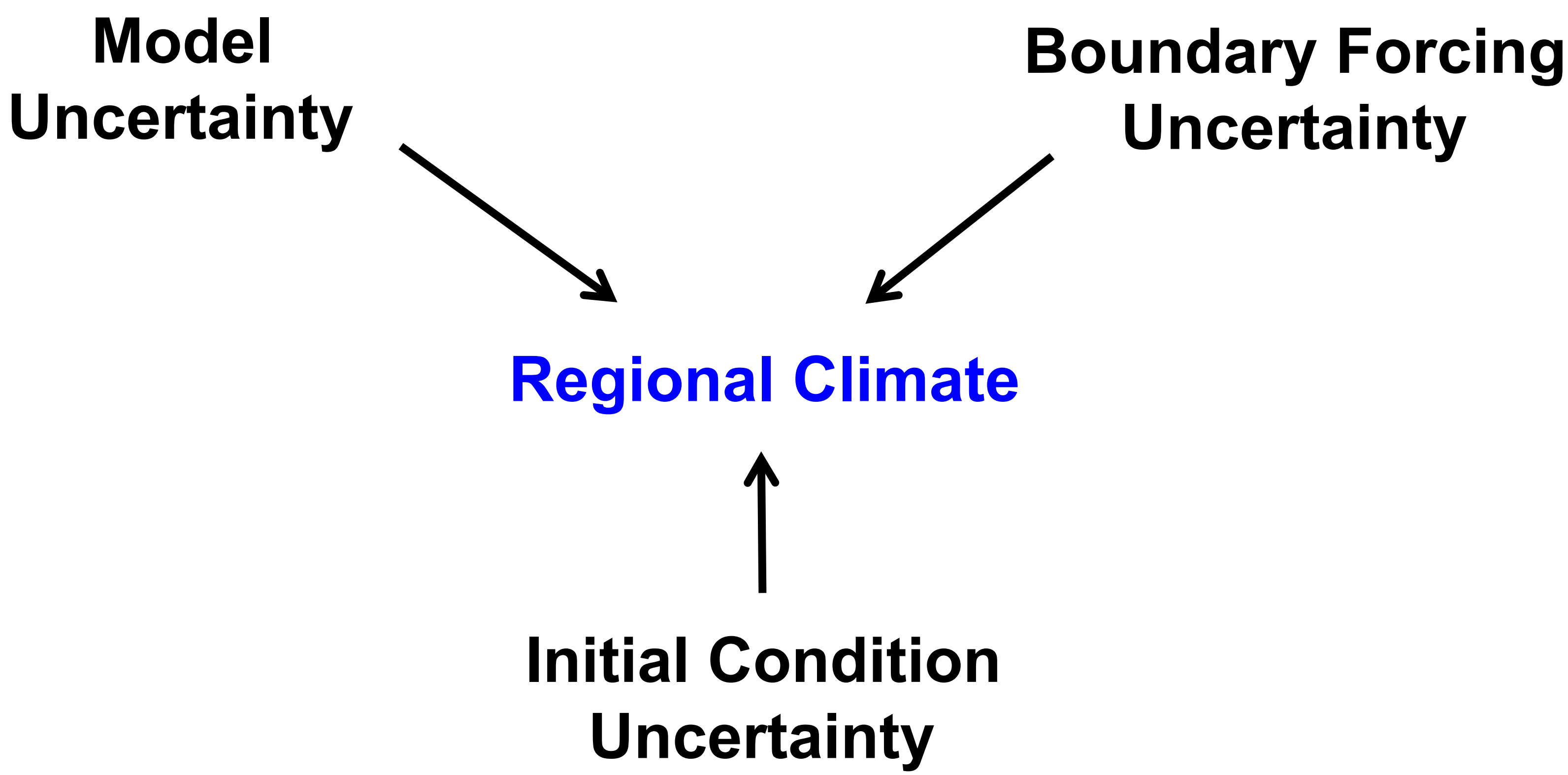
Area of damaging winds



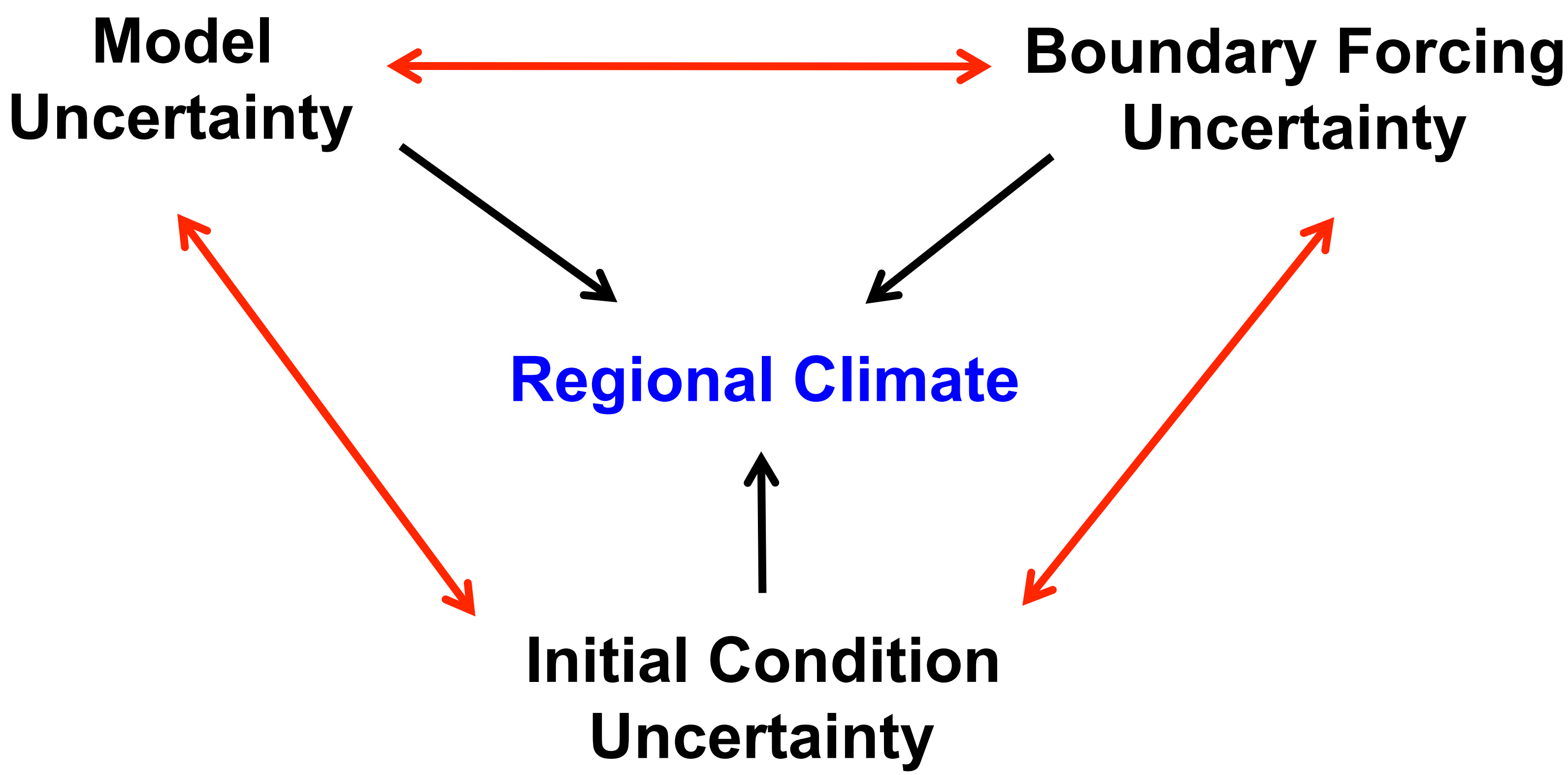
Flooding Rains



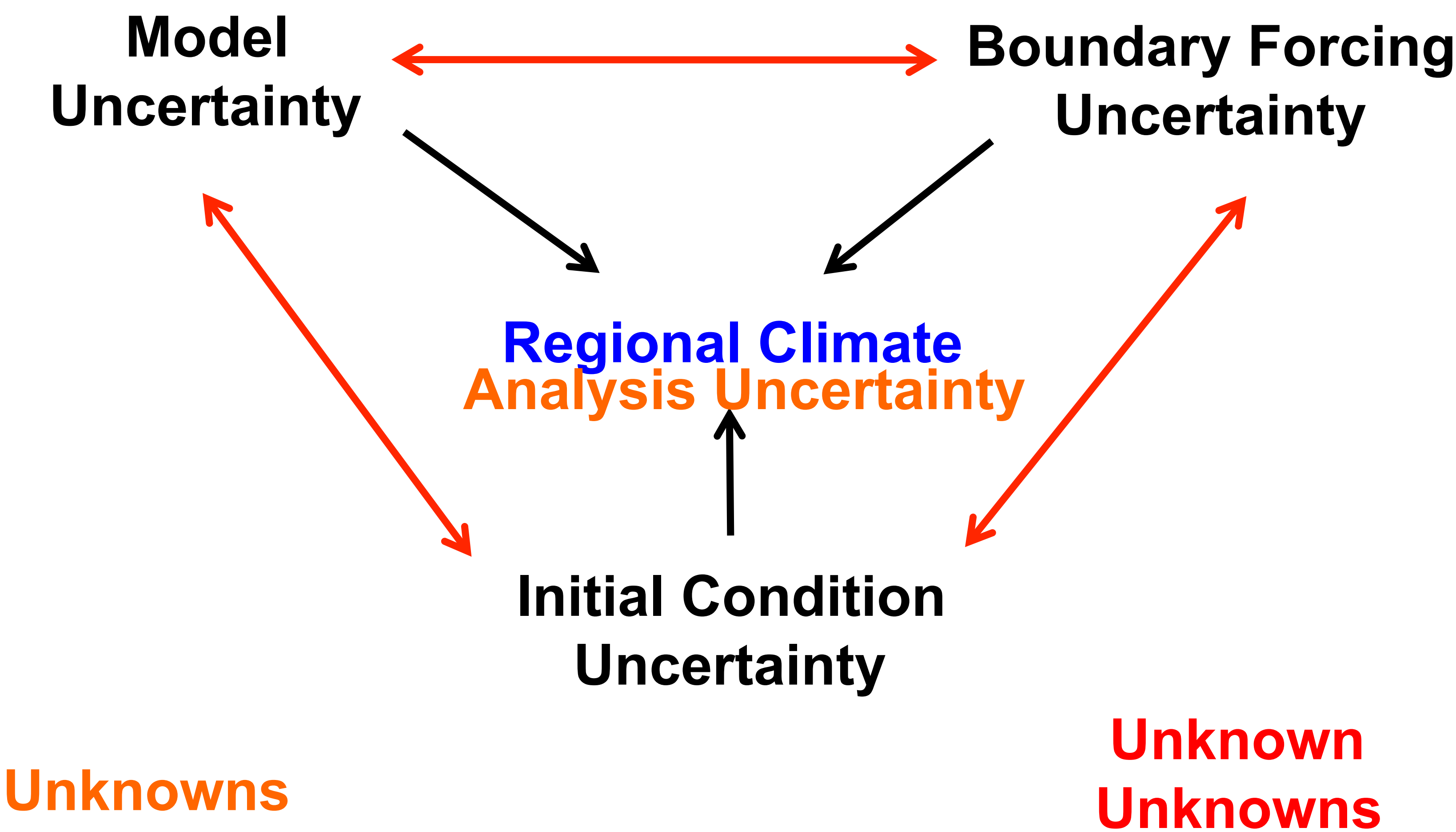
Uncertainty Sources for Regional Climate



Uncertainty Sources for Regional Climate



Uncertainty Sources for Regional Climate

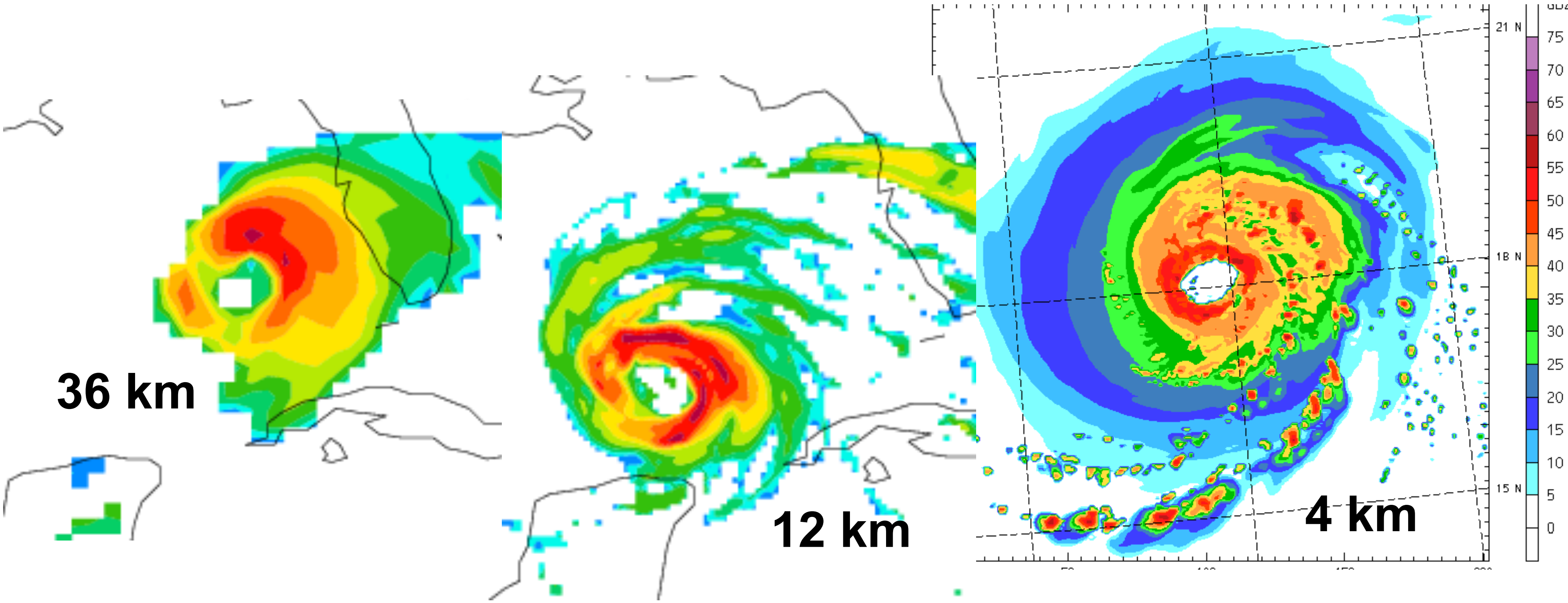


Uncertainty Sources for Climate Simulation

Model Uncertainty:

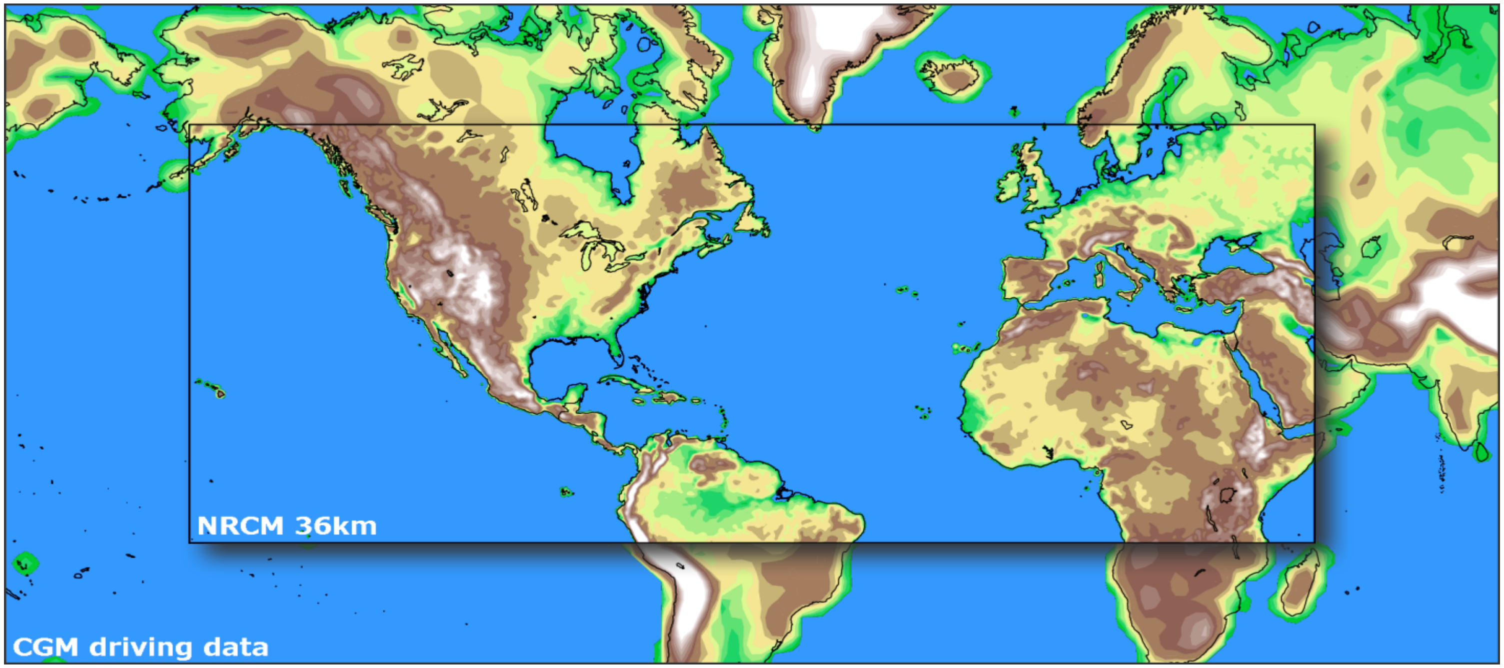
- formulation of dynamics and physics (packages and parameters);
- missing physics (e.g. aerosol, dust, ocean, land surface).

Resolution



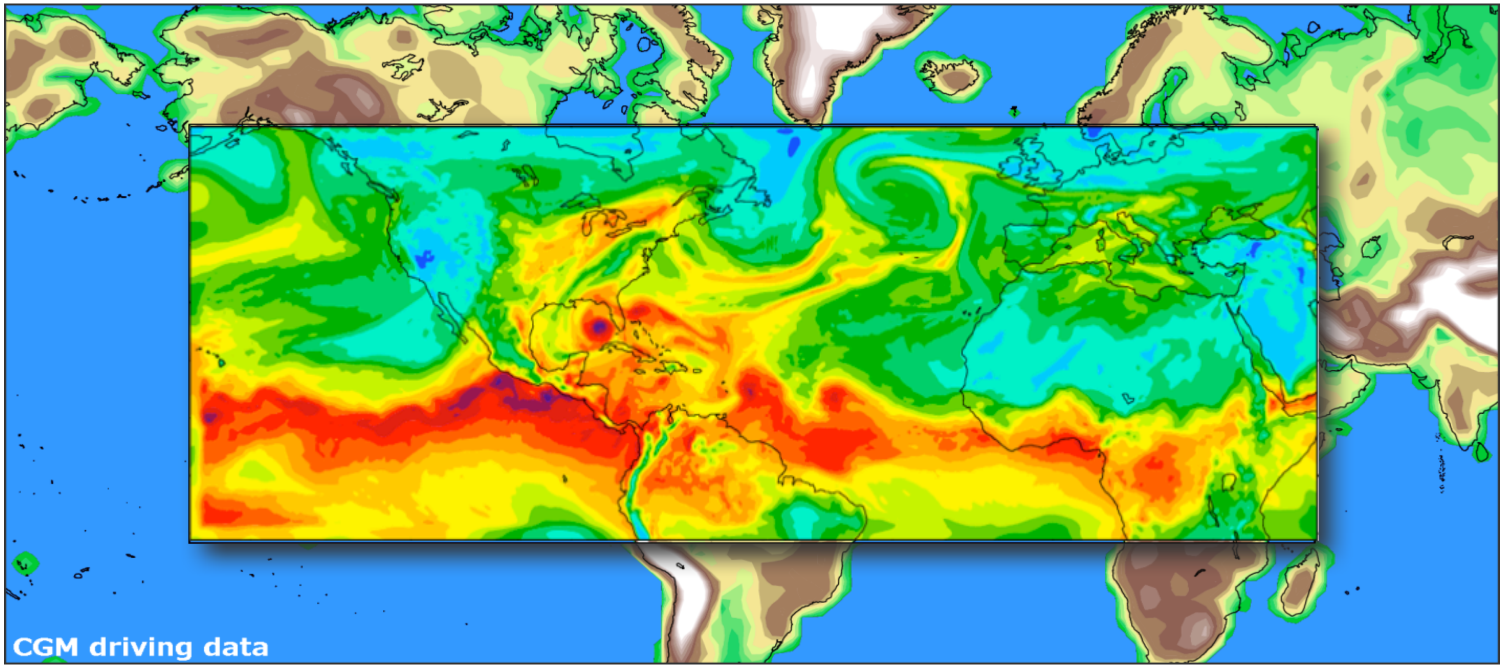
- Uncertainty due to missed processes: spiral rainbands, formation mechanism, strength of ocean coupling, upscale impacts.
- May impact the response to changes in the external forcing.

Domain Size



- Uncertainty due to missed regional climate processes.

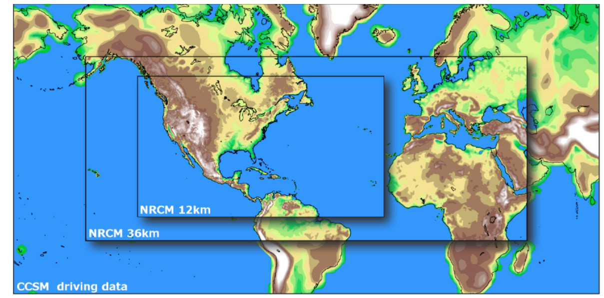
Domain Size



- Uncertainty due to missed regional climate processes.

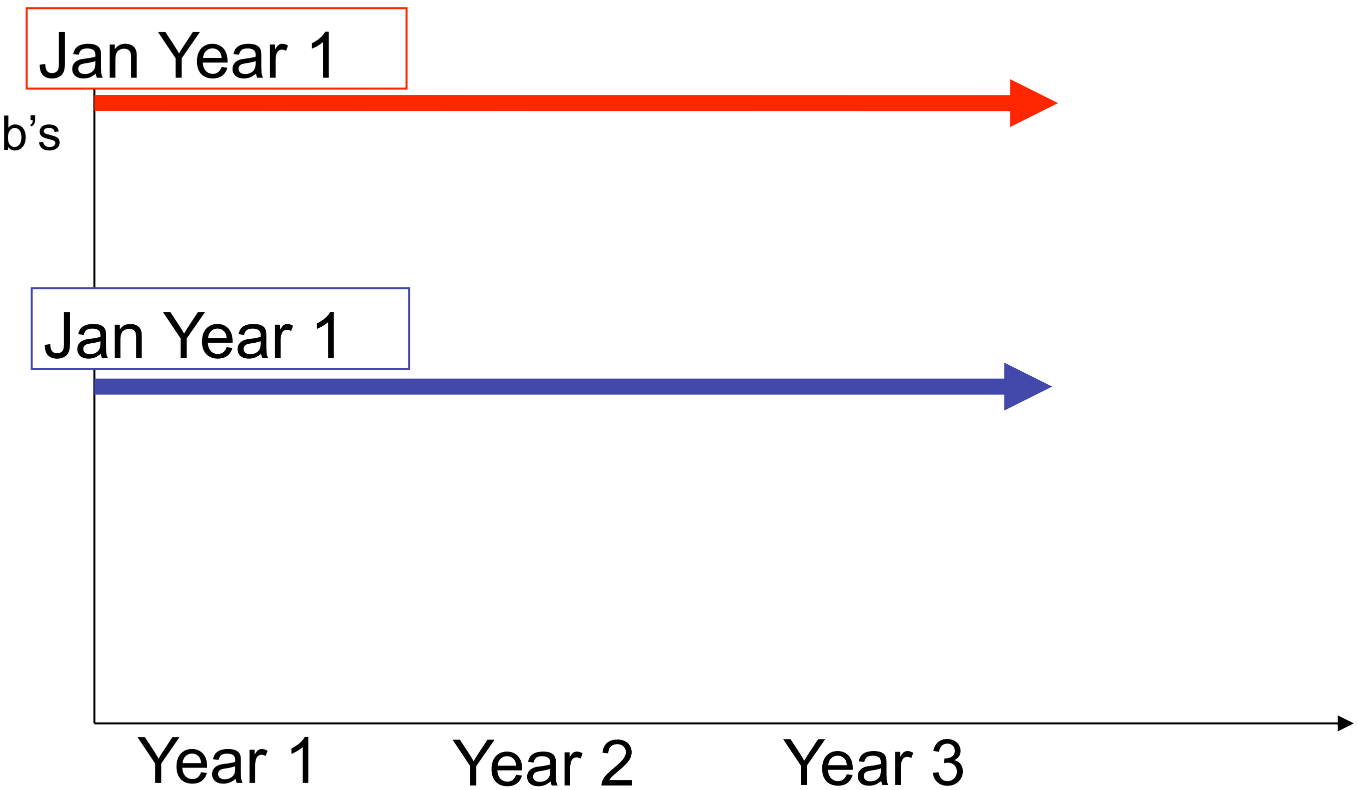
Machine Dependency

Experimental Design:

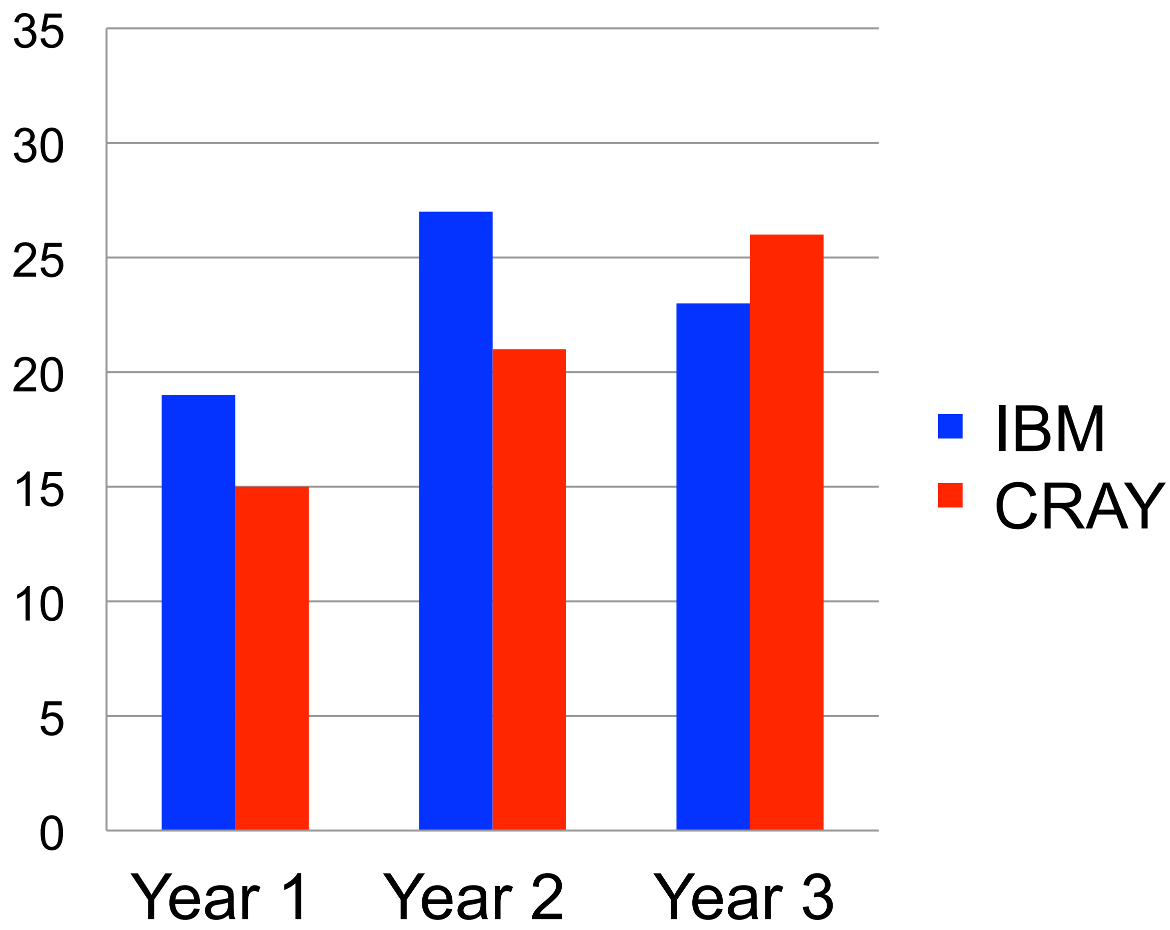


IBM
(Argonne National Lab's Intrepid)

CRAY
(NCAR's Lynx)



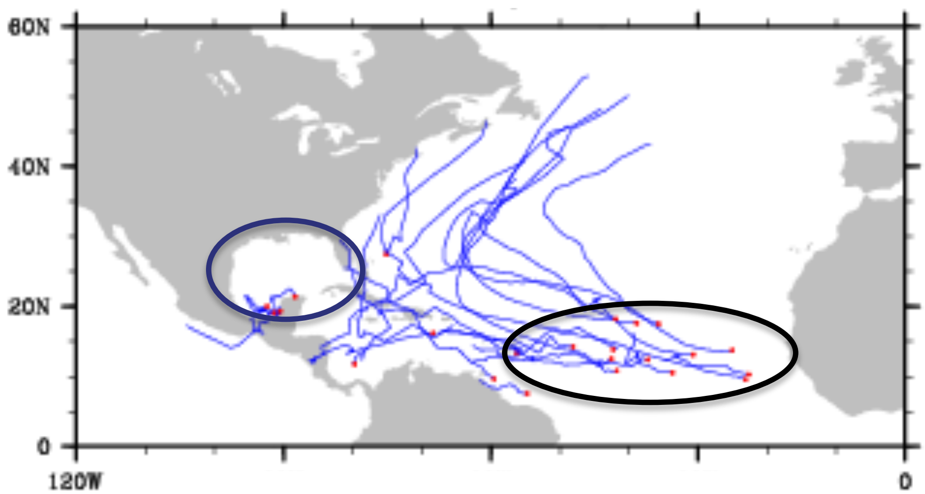
Tropical Cyclone Frequency



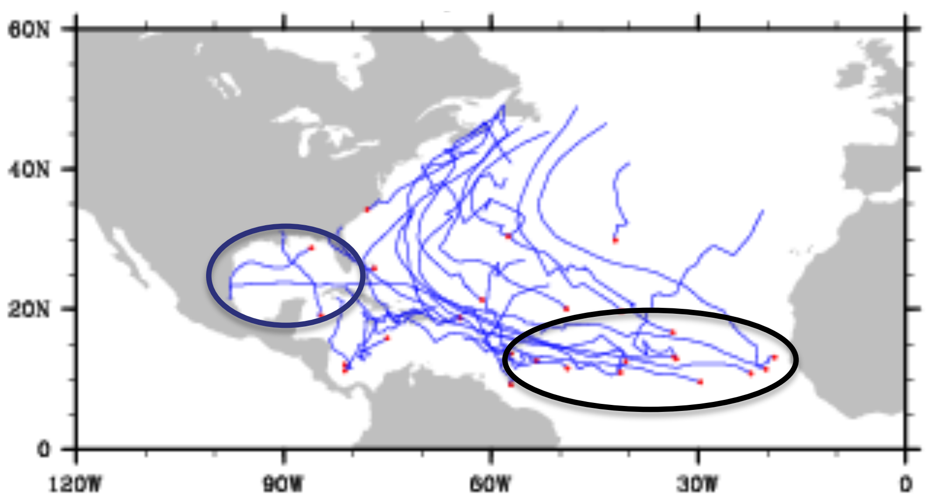
• Differences in annual frequency and interannual variability

Tropical Cyclone Tracks

IBM



CRAY



Uncertainty Sources for Climate Simulation

Boundary and Initial Condition Uncertainty:

- reanalysis uncertainty;
- boundary formulation – abrupt changes in model, temporal and spatial resolution.

Sensitivity of regional weather and weather *statistics* on annual and interannual timescales to initial condition!

Uncertainty Sources for Climate Simulation

Boundary and Initial Condition Uncertainty:

• reanalysis uncertainty;

• boundary formulation – abrupt changes in model, temporal and spatial resolution.

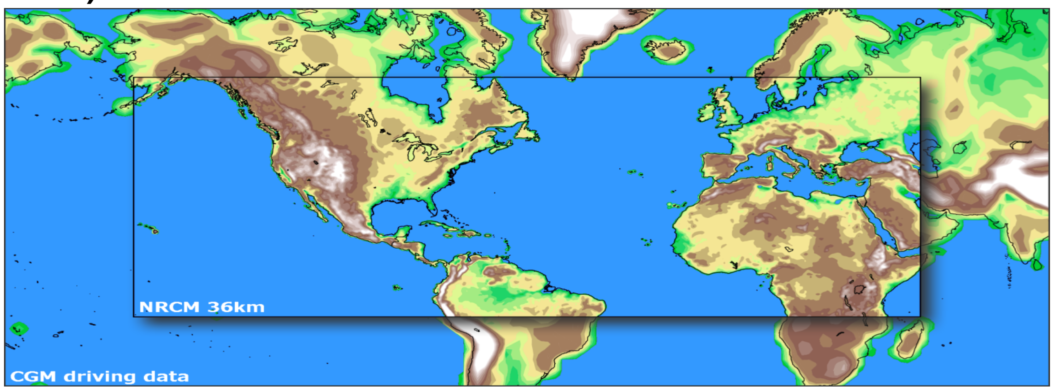
Sensitivity of regional weather and weather *statistics* on annual and interannual timescales to initial condition!

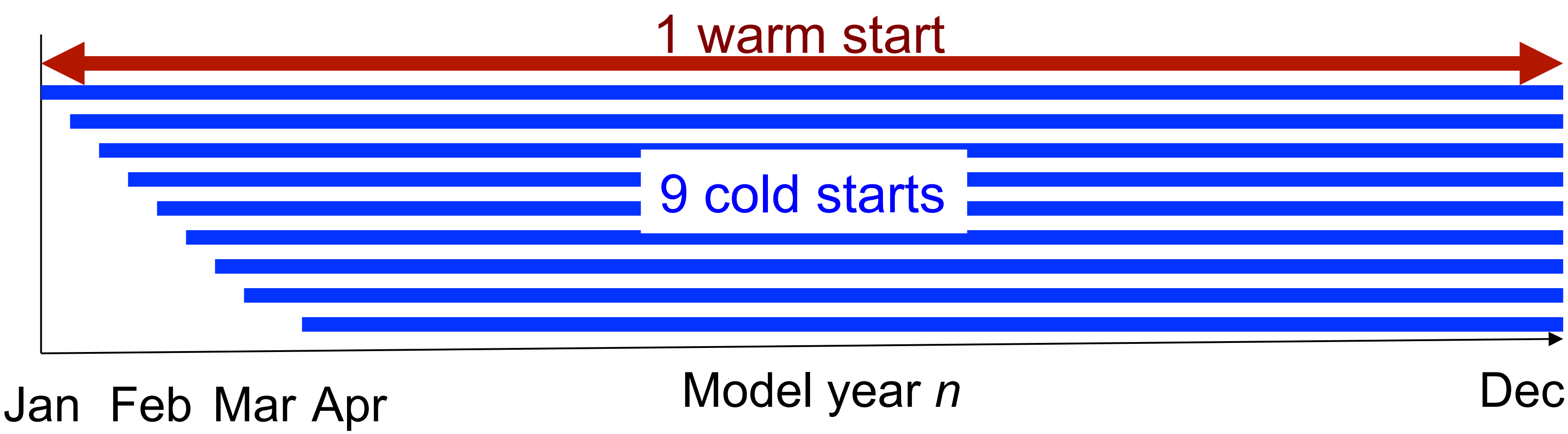
- arises form non-linear relations and multi-scale feedbacks;
- sources may include: stochastic convection; and interactions between surface-atmosphere, convection-environment, cloud-radiation.

Initial Condition Ensemble Experiment

Aim: determine the sensitivity of seasonal North Atlantic tropical cyclone activity to initial condition.

Downscale Global Model (CCSM3) using the Weather Research and Forecasting (WRF) model.





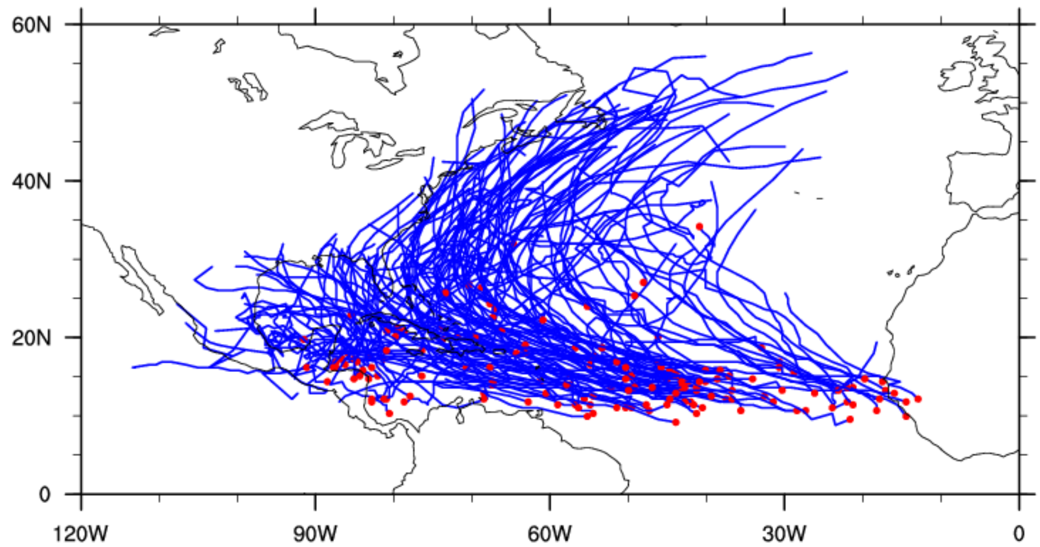
Tropical Cyclone Tracks

Ensemble:

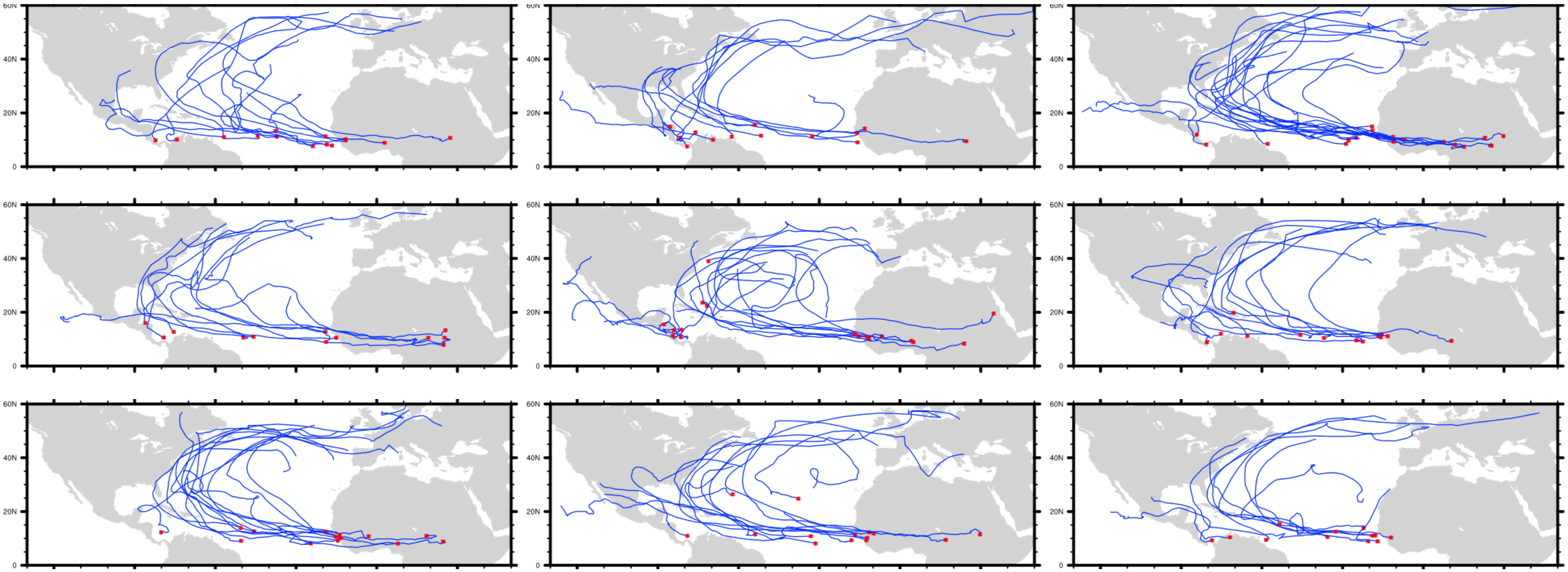
Annual mean: 15.2

Annual range: 13 – 20

Std dev / mean: 0.12



Ensemble Spread



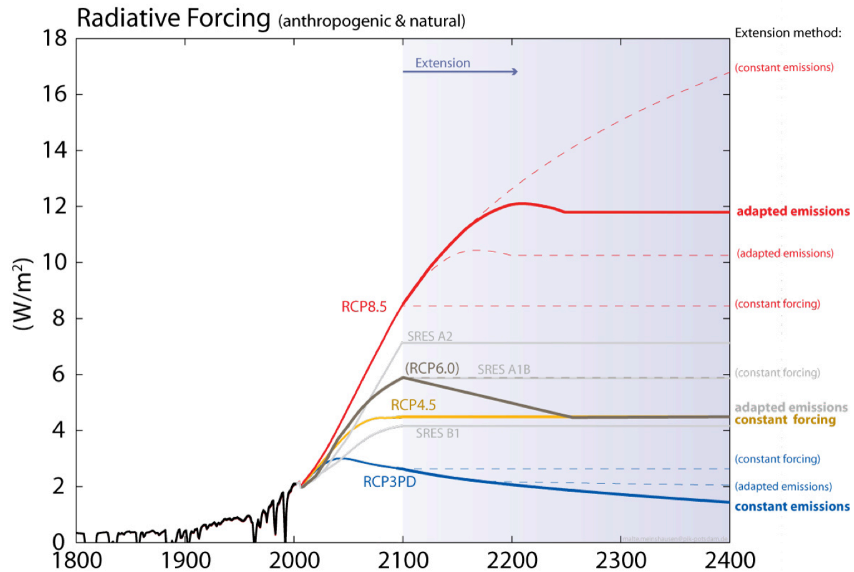
- Variability in frequency and locations between ensemble members.

- Consequence for regional climate sensitivity studies:

- need to account for internal variability.

Uncertainty Sources for Climate Prediction

Radiative Forcing:



Global radiative forcing for the high RCP8.5, the medium-high RCP6, the medium-low RCP4.5 and the low RCP3PD.

Uncertainties for Regional Climate Prediction

Climate Response:

- which GCM;
- which ensemble member;
- how to handle non-stationary climate bias (*Cindy Bruyère*);
- Inherent assumption: No remote small-scale process acts upscale to impact the region of interest.

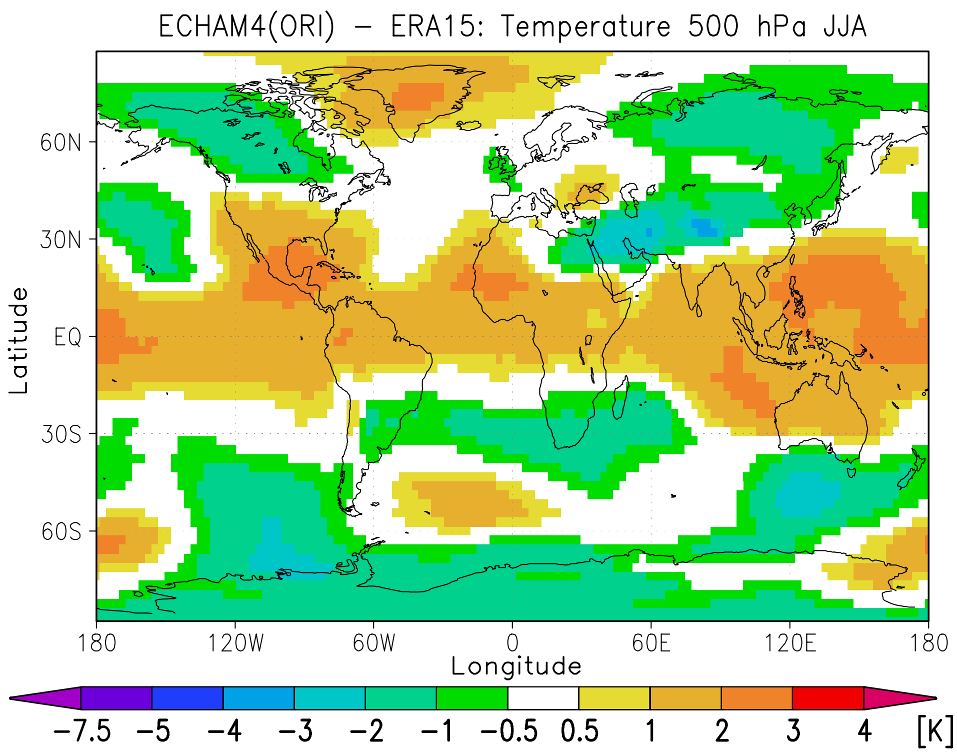
  - demonstrably false (e.g. S. Masson’s talk yesterday)

Importance of Upscaling

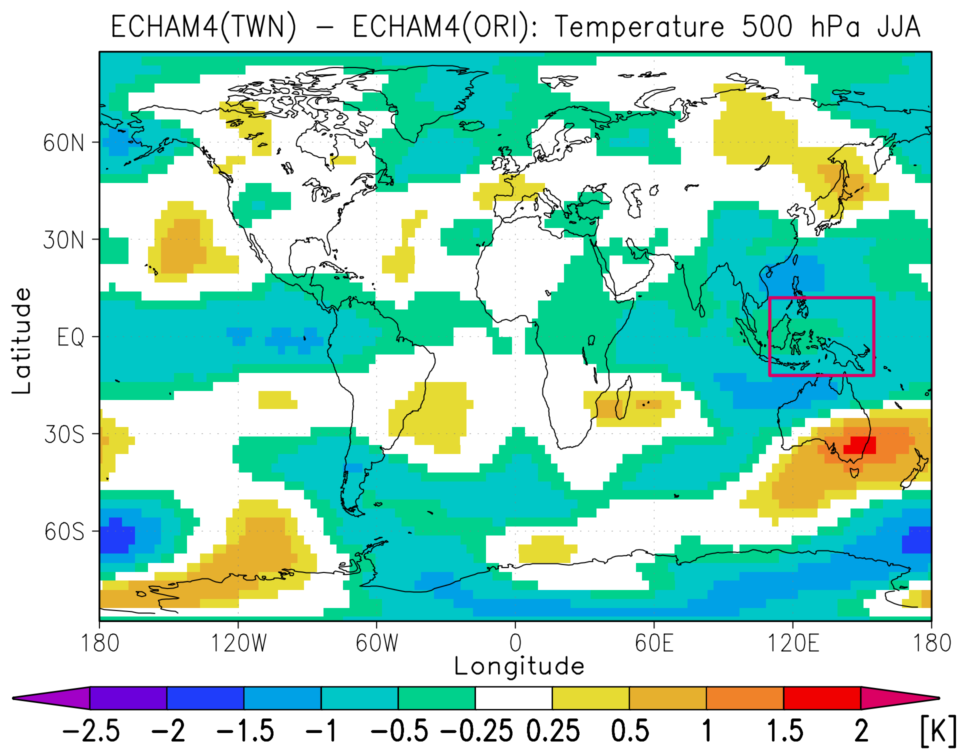
Lorenz and Jacob (2005):

10-year JJA 500hPa Temperature

GCM (2.8°) Bias



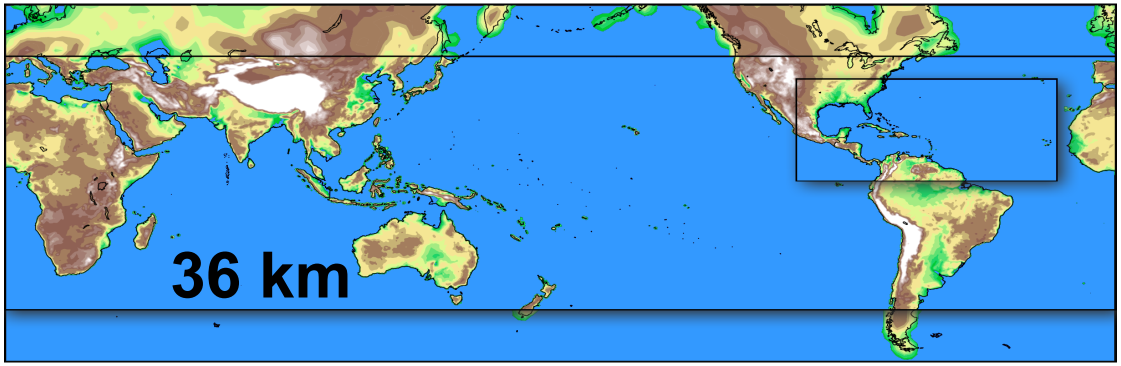
Impact of 2-way RCM 0.5° over Maritime Continent



Analysis Uncertainty

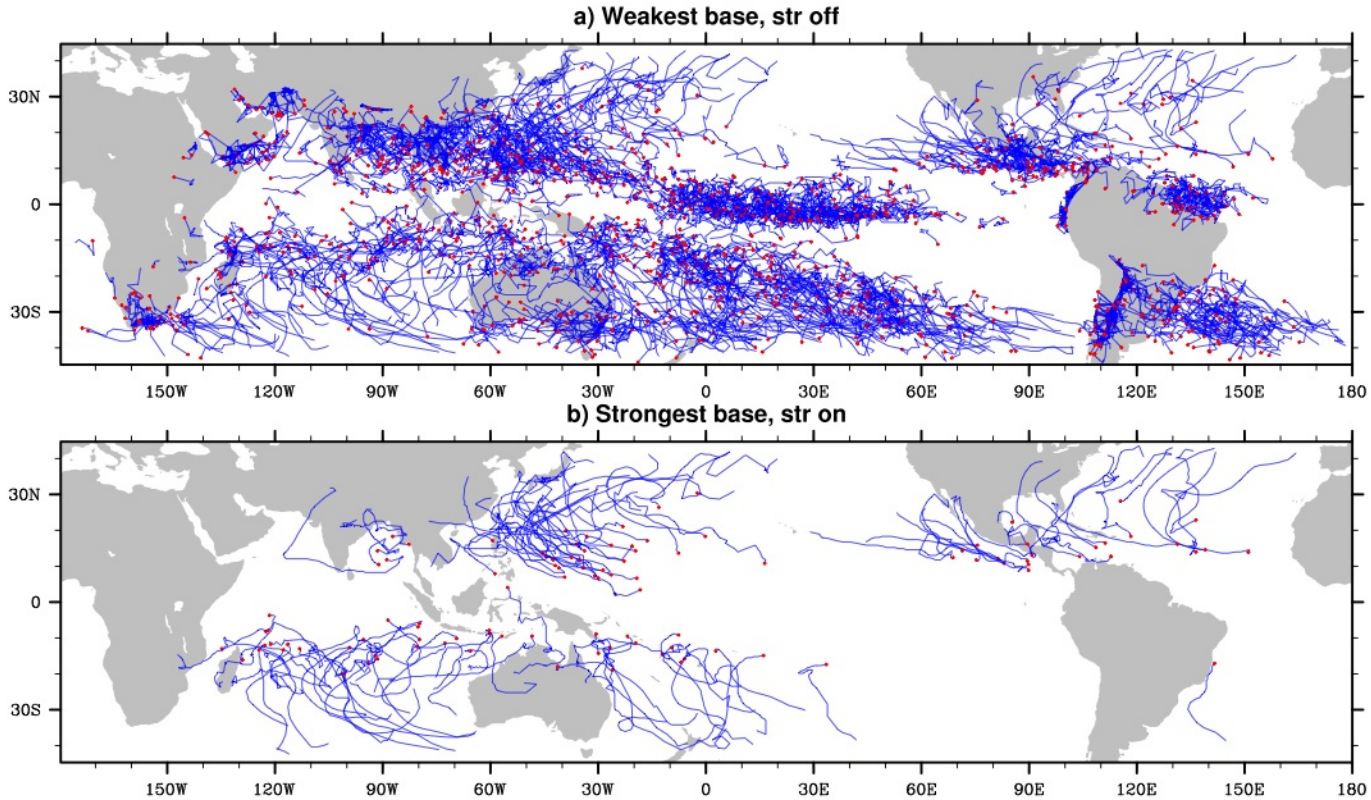
Example: Tropical Cyclones

- Tropical cyclone tracks are identified using automated tracking schemes.
- Assess sensitivity of cyclones to tracking scheme thresholds within the range in the published literature.



Asuka Suzuki-Parker

Impact of tracking criteria



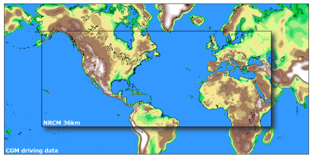
Relaxed criteria
1468 tracks/yr

Strict criteria
106 tracks/yr

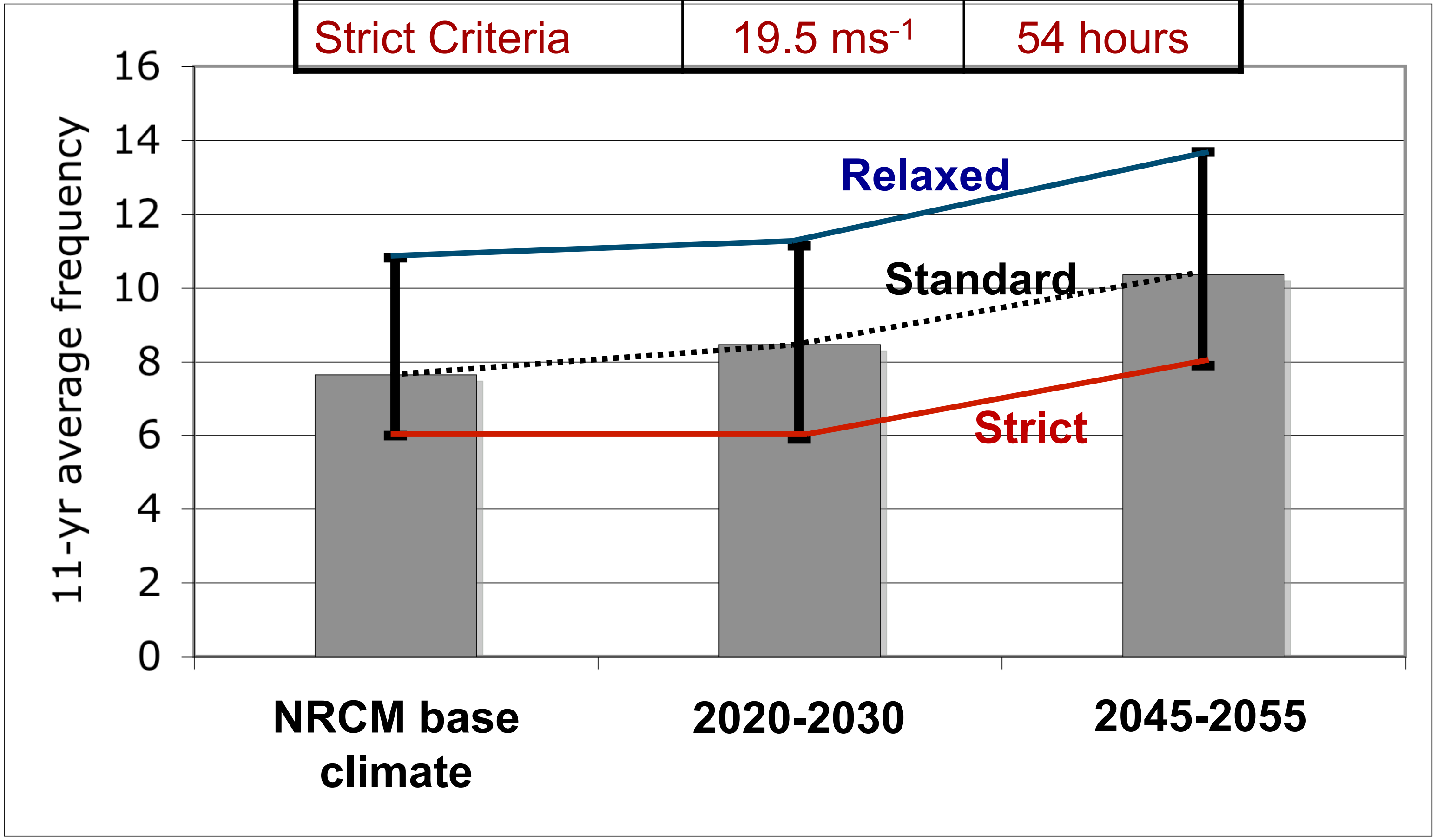
- Number is highly sensitive to tracking criteria.
- Is it acceptable to tune tracking criteria to compare well with obs?
- Automated analysis schemes can be a useful diagnostic tool.

Asuka Suzuki-Parker

Impact on Future Change



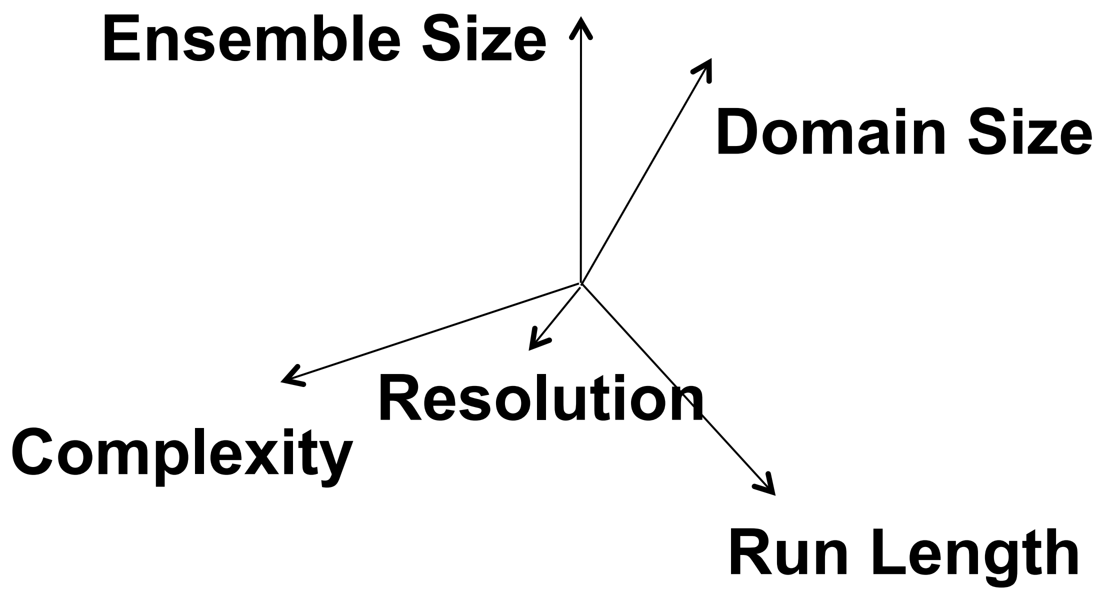
	Wind speed	Duration
Relaxed Criteria	14.5 ms^{-1}	42 hours
Strict Criteria	19.5 ms^{-1}	54 hours



Asuka Suzuki-Parker

Demands on Uncertainty Estimation

Developing an understanding of uncertainty in the context of finite computational capacity: A balance between competing demands?



Demands on Uncertainty Estimation

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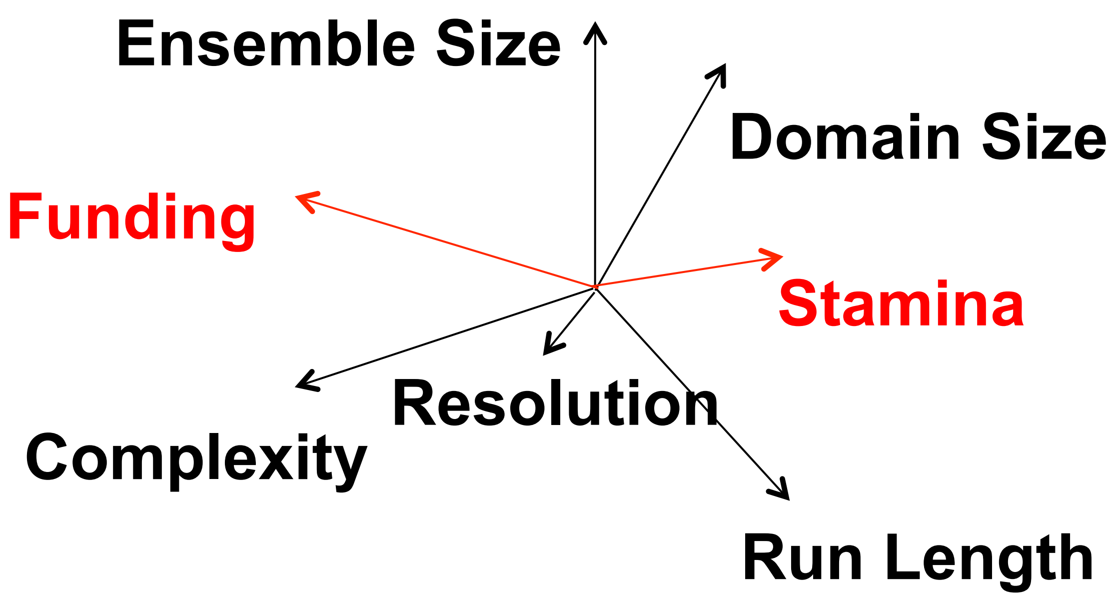
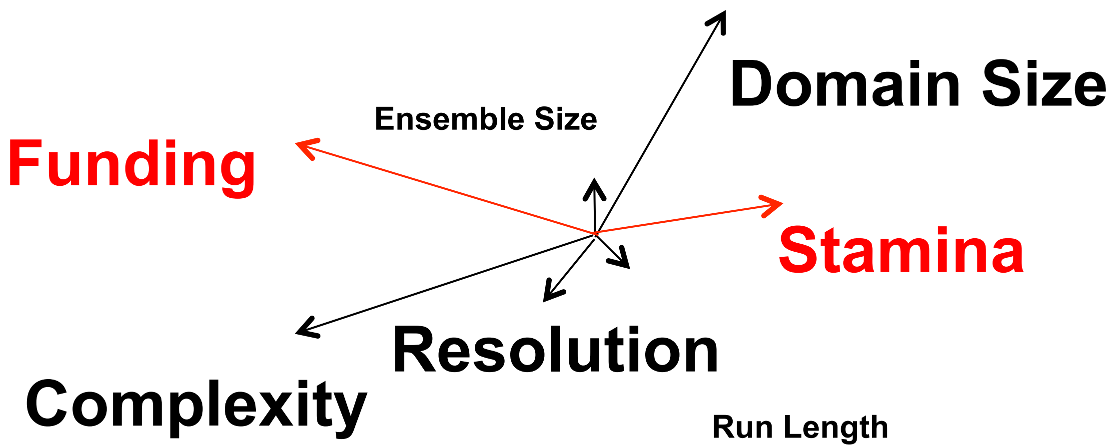


Demands on Uncertainty Estimation

Developing an understanding of uncertainty in the context of finite computational capacity: A balance between competing demands?



Evaluation Uncertainty

Regional Climate Simulation:

Issues with the historical record:

• Short period: low sample size of the parent distribution.

• Assumption of stationarity: that each year samples from the same parent distribution.

• Discontinuities in data quality due to changes in data collection methods.

- opportunity for theoretical statistical distributions.

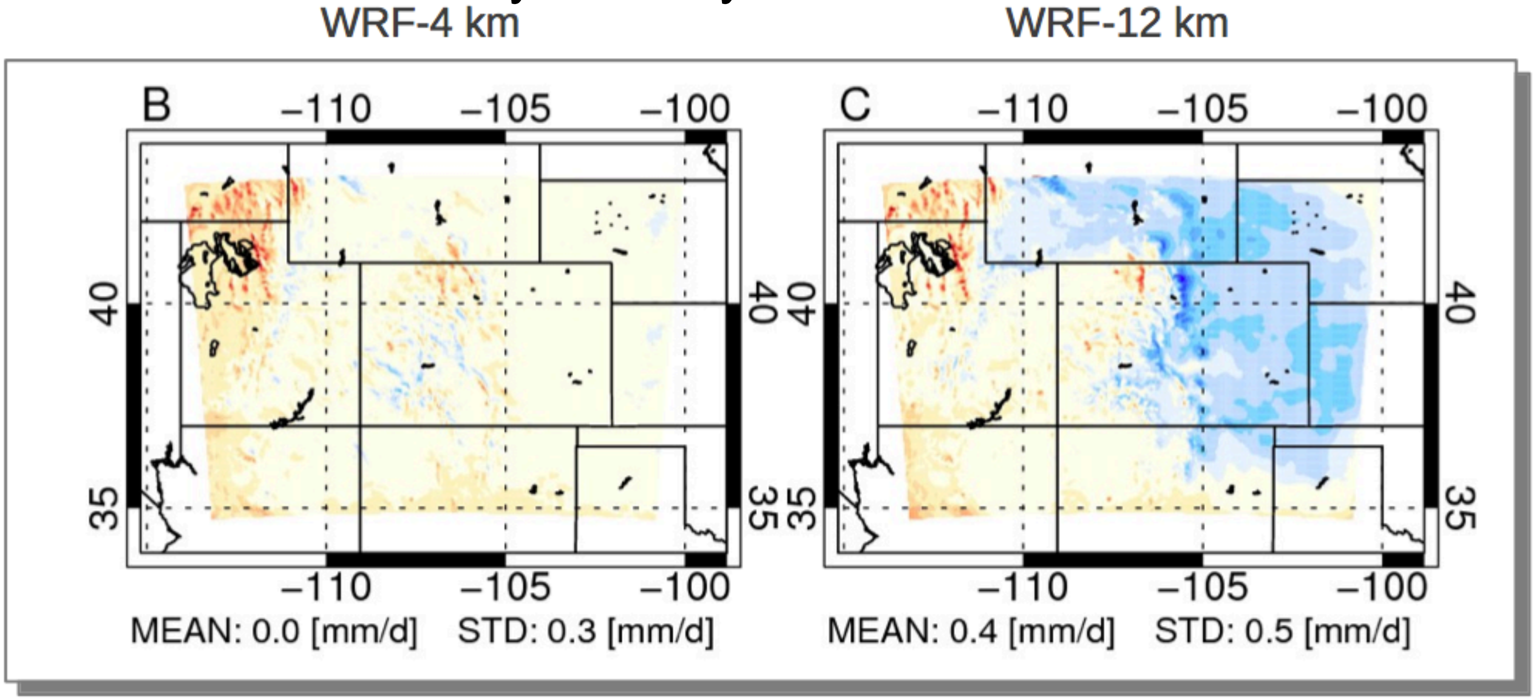
Regional Climate Prediction:

• Process-based evaluation.

Evaluation Uncertainty

- Observed regional climate datasets are considered our 'best guess'.
- Suggestion that WRF can improve on these datasets . . . . .

10-year Daily Rainfall Bias

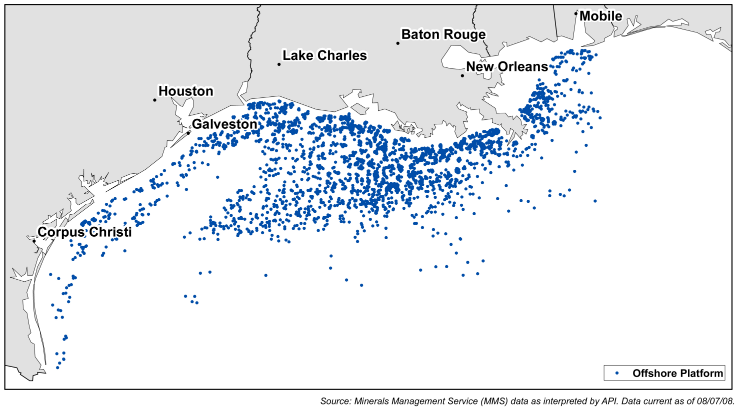


Reference: PRISM

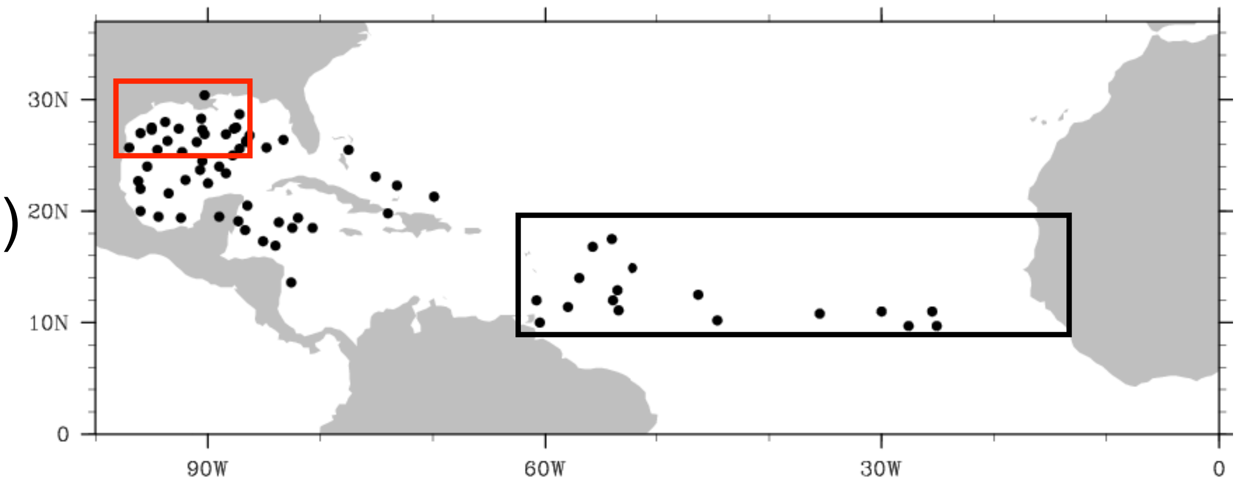
Andreas Prein

End Users: The Offshore Energy Industry

Collaboration is driving new approaches to understanding regional climate uncertainty on small regions (*Talk: Greg Holland*)



Genesis locations of storms that entered the red box (obs: 1966-2008) ¼ formed in black box.



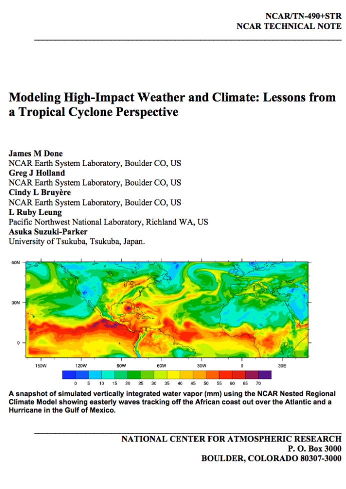
End Users: The Re/Insurance Industry

- 1950-2008: 80% of worldwide insured losses were weather related, dominated by tropical cyclones.
- The re/insurance business is in understanding uncertainty.
- Industry is dominated by a 3-member ensemble of risk.
- Regional climate modeling, coupled with exposure, vulnerability and financial modules is poised to be a game changer for the industry.

Take Home Messages

NCAR is Sponsored by NSF

- The value of regional climate simulation and prediction is limited without an assessment of uncertainty.
- Many sources of regional climate uncertainty.
- The statistical-dynamical modeling approach can provide estimation of uncertainty, yet remains largely unexplored.


NCAR/TN-490+STR
NCAR TECHNICAL NOTE

Modeling High-Impact Weather and Climate: Lessons from a Tropical Cyclone Perspective

James M Done
NCAR Earth System Laboratory, Boulder CO, US
Greg J Holland
NCAR Earth System Laboratory, Boulder CO, US
Cindy L Bruyère
NCAR Earth System Laboratory, Boulder CO, US
L Ruby Leung
Pacific Northwest National Laboratory, Richland WA, US
Asuka Suzuki-Parker
University of Tsukuba, Tsukuba, Japan.

A snapshot of simulated vertically integrated water vapor (mm) using the NCAR Nested Regional Climate Model showing easterly waves tracking off the African coast out over the Atlantic and a Hurricane in the Gulf of Mexico.

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH
P. O. Box 3000
BOULDER, COLORADO 80307-3000

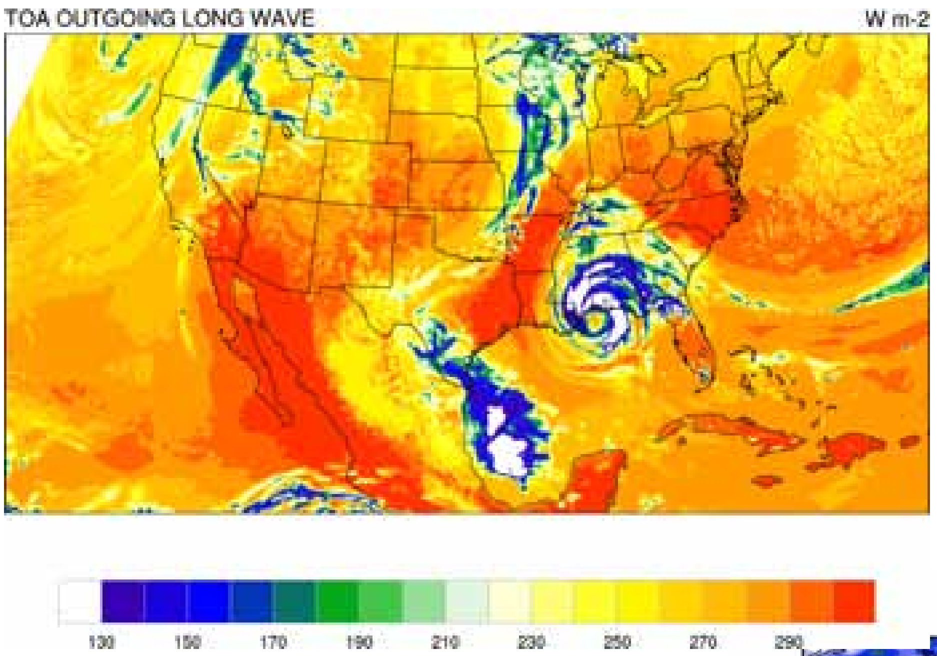
3

NCAR Tech Note:
http://nldr.library.ucar.edu/repository/assets/technotes/TECH-NOTE-000-000-000-854.pdf

Bias Correction Methods

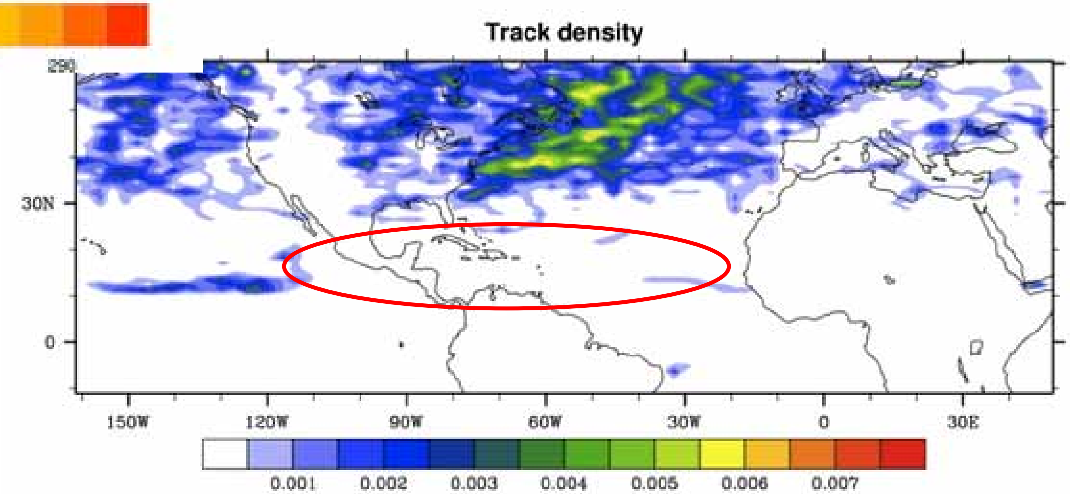
Cindy Bruyère

Biases in Climate Model Data



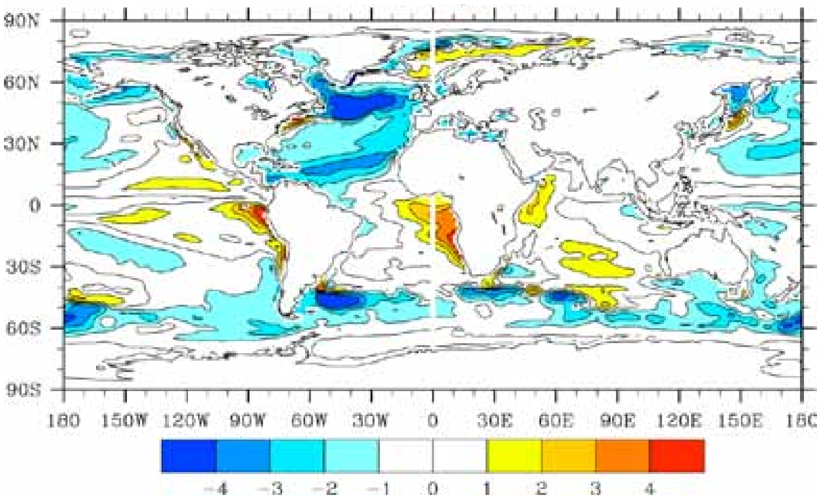
Cat 3 Hurricane
October 2046

Track density of model tropical and extratropical storms
Jan-Dec 1995

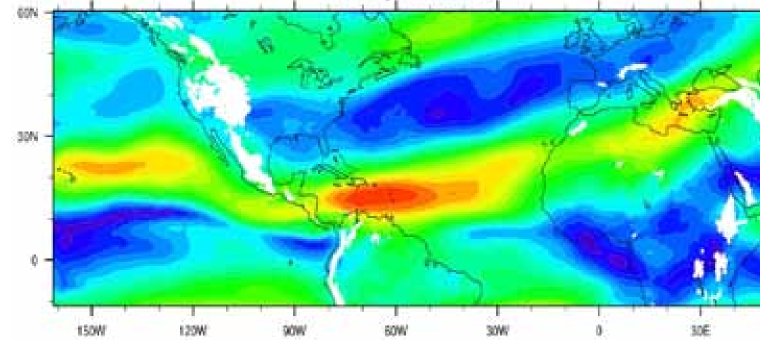


Bias in CCSM Model

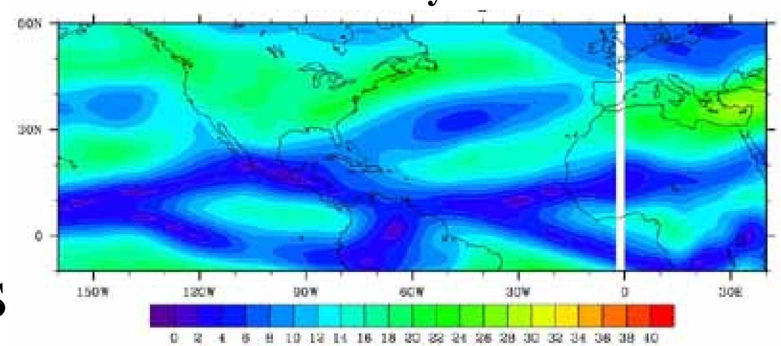
CCSM - Observed ASO Averaged SST



CCSM ASO Averaged shear (m/s)

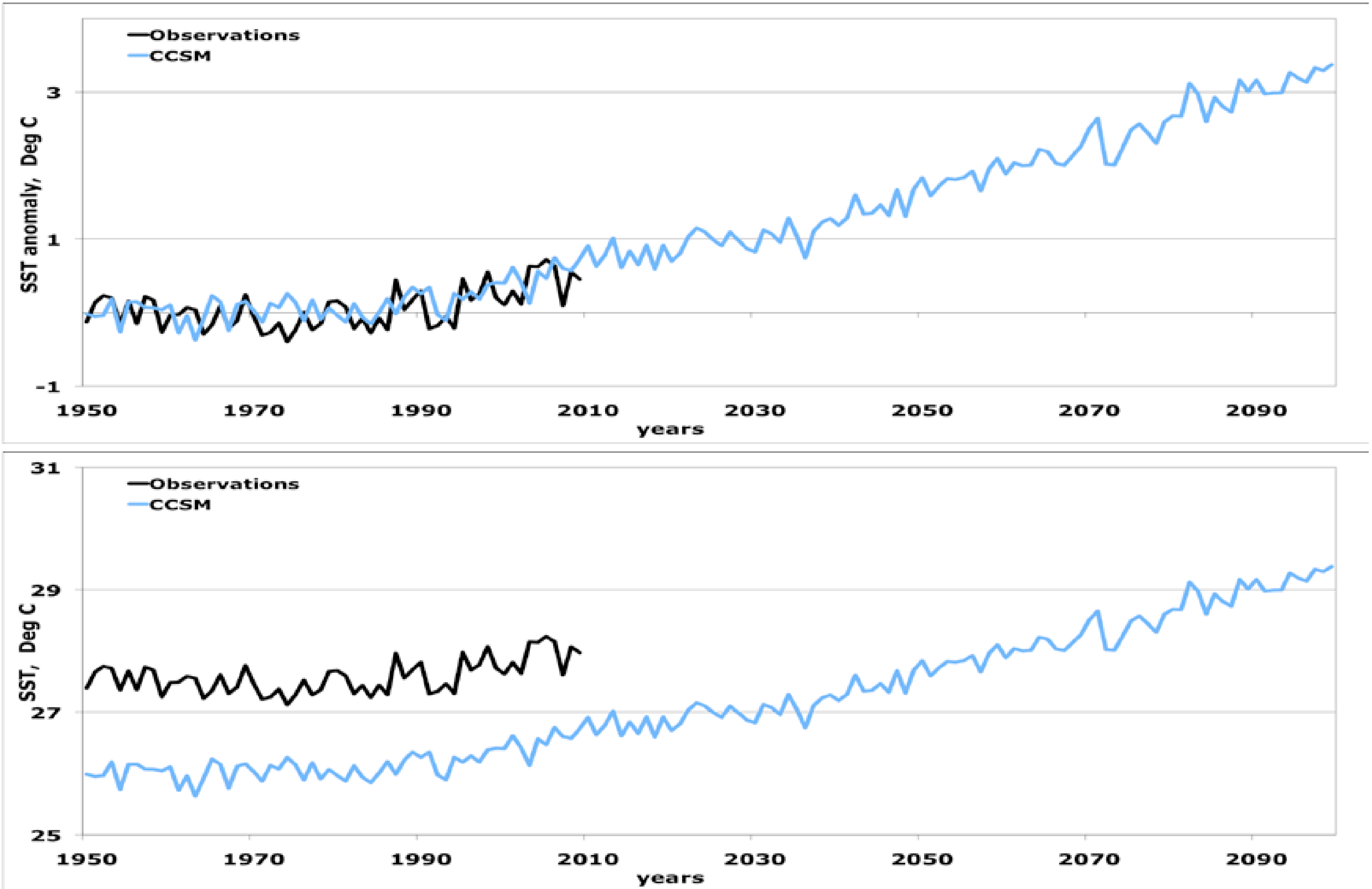


NCEP/NCAR Reanalysis



- The accepted approach in evaluating climate models is to utilize anomalies rather than absolute fields.
  - If decadal anomaly trends in the current climate is correct, we have some degree of confidence in the future anomaly predictions.
  - *We have confidence in the anomalies, even if there may be biases in the absolute fields.*

Climate Model Fields *(SST in MDR)*

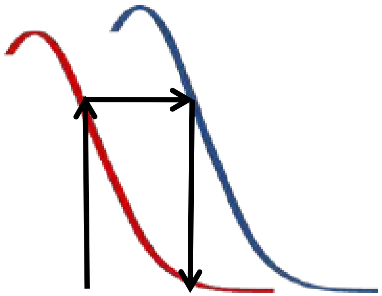


Correcting Biases

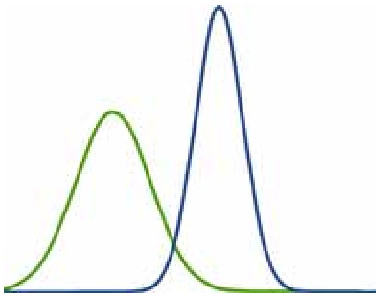
Altering the mean state

Perturbing current climate (Pseudo Global Climate Warming)

Quantile-Quantile mapping

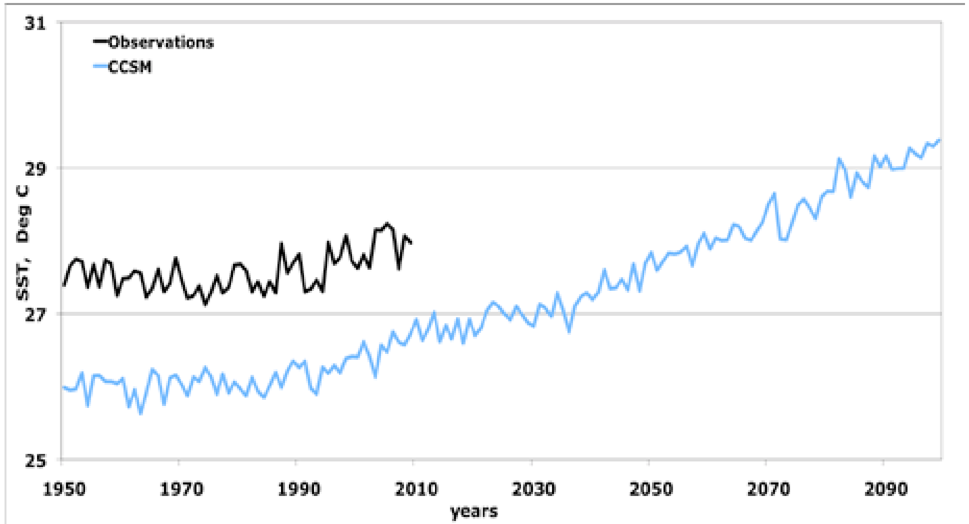


Altering the mean and variance

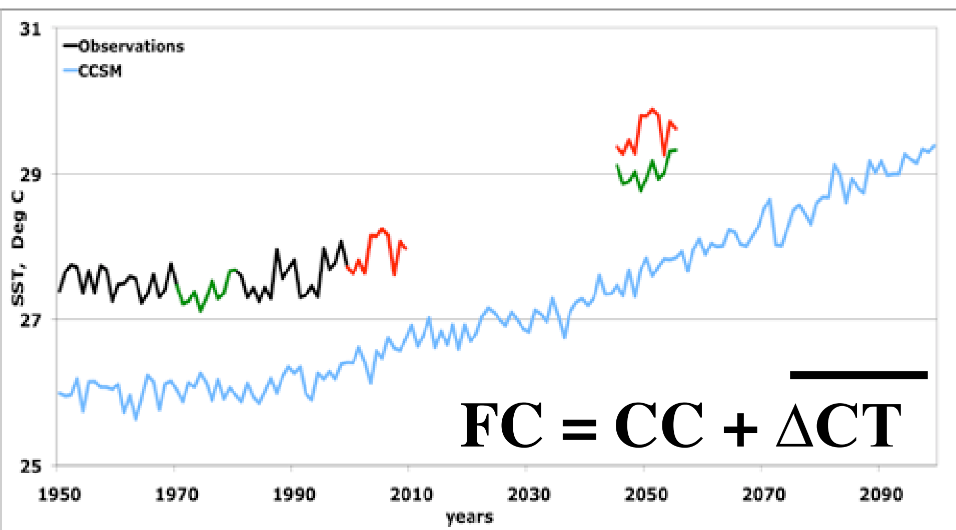


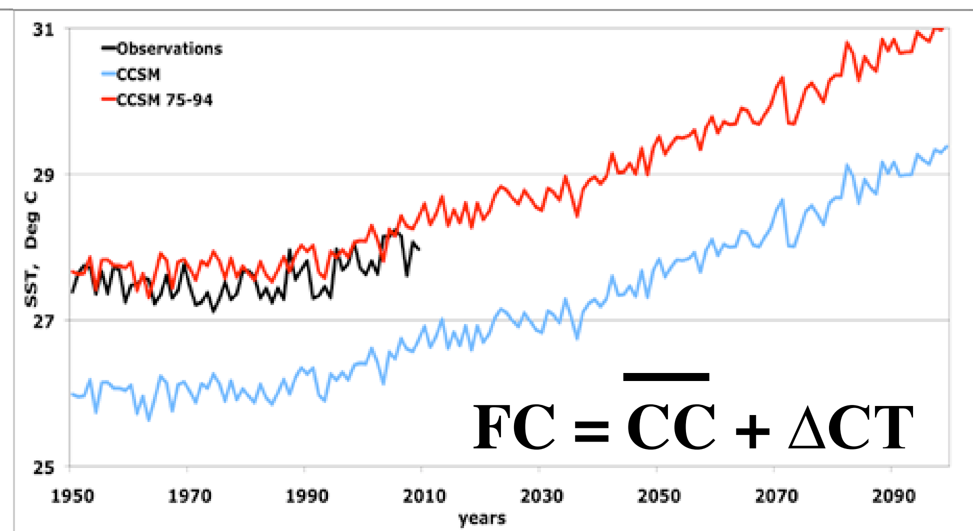
Biases in Climate Model Data

Use current climate variability, and perturb with an estimated climate change



Use a current climate average and the predicted future climate tends and variability





Bias Correction

- Describe 6-hourly CCSM data for entire simulation (1950-2060) as an average annual cycle plus a perturbation term:

$$CCSM = \overline{CCSM} + CCSM' \quad (1)$$

  - using a 20-year averaging period (1975-1994),
  - applied to variables: *U,V,Z,T,RH,Surface T and PMSL*

- Do the same for NCEP-NCAR Reanalysis data:

$$NNRP = \overline{NNRP} + NNRP' \quad (2)$$

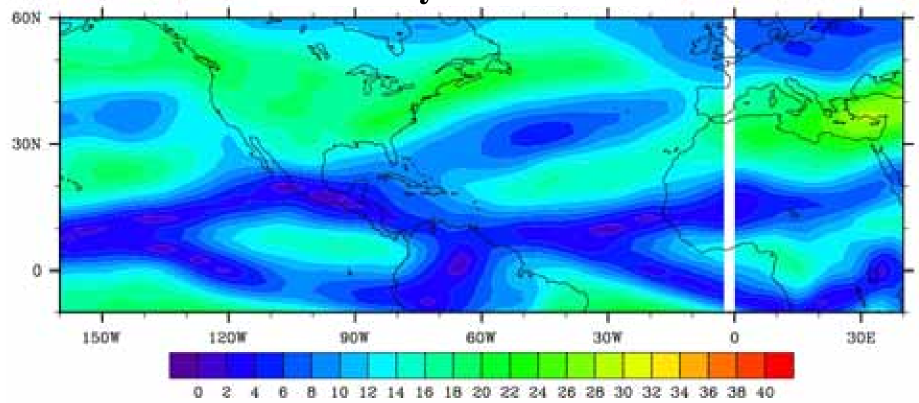
- Replace $\overline{CCSM}$ with $\overline{NNRP}$:

$$CCSMc = \overline{NNRP} + CCSM' \quad (3)$$

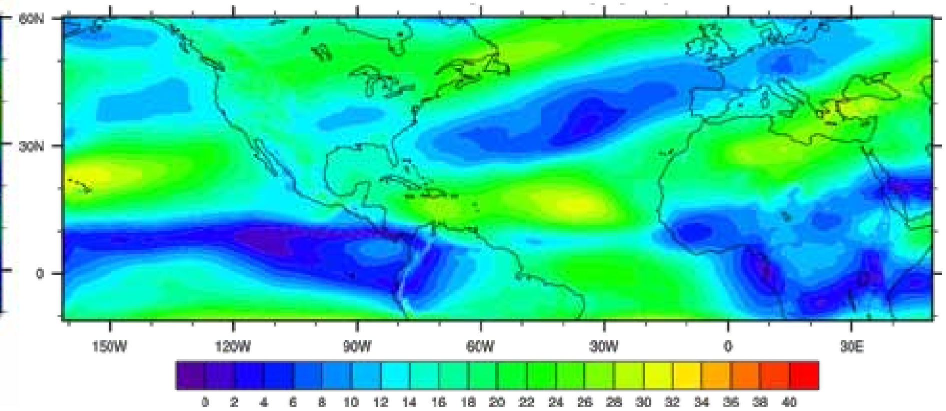
- Base climate provided by NCEP-NCAR Reanalysis data and the weather and climate change signal provided by CCSM

Sensitivity Studies

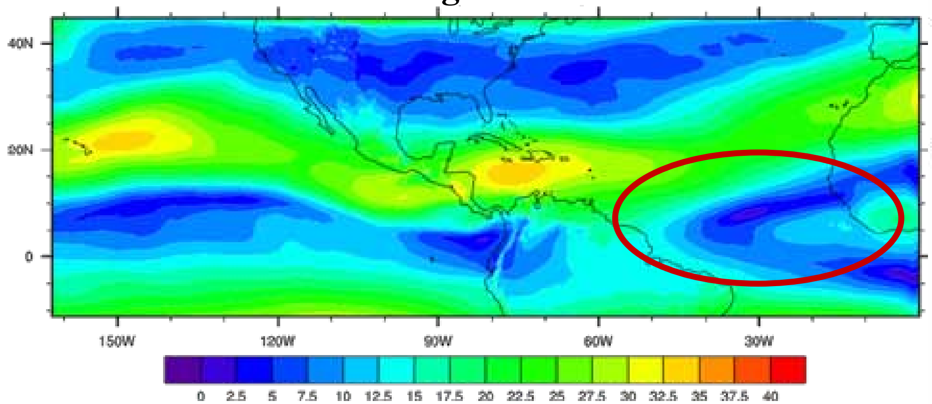
NCEP/NCAR Reanalysis



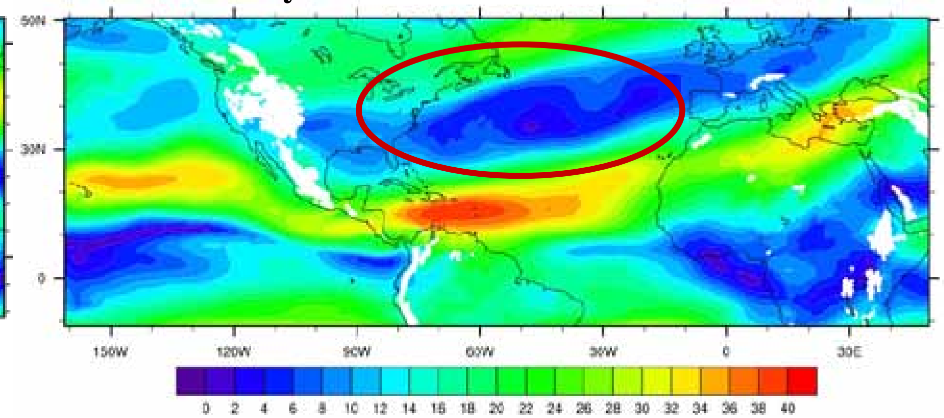
NRCM



NRCM + channel configuration



NRCM + Reynolds SST



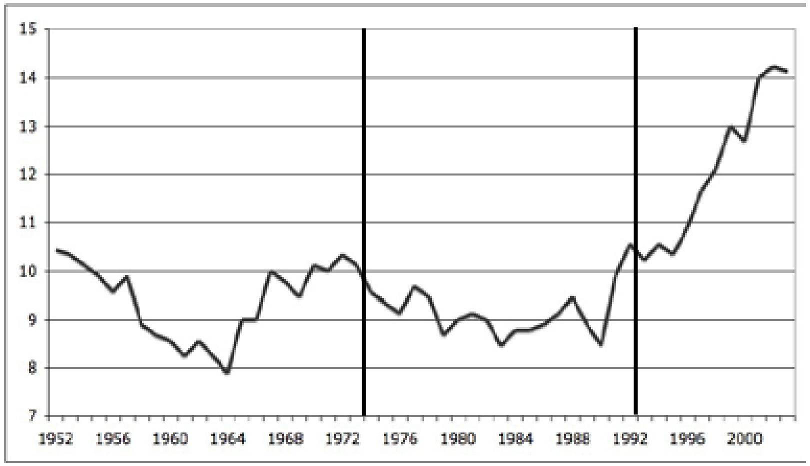
Choice of Base Period

The 20-year period of 1975-1994 was chosen based on:

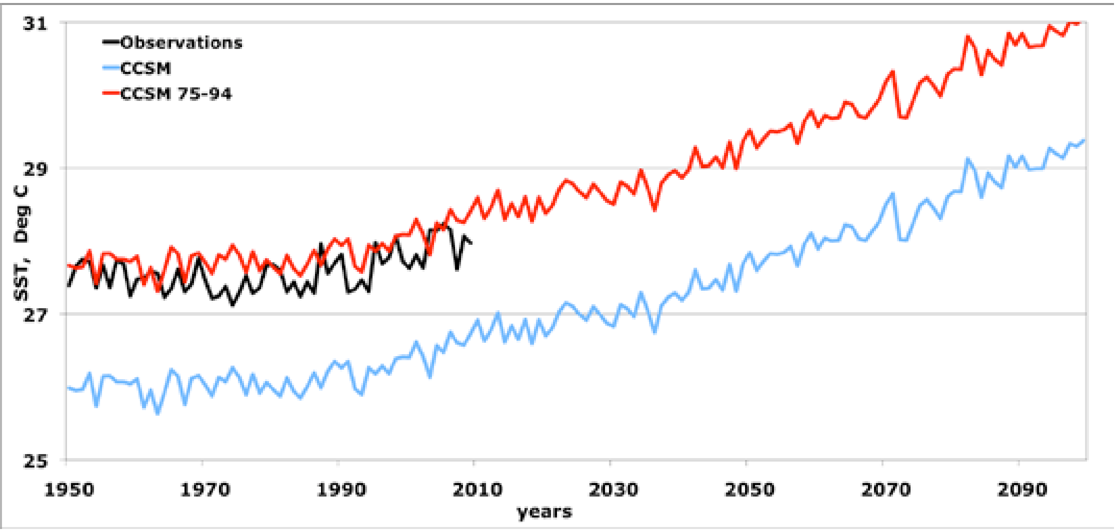
- long enough time to smooth out El Niño oscillation
- quality of data prior to 1970’s is questionable
- exclude climate shift in 1990’s
- a period away from our modeling time slice of 1995-2005

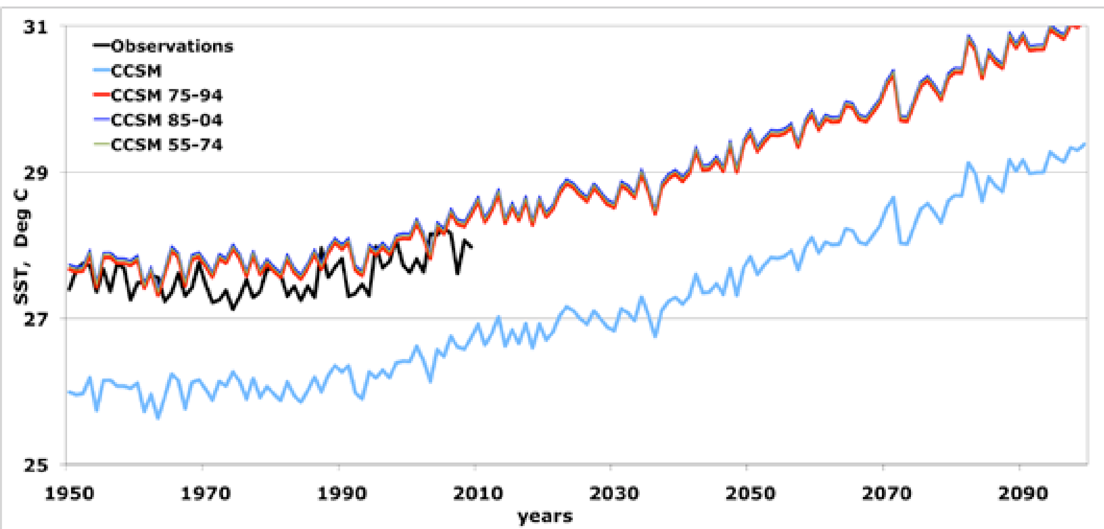
Caution: Multi-decadal variability, climate trends and shifts.

- 1975-1994 (average 8.9 TC/y)
- 1995-2005 (average 14.3 TC/y)

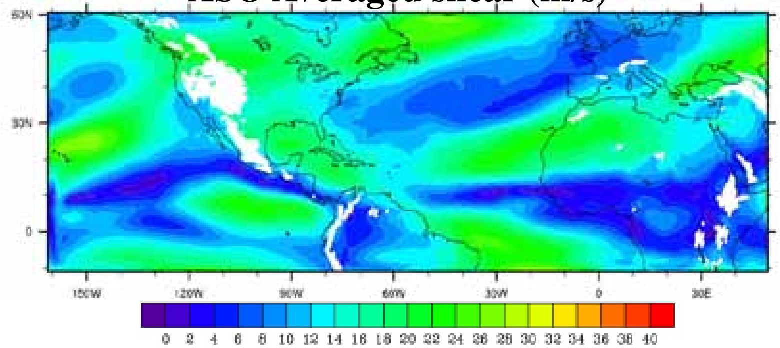


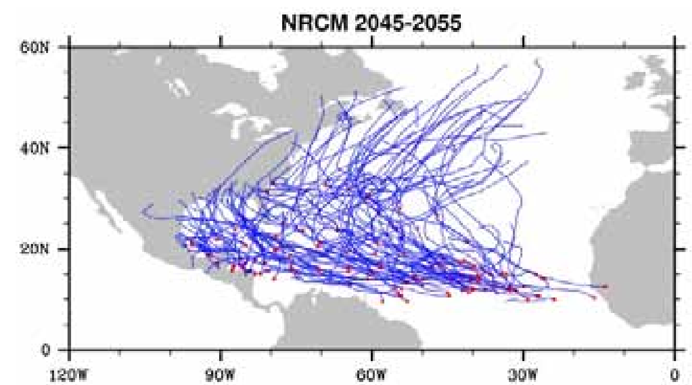
Choice of Base Period





Adjusted N. A. Regional Climate ASO Averaged shear (m/s)

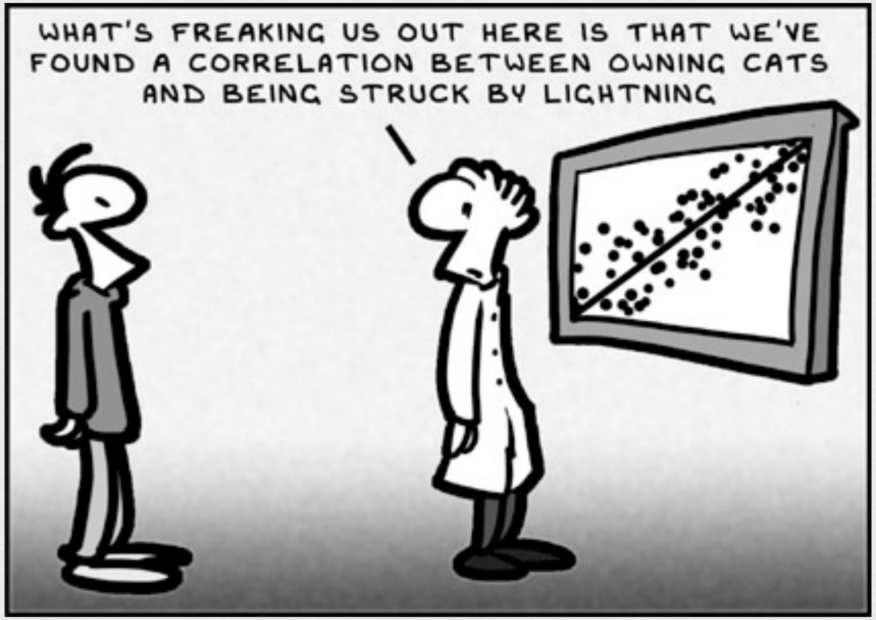




Hybrid Statistical-Dynamical Approach to Regional Climate Prediction

Greg Holland and many others

Regional Climate Research Section
NCAR Earth System Laboratory



NCAR is Sponsored by NSF and this work is partially supported by the
Willis Research Network, the Research Program to Secure Energy for America,
and NSF EASM Grant 16045

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Summary

- **Why Bother?**
- **The Weather Prediction Experience**
- **Example Approaches**
  - *Ensembles*
  - *Uncertainty Analysis (James Done)*
  - *MOS*
  - *Downscaling:*
    - *Empirical*
    - *"Weather" Generators*
    - *Direct Societal Downscaling*
  - *"Rescaling"*
    - *Extreme Value Theory*

Why Bother?

- **Society demands climate information at local levels**
- All climate models have biases and these have the highest impact at small scales
- Individual components of models (e.g. parameterization) contain errors that are situation and model dependent
- Dynamical downscaling is computer expensive and there is tentative evidence that going below, say, 20 km may not provide a benefit corresponding to the cost
- Much high-impact weather is truncated by achievable resolutions
- **Societal and Ecological modules demonstrably can benefit from a statistical interface between them and the dynamical predictions.**

The Weather Prediction Experience

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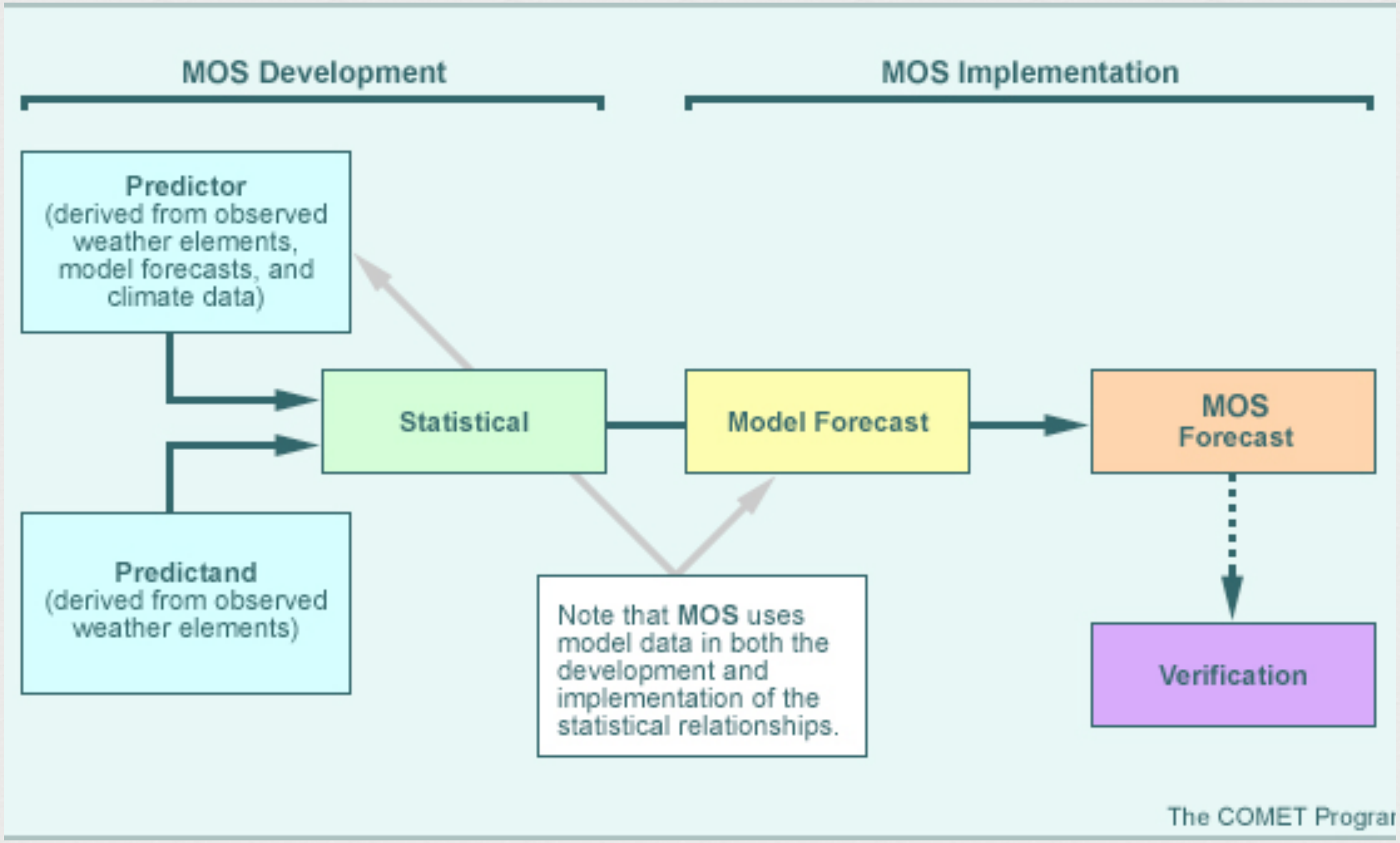
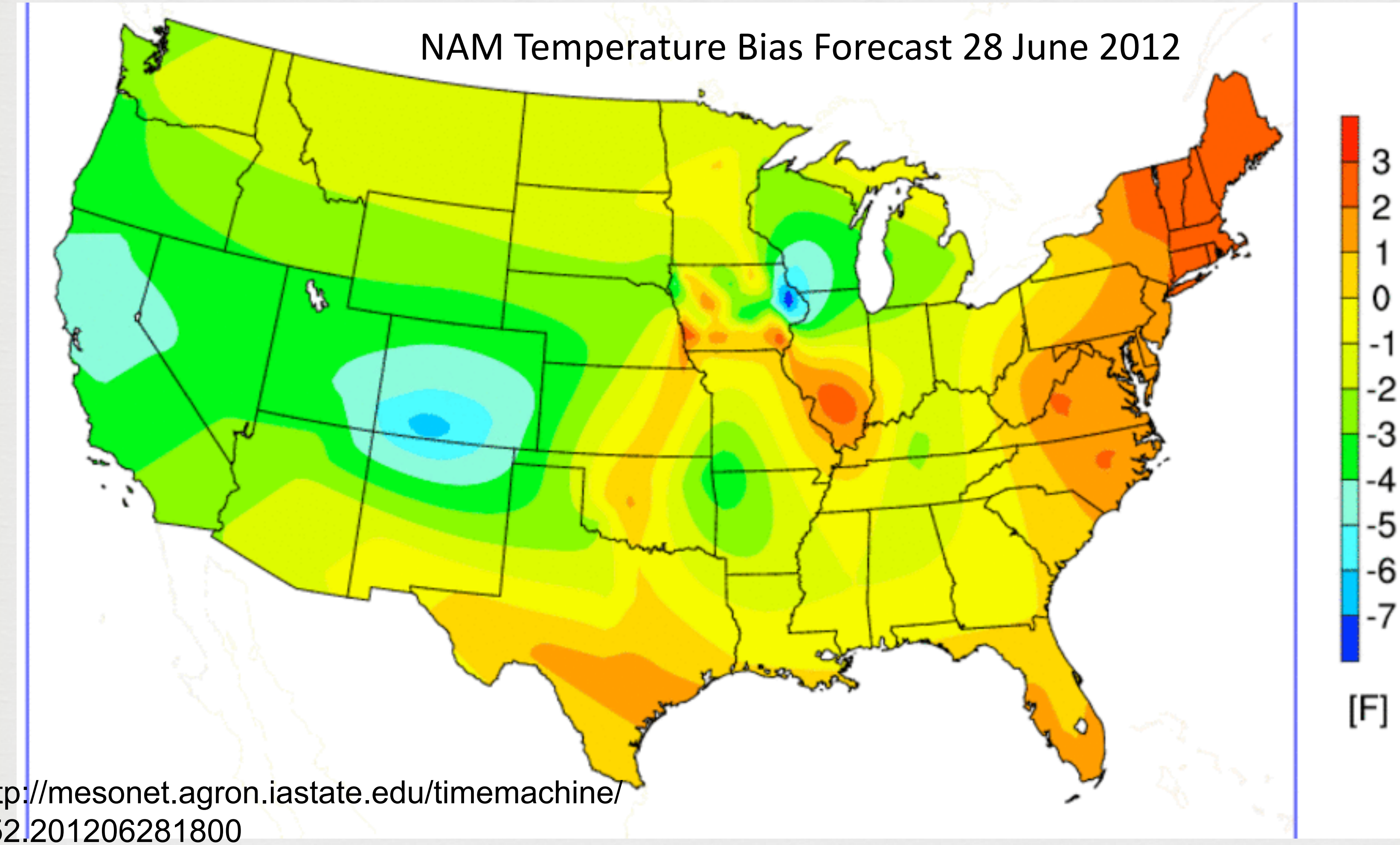
Model Output Statistcis



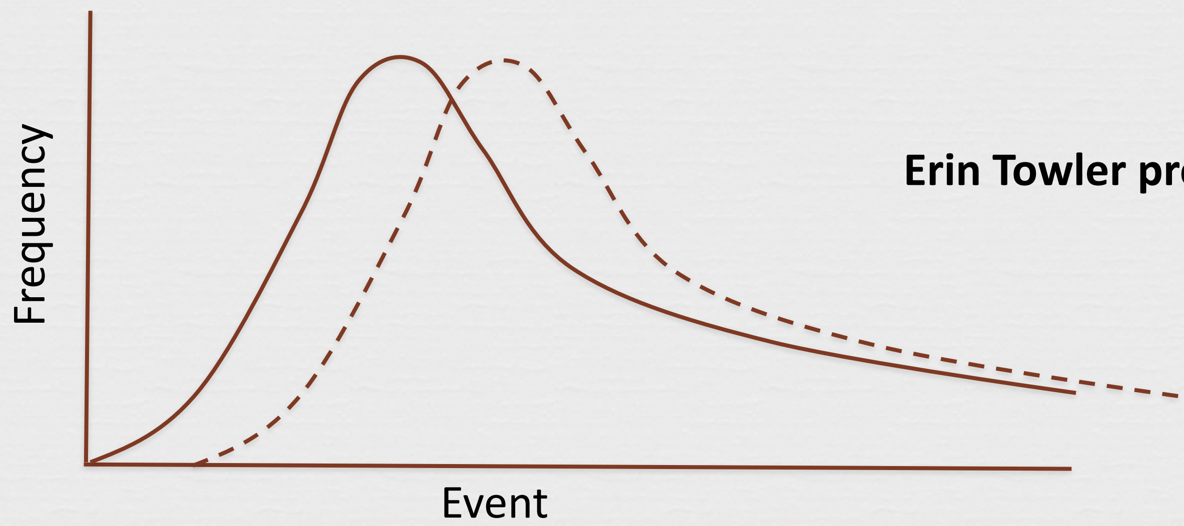
MOS Detail



http://mesonet.agron.iastate.edu/timemachine/
#52.201206281800

Statistical Downscaling

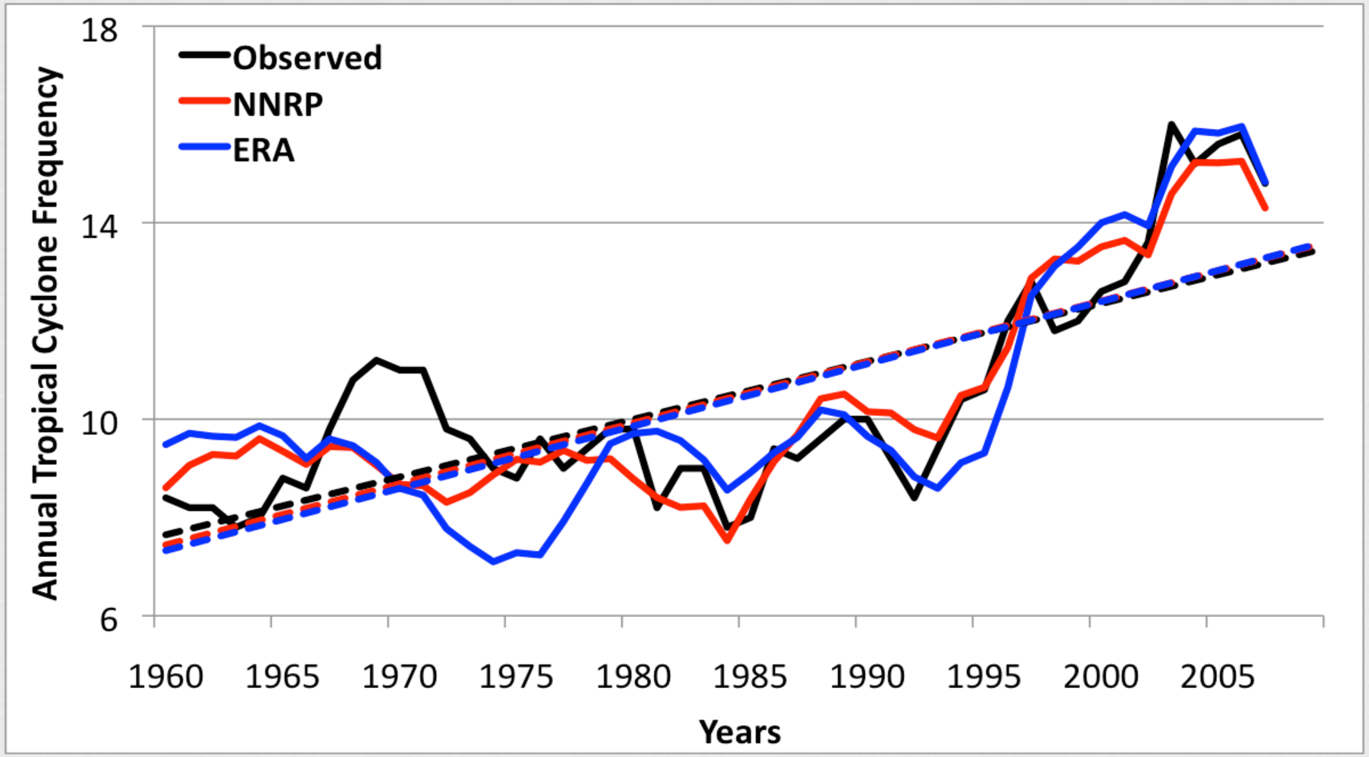
- Apply Empirical Relationships
  - *Applied to specific weather systems (e.g. hurricanes)*
  - *Applied to specific locations (perfect prog. approach)*
- Weather Generators
  - *Stochastic series generated from observed weather characteristics at a specific location (can be spatial)*



Erin Towler presentation

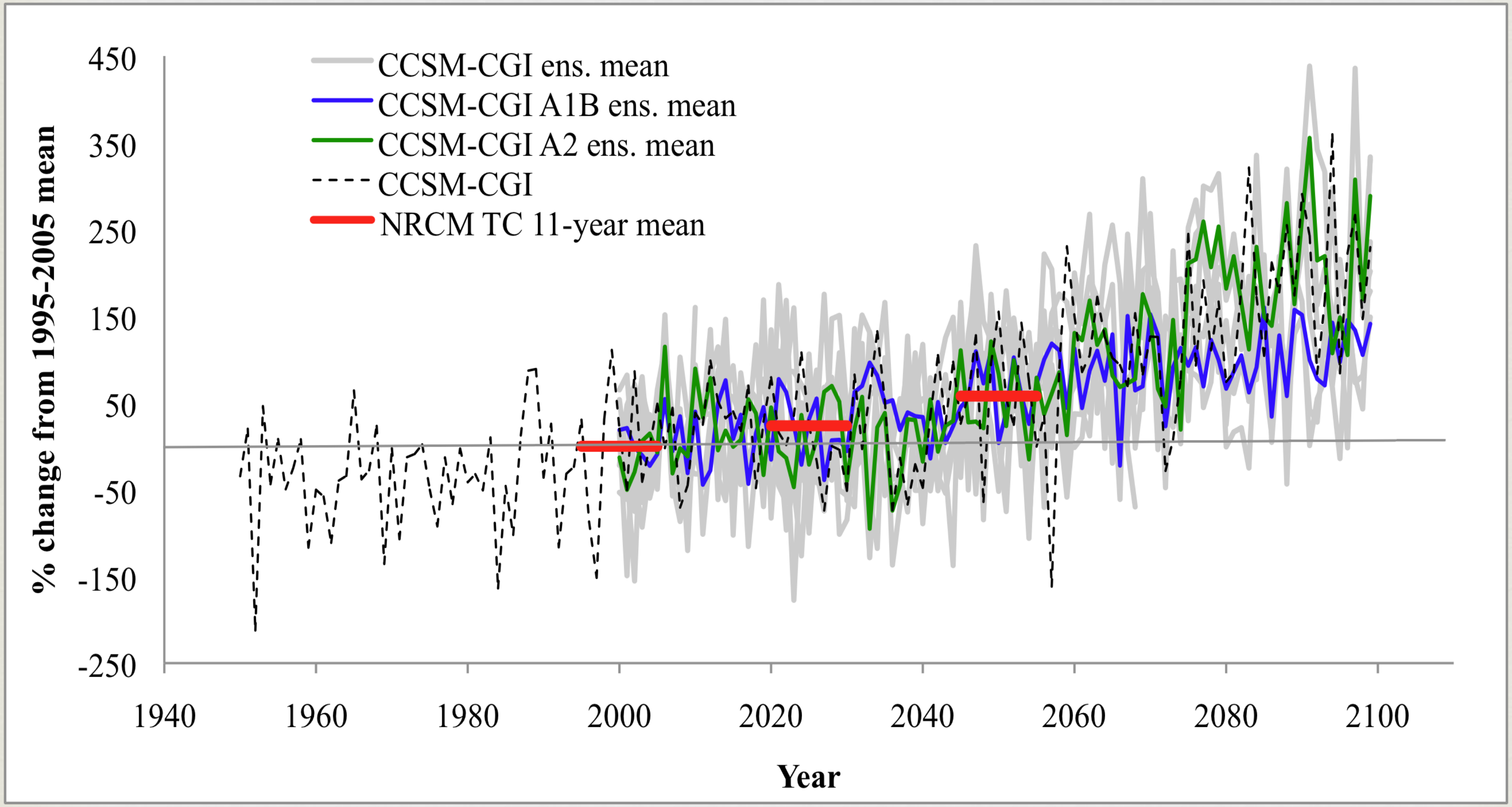
Example: The Cyclone Genesis Index

$$CGI = \left(\frac{PI}{70}\right)^3 \left(1 + 0.1(V_{shear} + a)\right)^{-2}$$



(Bruyere et al 2012)

Climate Applications



Direct Societal Application

- Most societal impacts go via an extended path, e.g.

Model Prediction….Statistical Downscaling…..Impacts Model

- The extra steps introduce additional errors
- If possible a single-step approach will almost always be better.

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Example:
Cyclone Damage Potential

$$CDP = 4\frac{[(\frac{v_m}{65})^3 + 5(\frac{R_h}{50})]}{v_t},$$

$$For\, v_m > 65;\ if\ v_t < 5,\ set\ v_t = 5;$$

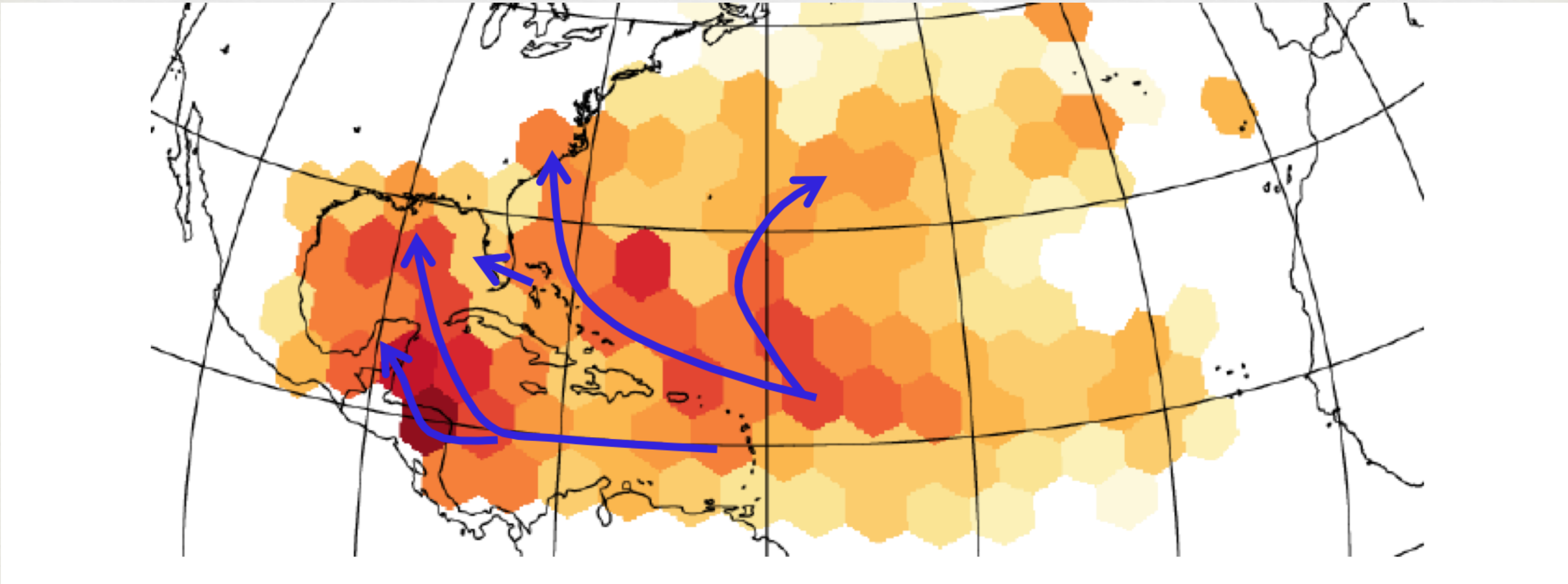
$$if\ CDP > 10\ set\ CDP = 10.$$

- Will require scaling to accommodate varying structures and engineering design levels for explicit damage assessment.

- We are developing the CDP to work directly from proportion of insured loss compared to the total portfolio. This removes difficulties with assessing direct absolute damage.

(Holland and Done AGU 2011)

Damage Potential Paths
Historical Tropical Cyclones



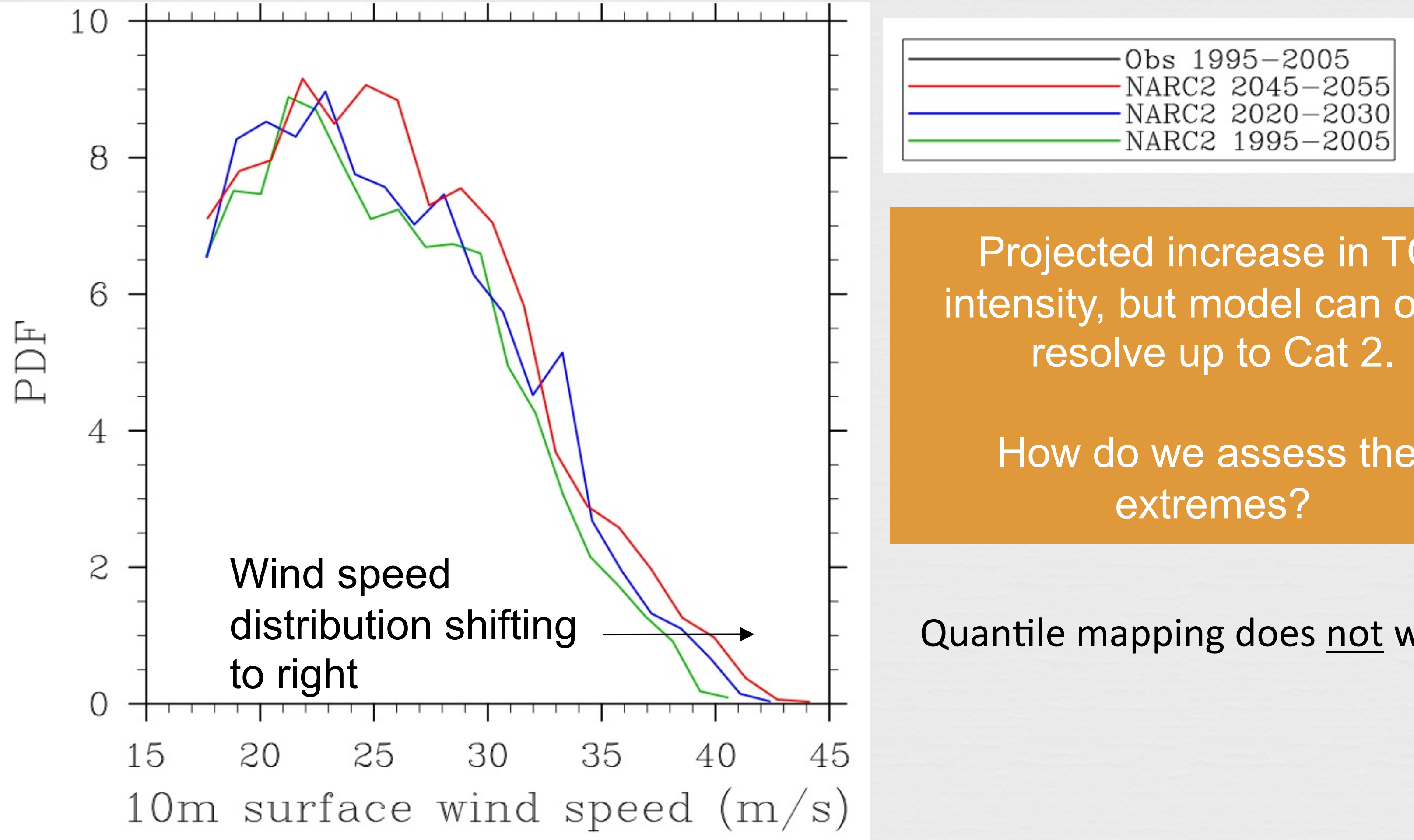
(Done 2011)

Potential Future Changes: Gulf of Mexico

	1995-2005	2020-2030	2045-2055
# Tropical Cyclones	16	13	11
# 6-hourly data points	108	75	33
Average V_m (kt) Max V_m (kt)	55 87	63 91	50 88
Average R_{max} (nm)	49	31	34
Average V_t (kt)	12	15	19
Average CDP Max CDP	4.6 7.7	4.5 8.1	2.2 5.0

(Done et al 2011)

Rescaling



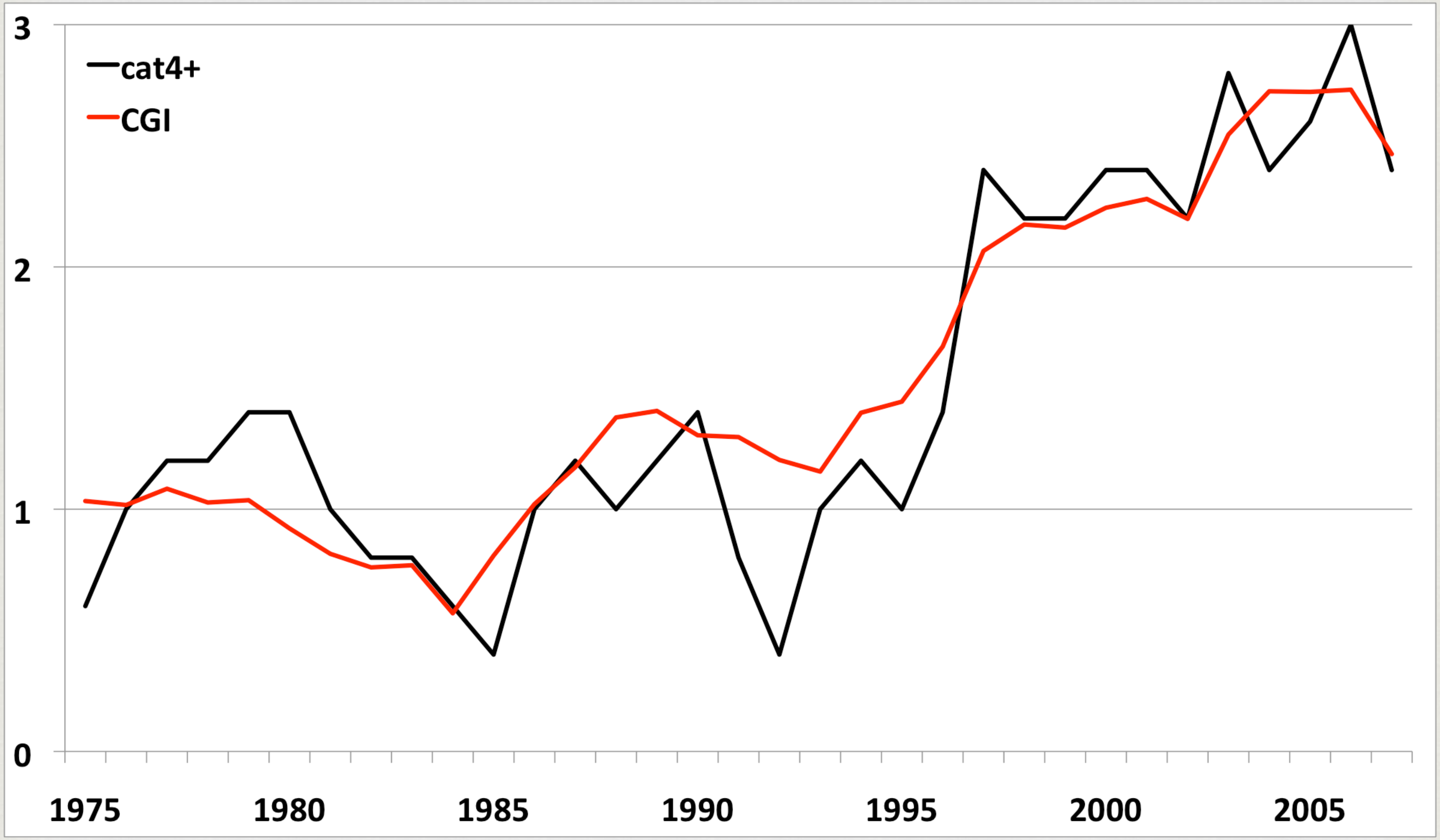
Projected increase in TC intensity, but model can only resolve up to Cat 2.

How do we assess the extremes?

Quantile mapping does not work

(Holland and Suzuki 2012)

Empirical (CGI)



EVT Approach

- Create PDF of the field of interest for current climate
  - *e.g hurricane intensity, daily rainfall, daily maximum temperatures*
- Fit an extreme distribution to this
  - *e.g. GEV, GPD, Weilbull*
  - *Note the fitting parameters, which also define the mean and SD*
- Estimate the changes to the mean and SD from the climate simulations
- Derive new estimates of the fitting parameters
- Voila!

Example: Weibull Distribution

We utilize the Weibull distribution for which the CDF and PDF are:

$$CDF = f(x) = 1 - e^{-\left(\frac{x}{a}\right)^{b}}$$

$$PDF = f'(x) = \frac{b}{a}\left(\frac{x}{a}\right)^{b-1} e^{-\left(\frac{x}{a}\right)^{b}}$$

Where parameters a and b determine the scale and the shape, respectively.

Derived Features

- Mean and SD

$$Mean : \mu := a\Gamma\left(1+\frac{1}{b}\right)$$

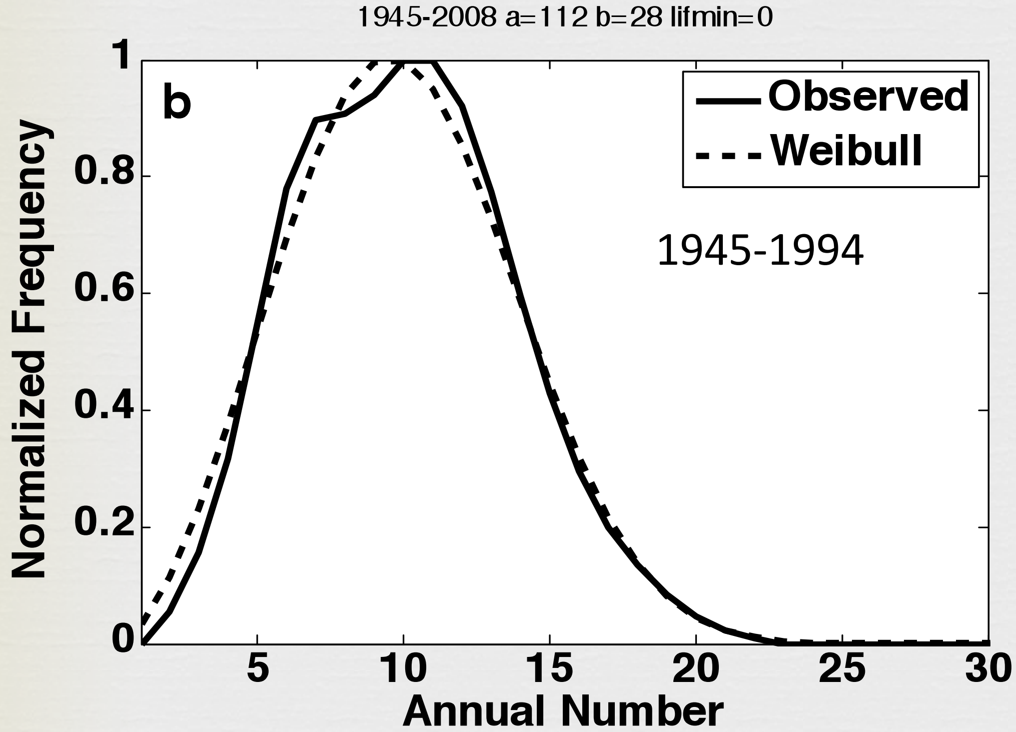
$$Variance : \sigma^2 := a^2\Gamma\left(1+\frac{2}{b}\right)-\mu^2,$$

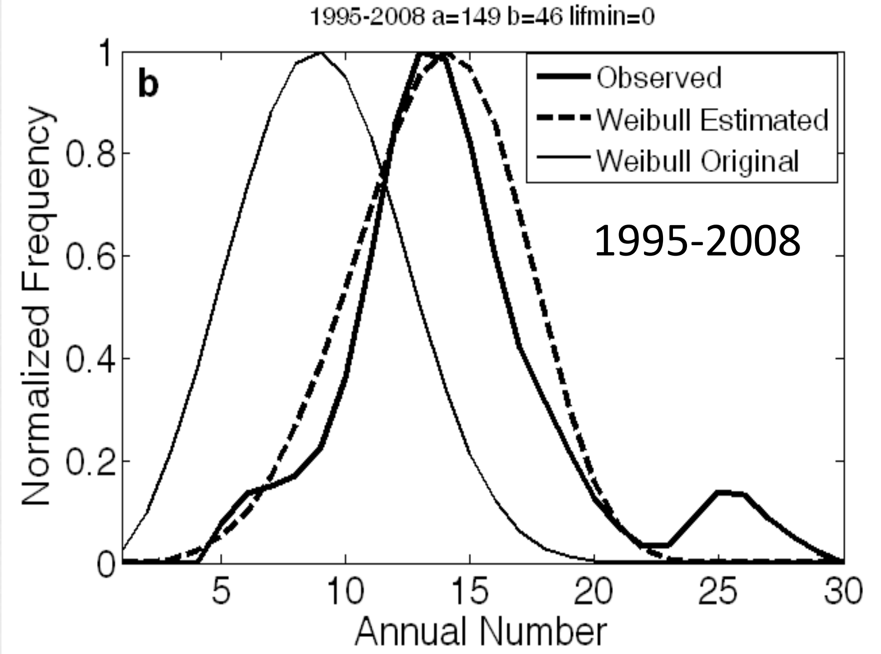
- Probability of exceeding a threshold event, E{x>c},

$$P(E\{x > c\}) = 1 - f(c) = e^{-\left(\frac{c}{a}\right)^b}$$

- The excedent likelihood decreases as the event becomes rarer (c/a increases), and/or the population less variable (b increases).

Example Application: Annual TC Frequency





(Holland and Suzuki 2012)

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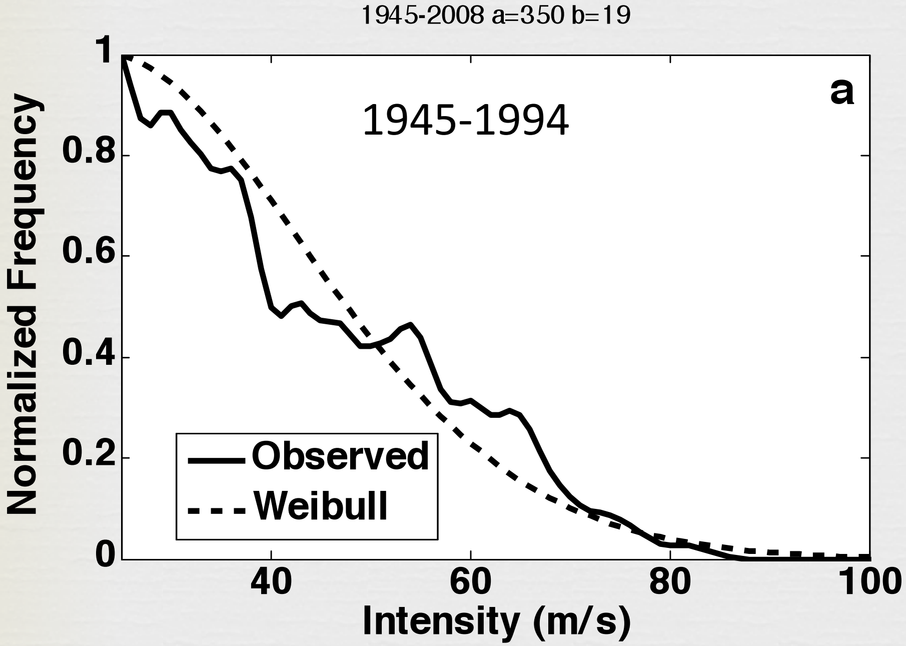
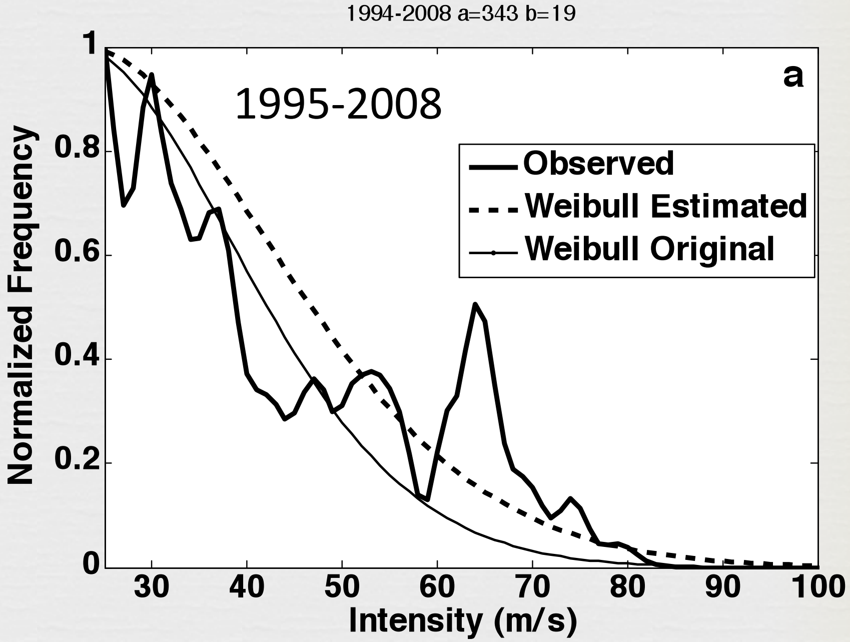
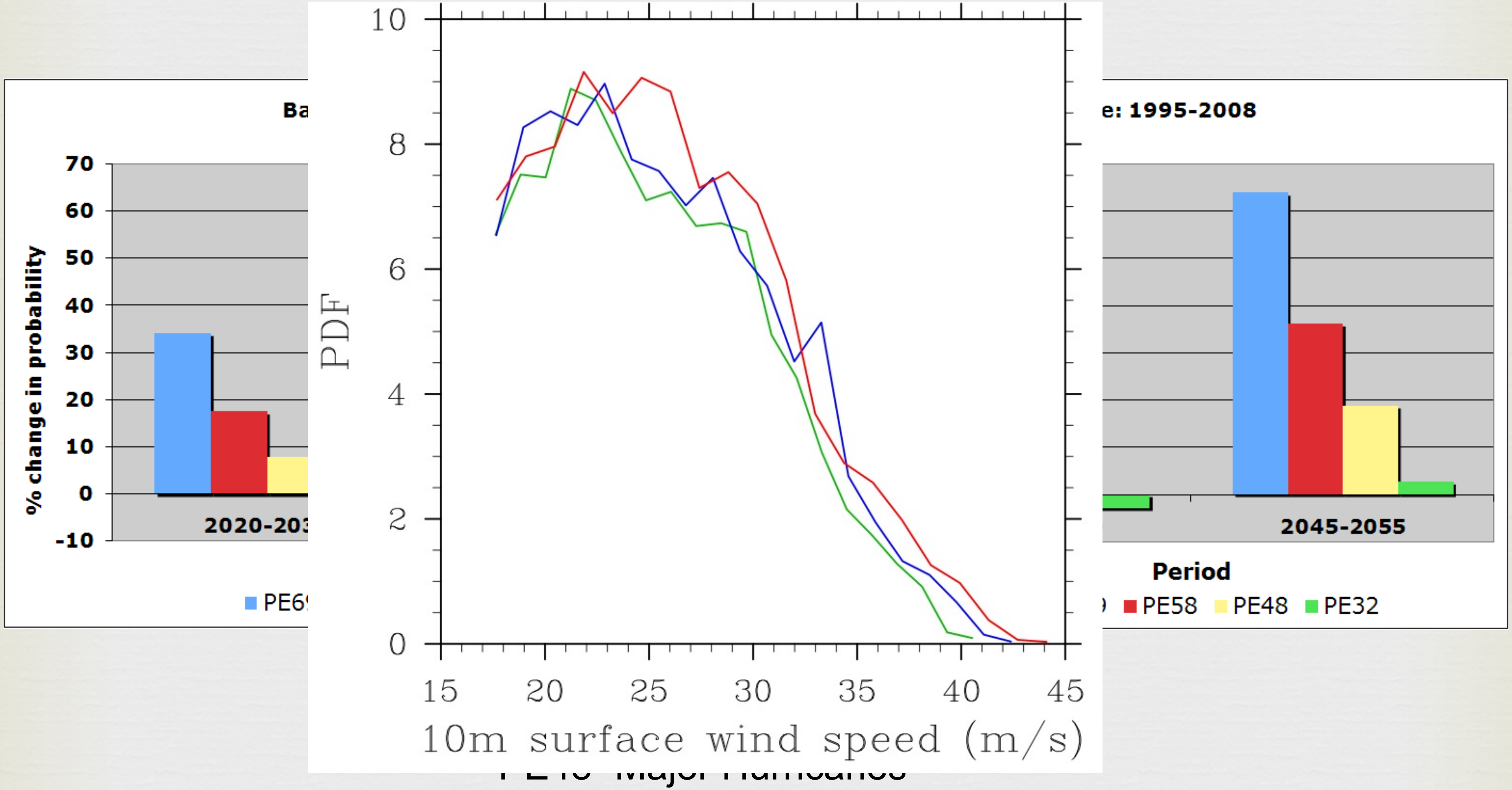
TC Intensity Example





(Holland and Suzuki 2012)

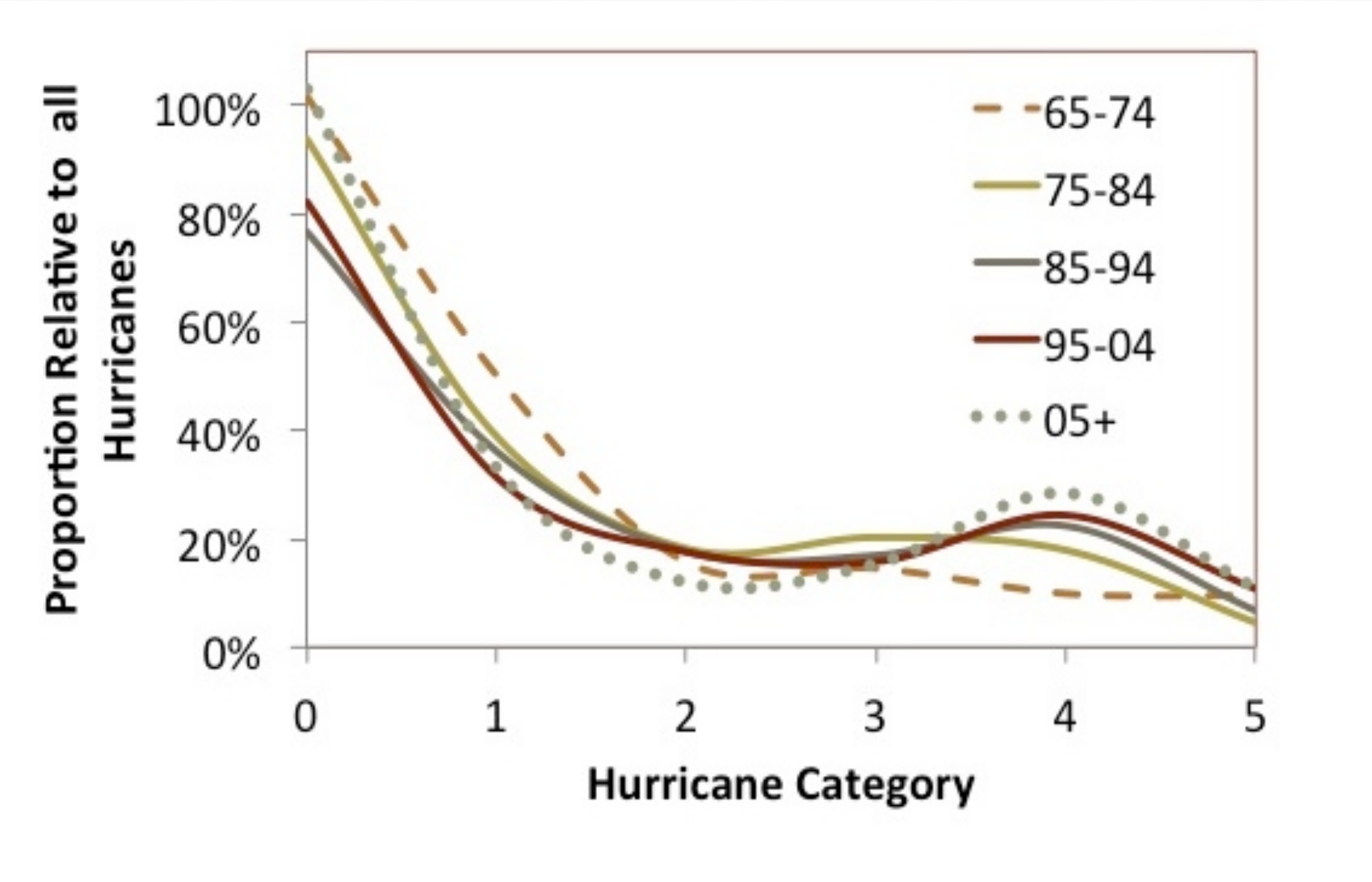
Application to NRCM Predictions



PE32=Hurricanes

(Holland and Suzuki 2012)

However!



(Holland et al 2012)

Summary

- **Hybrid Statistical-Dynamical Approaches will be an essential component of any regional climate application.**
- **Examples Include:**
  - *Ensembles*
  - *Uncertainty Analysis (James Done)*
  - *MOS*
  - *Downscaling:*
    - *Empirical*
    - *"Weather" Generators*
    - *Direct Societal Downscaling*
  - *"Rescaling"*
    - *Extreme Value Theory*
  - *Other???*

Because ***extremes*** matter:
Applications and use of model data

Regional Climate Downscaling Tutorial

June 29, 2012

Tom Galarneau, Heather Lazrus,

Debasish PaiMazumder, and Erin Towler

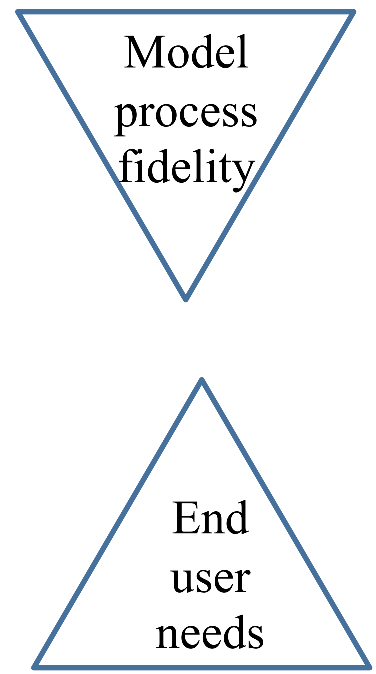
Why do we need to use a high-resolution climate model?

Because *extremes* matter

- Models resolve multi-scale processes that influence high impact weather.
- Extremes are important across disciplines and applications

How do we use regional climate modeling?

- Explore high impact weather
  - Hurricanes (Tom)
  - Drought (Deb)
- Investigate impacts
  - Eco-hydrology (Erin)
  - Societal (Heather)



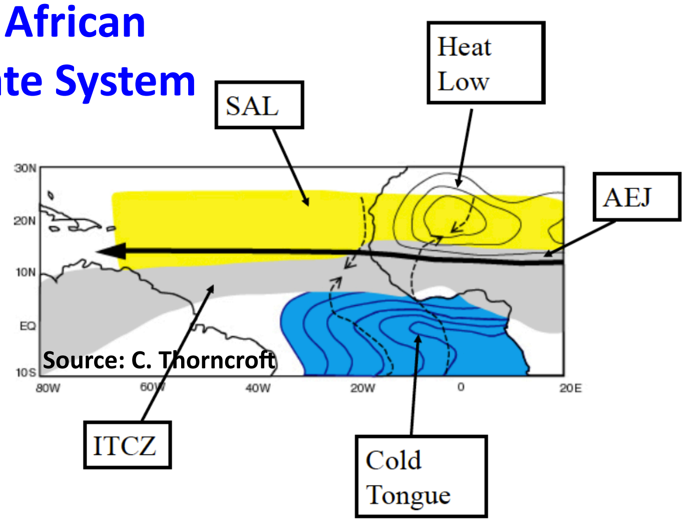
Interannual Variability of African Easterly Waves in NRCM

Thomas J. Galarneau, Jr.

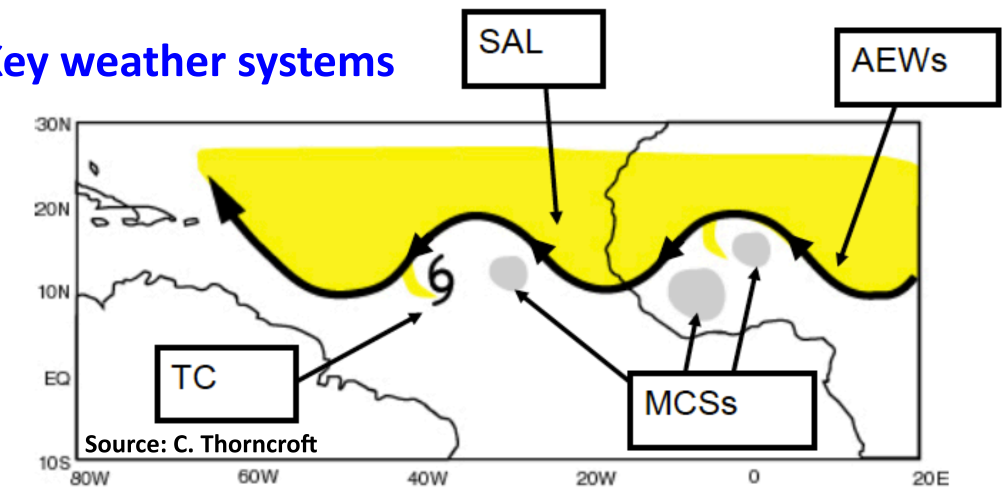
Mesoscale and Microscale Meteorology Division

National Center for Atmospheric Research

West African Climate System



Key weather systems



13th Annual WRF Users' Workshop, Regional Climate Downscaling Tutorial, 29 June 2012

Goals

- **In the dynamical downscaling framework, illustrate two possible approaches for examining the interannual variability of African easterly waves in NRCM**
  - **Track individual weather systems**
  - **Assess wave activity using Eddy Kinetic Energy**

- **Investigate interannual variability of AEWs from synoptic-dynamic meteorology perspective**

Tracking Methodology

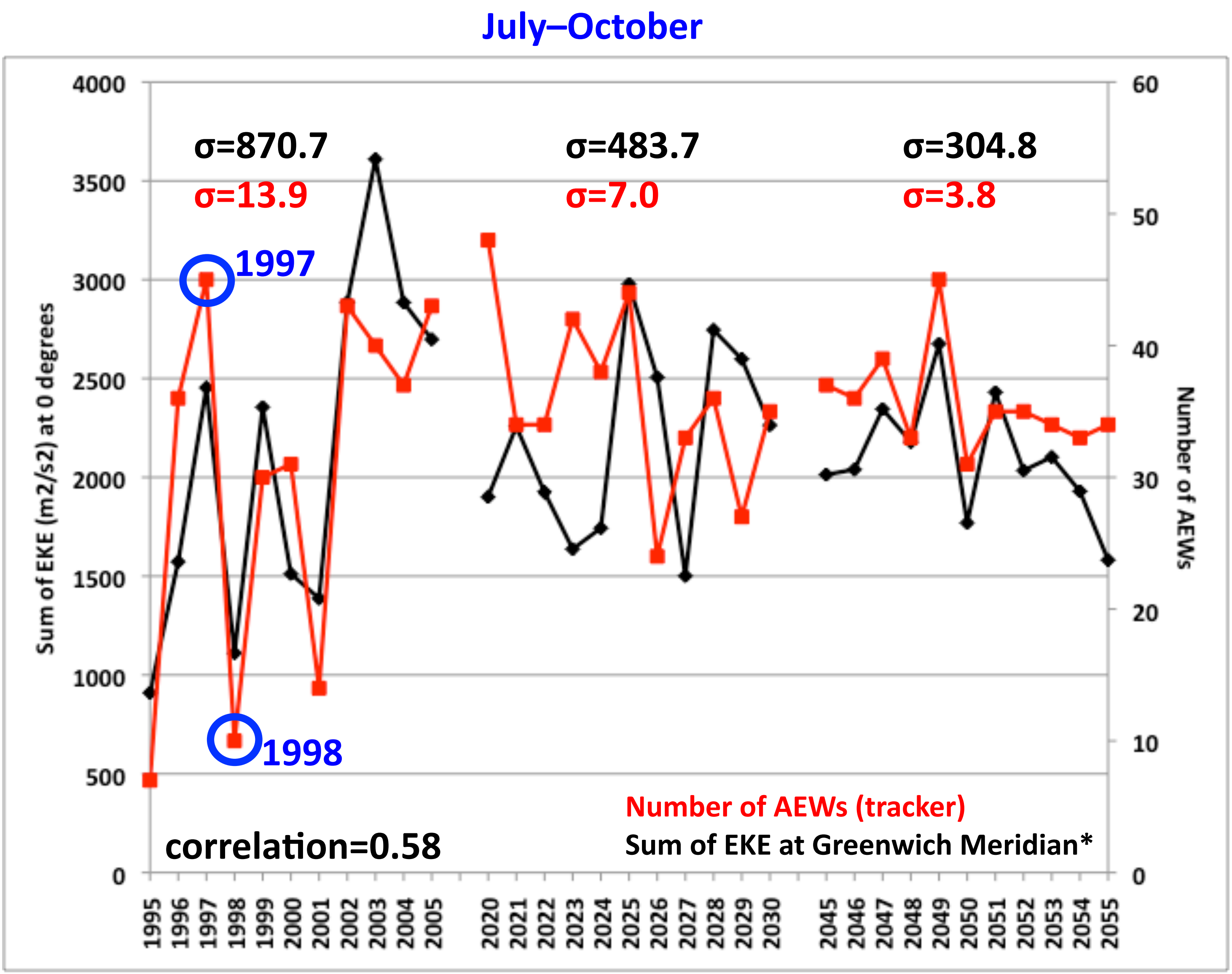
- **Track 700 mb cyclonic vorticity centers (Thorncroft and Hodges 2001)**
  - $\zeta \geq 2.0\times10^{-5}\ s^{-1}$ for $\geq$ 48 h
- **TCs identified based on structural characteristics:**
  - 10-m wind $\geq$ 17.0 $m\ s^{-1}$
  - 850-mb $\zeta \geq 1.0\times10^{-5}\ s^{-1}$
  - 300-mb T' > 850-mb T'
  - $T'_{300\text{-mb}} + T'_{500\text{-mb}} + T'_{700\text{-mb}} \geq 2$ K
  - 850-mb wind > 300-mb wind
  - Cyclone phase space parameters:
    - B<10; −VTL>0; −VTU>0

Eddy Kinetic Energy

- **Eddy energetic diagnostics based on wave energy equations developed by Lorenz (1955)**
  - **Subsequently used by Muench (1966), Norquist et al. (1977), Parker and Thorpe (1995), McTaggart-Cowan et al. (2010)**
- **Here, eddy kinetic energy (EKE) is computed at 600 mb and is defined as:**

$$EKE = \frac{\left(u'^2 + v'^2\right)}{2}$$

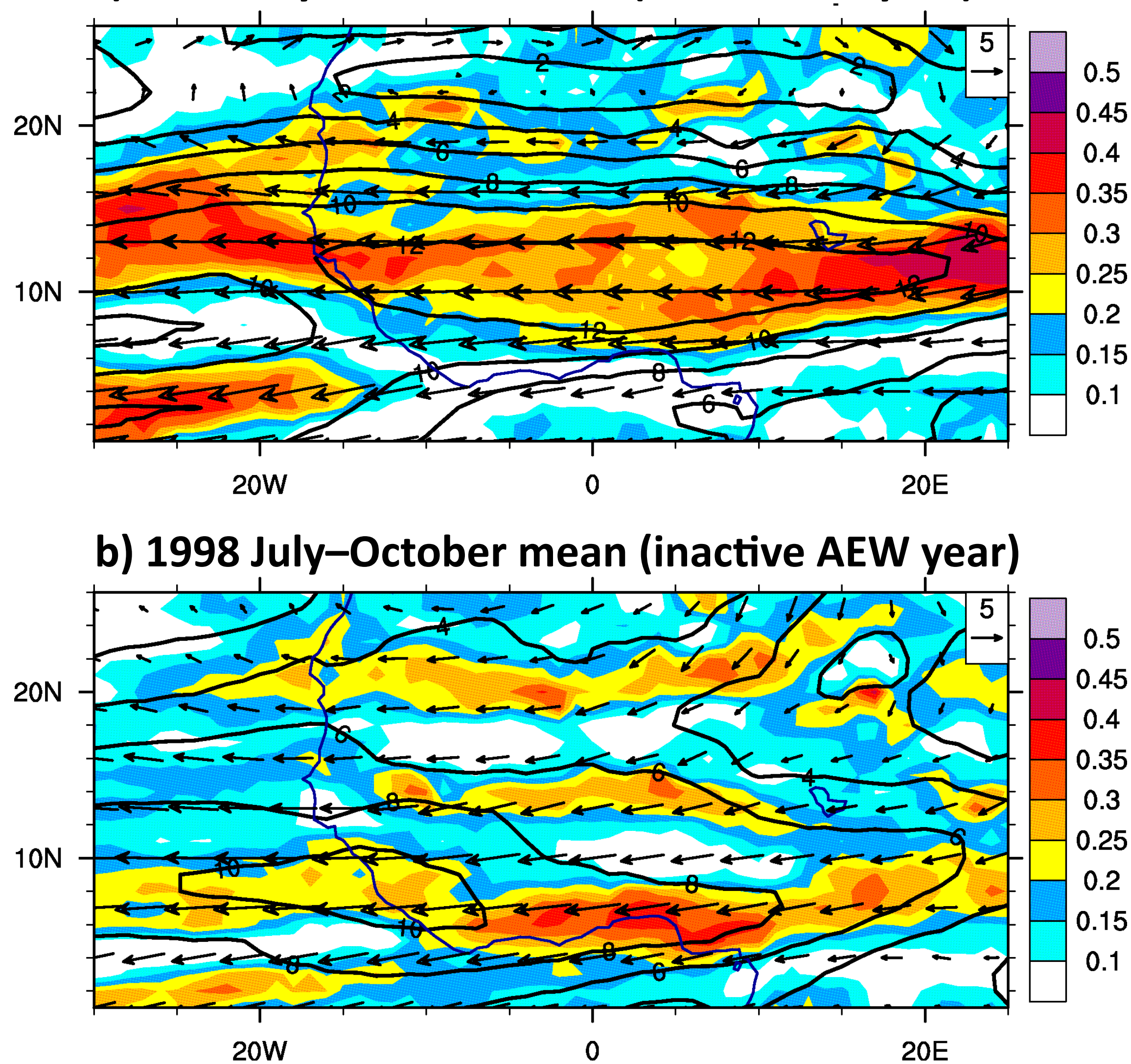
Inter-annual Variability of AEWs in NRCM



*Add 6-hourly area-average 600 mb 2–10 day filtered EKE in 5–15°N; 5°W–5°E box

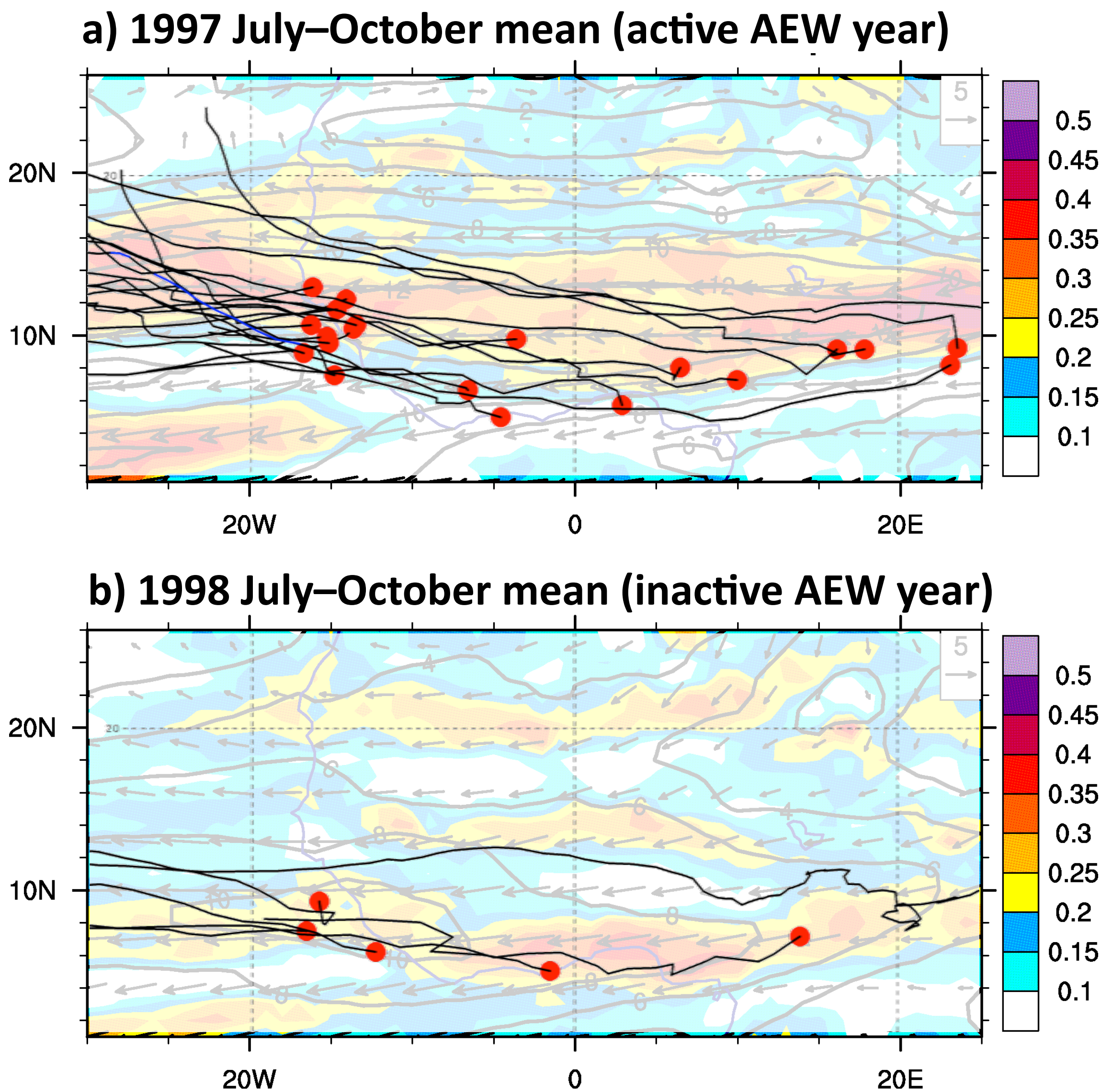
a) 1997 July–October mean (active AEW year)

b) 1998 July–October mean (inactive AEW year)



July–October mean 600 mb wind (arrows in m s^{-1}), wind speed (contours every 2.0 m s^{-1}), and frequency of barotropic instability criterion (shaded; 0.1 = 10%) for (a) 1997 and (b) 1998. The wind field was smoothed using a 7-day low-pass filter prior to computing fields. Barotropic instability criterion:

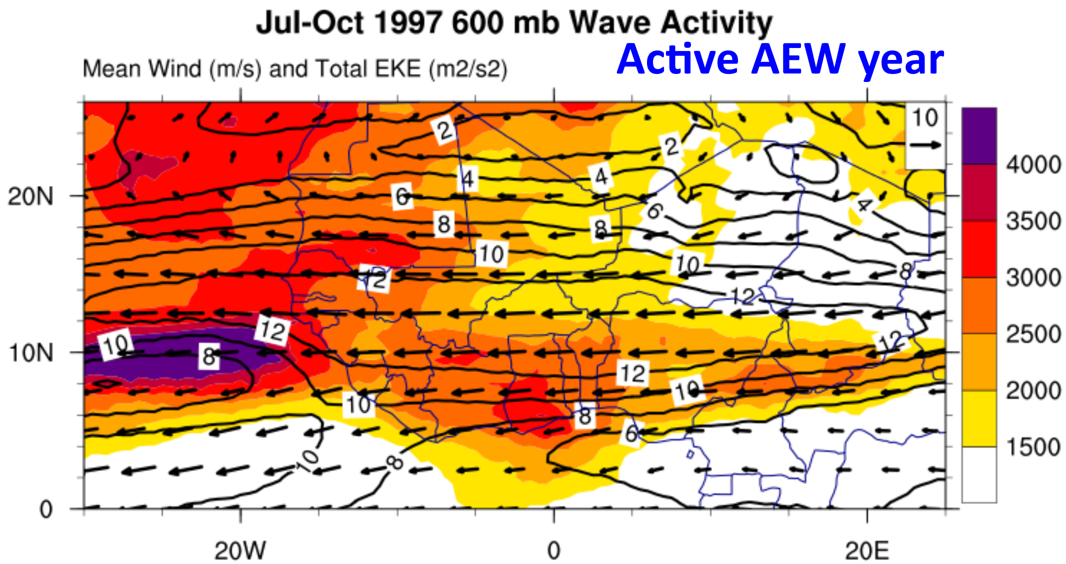
$$\frac{\partial}{\partial y}\left[f - \frac{\partial u}{\partial y}\right] < 0$$

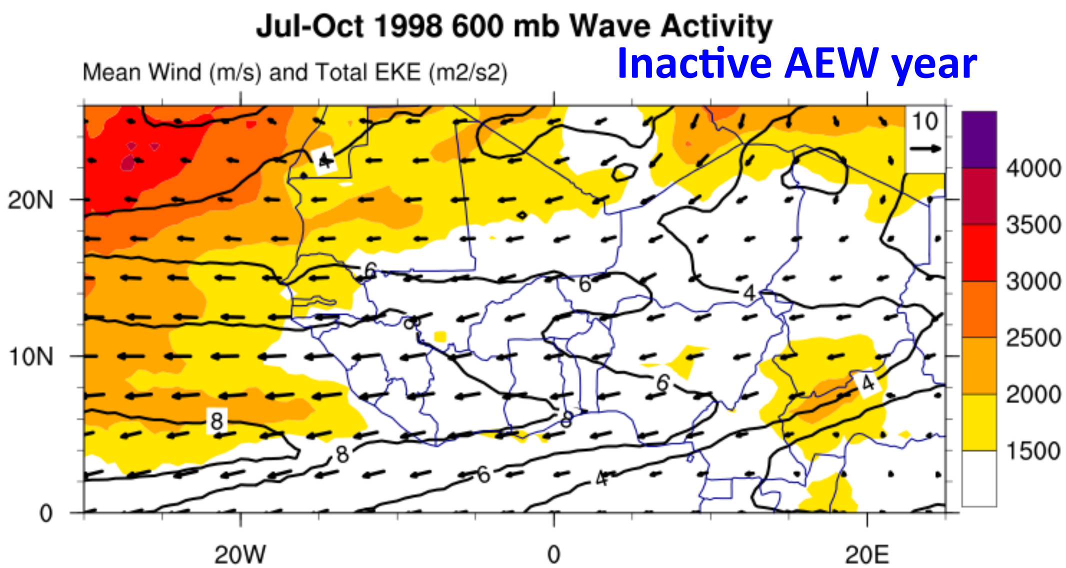


with AEW tracks

July–October mean 600 mb wind (arrows in m s^{-1}), wind speed (contours every 2.0 m s^{-1}), and frequency of barotropic instability criterion (shaded; 0.1 = 10%) for (a) 1997 and (b) 1998. The wind field was smoothed using a 7-day low-pass filter prior to computing fields. Barotropic instability criterion:

$$\frac{\partial}{\partial y}\left[f-\frac{\partial u}{\partial y}\right]<0$$





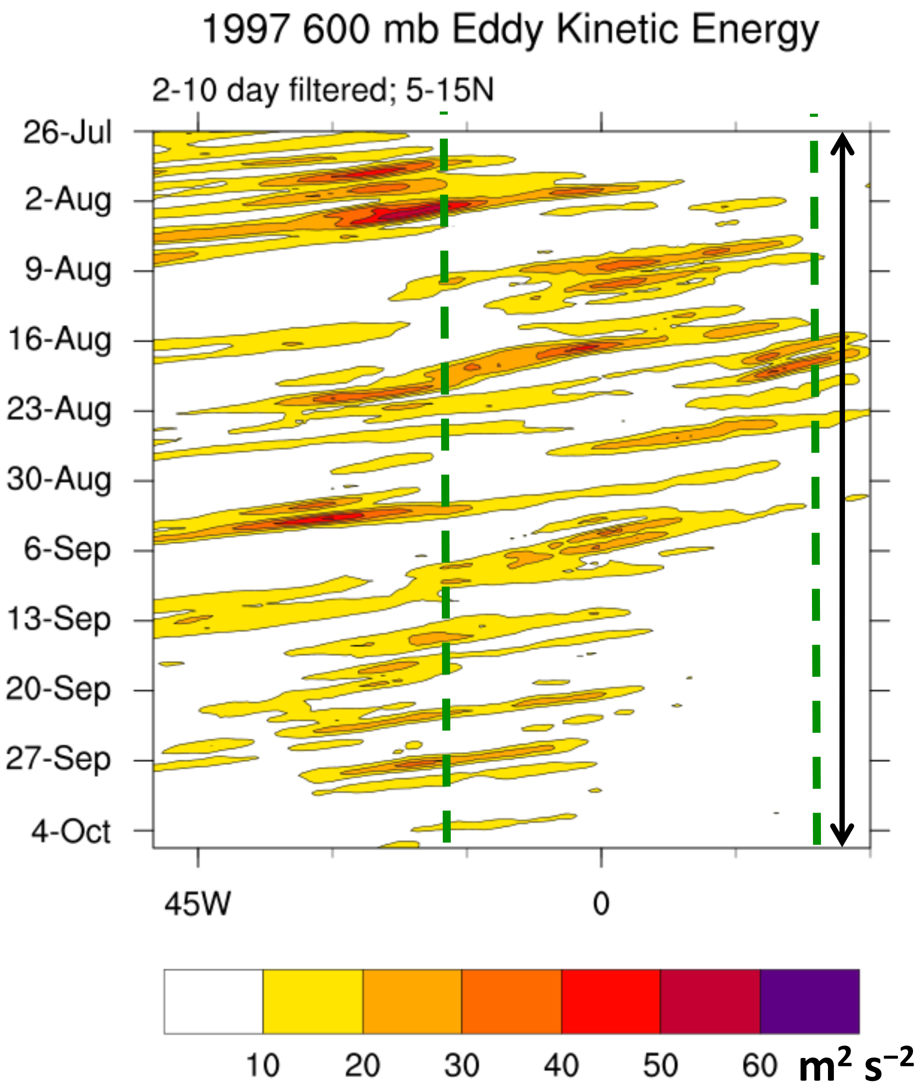
July–October mean 600 mb wind (arrows in m s^{-1}), wind speed (contours every 2.0 m s^{-1}), and total EKE (shaded in m^2 s^{-2}) for (a) 1997 and (b) 1998.

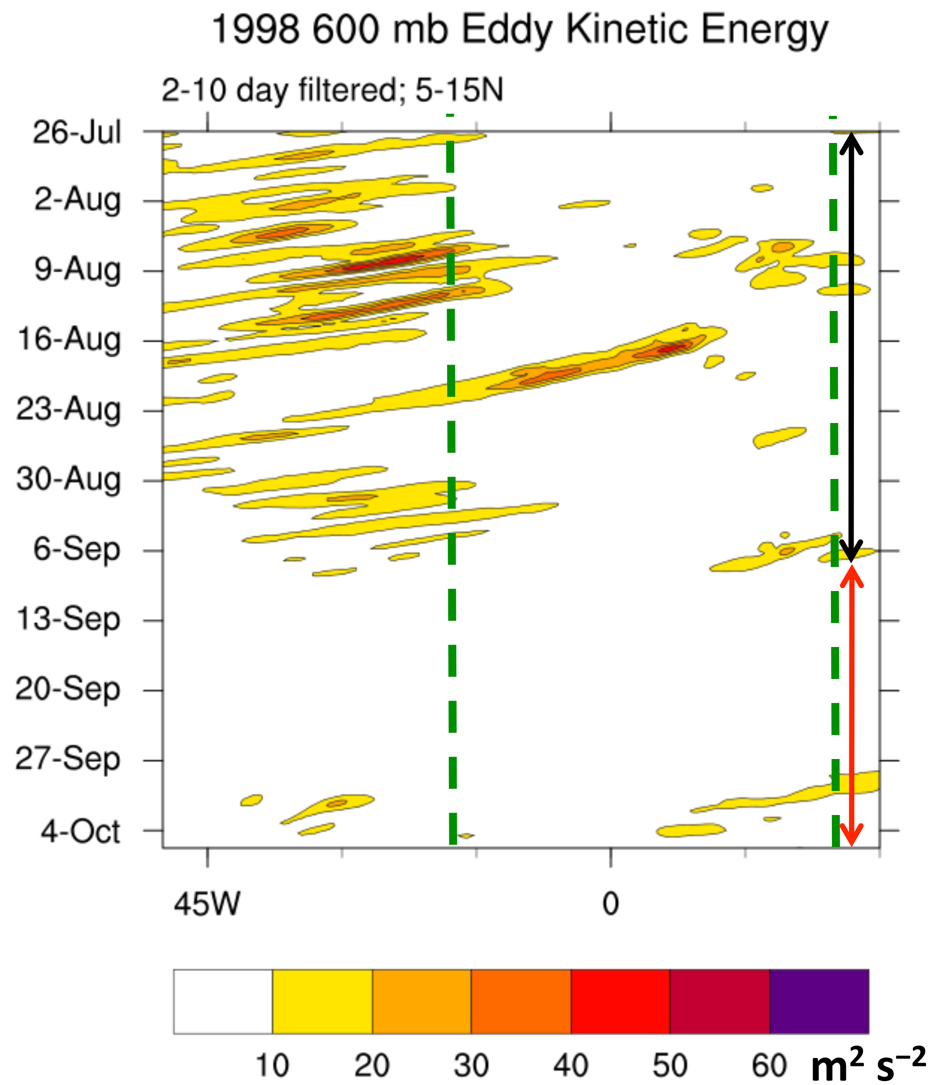
EKE was computed on the 2–10 day band-pass filtered wind.

The mean wind was computed from the 10-day low-pass filtered wind.

$$EKE = \frac{\left(u'^2 + v'^2\right)}{2}$$

AEW Activity in 1997 and 1998



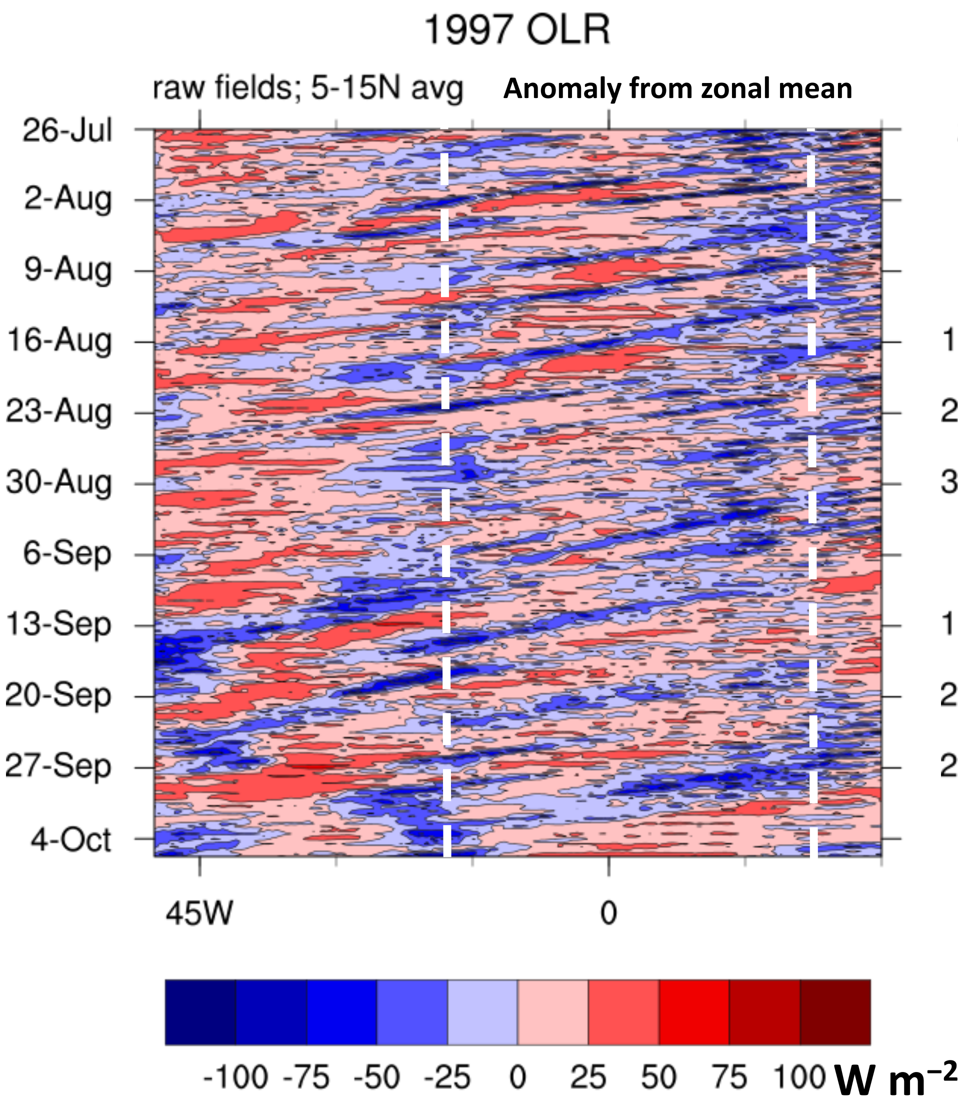


Active year

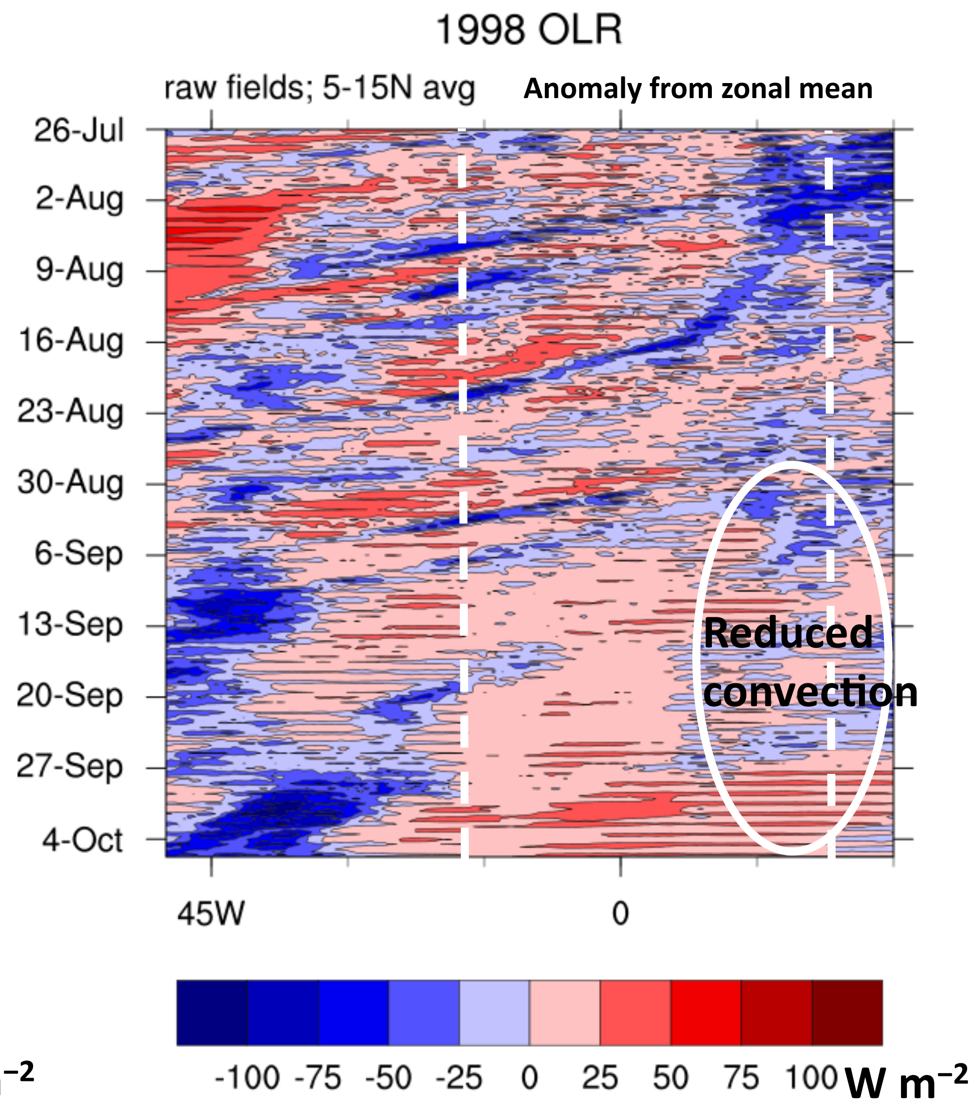
$$EKE = \frac{u'^2 + v'^2}{2}$$

Inactive year

Convection in 1997 and 1998

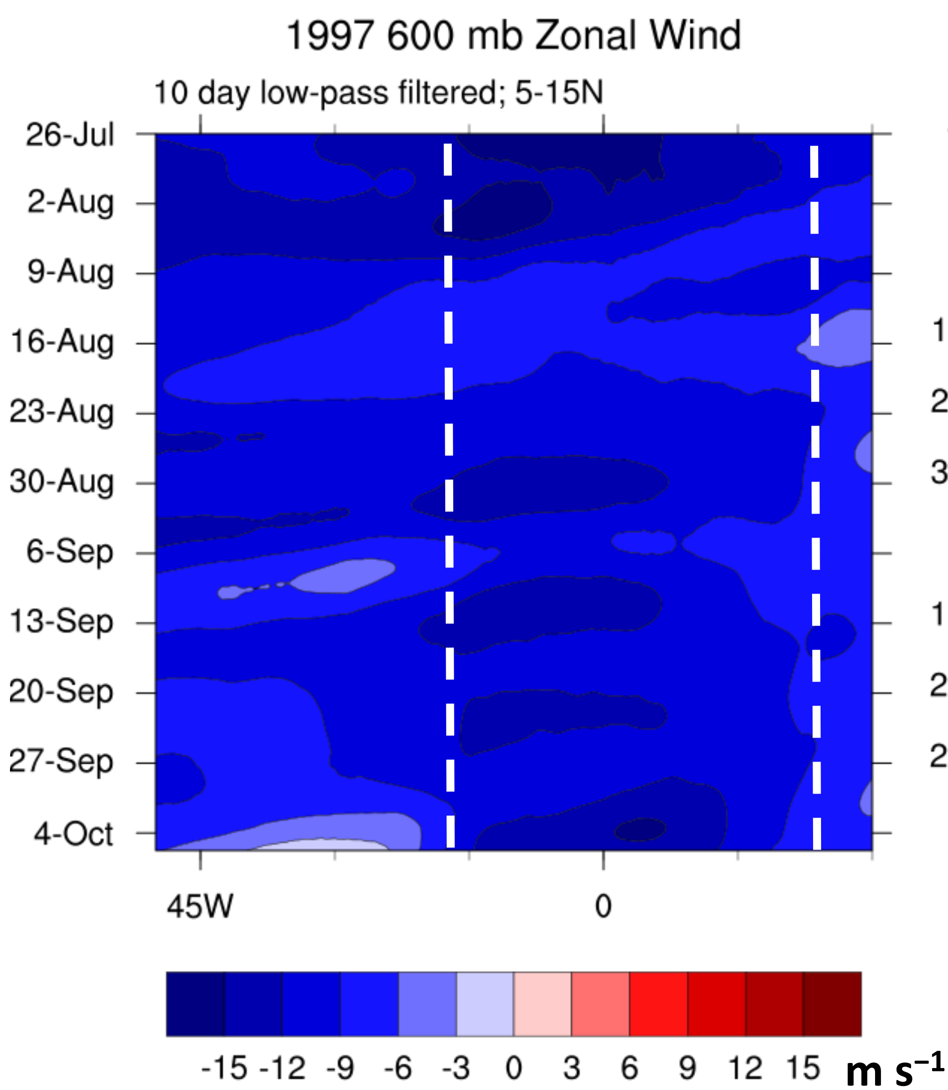


Active year

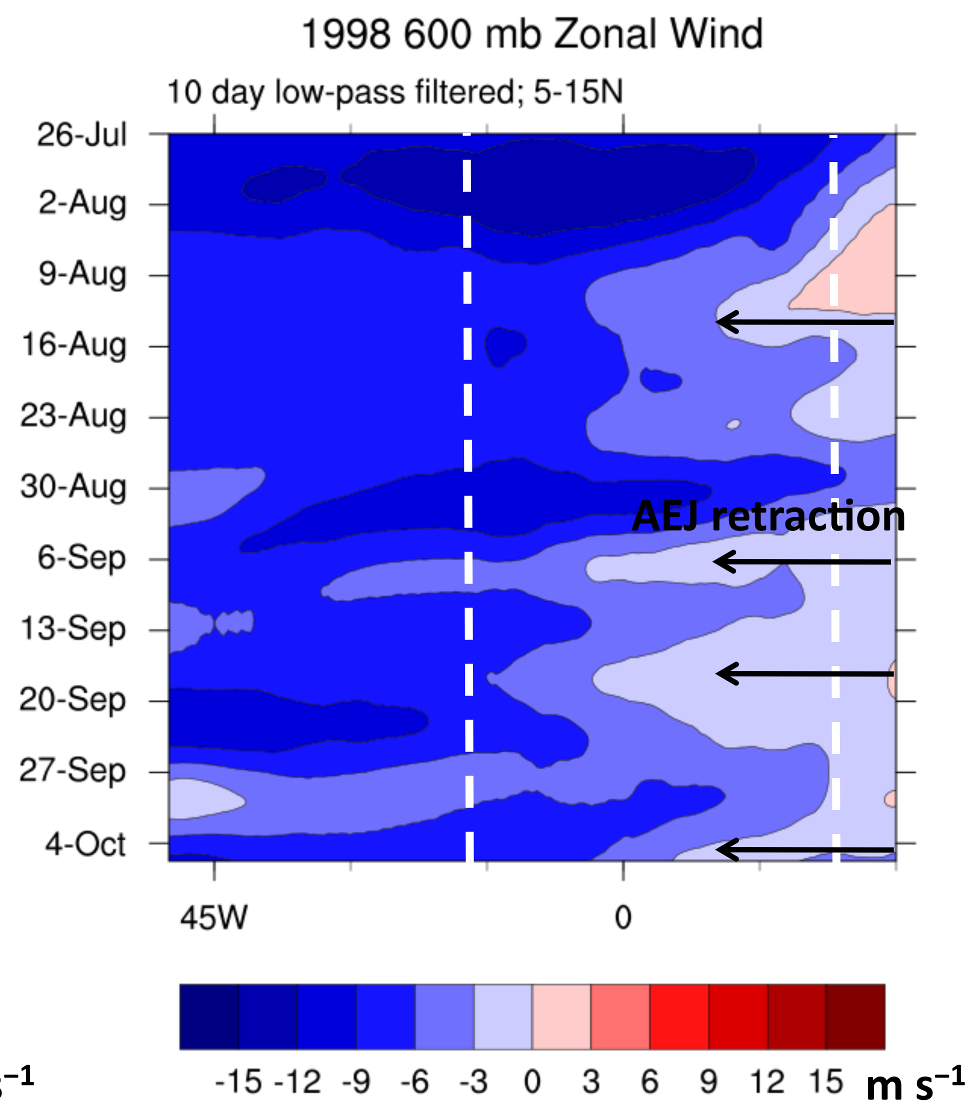


Inactive year

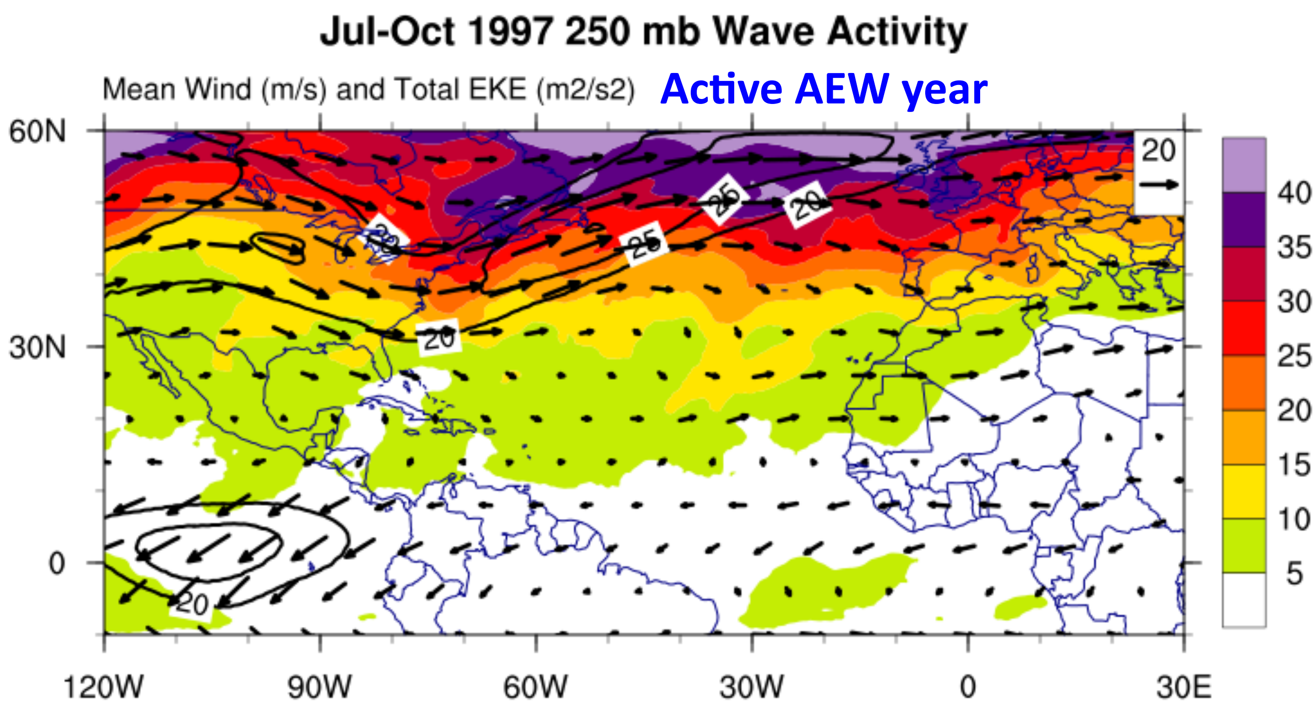
AEJ Variability in 1997 and 1998

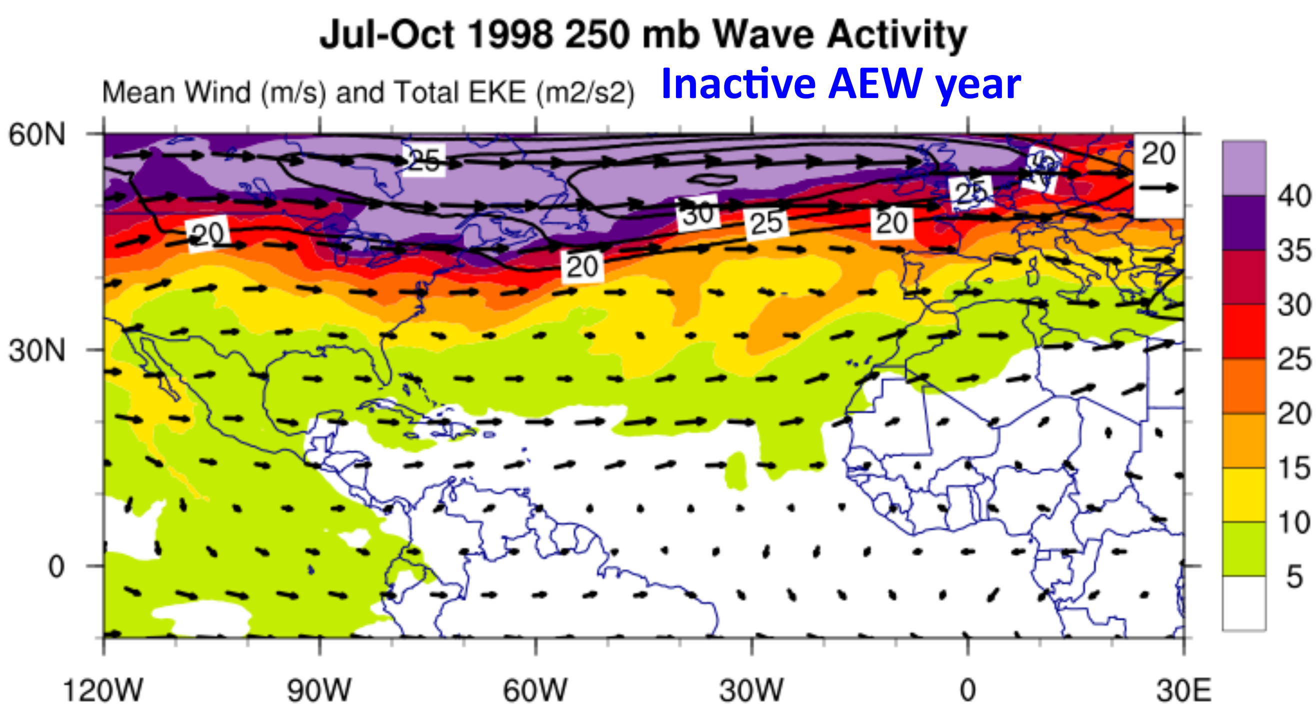


Active year



Inactive year

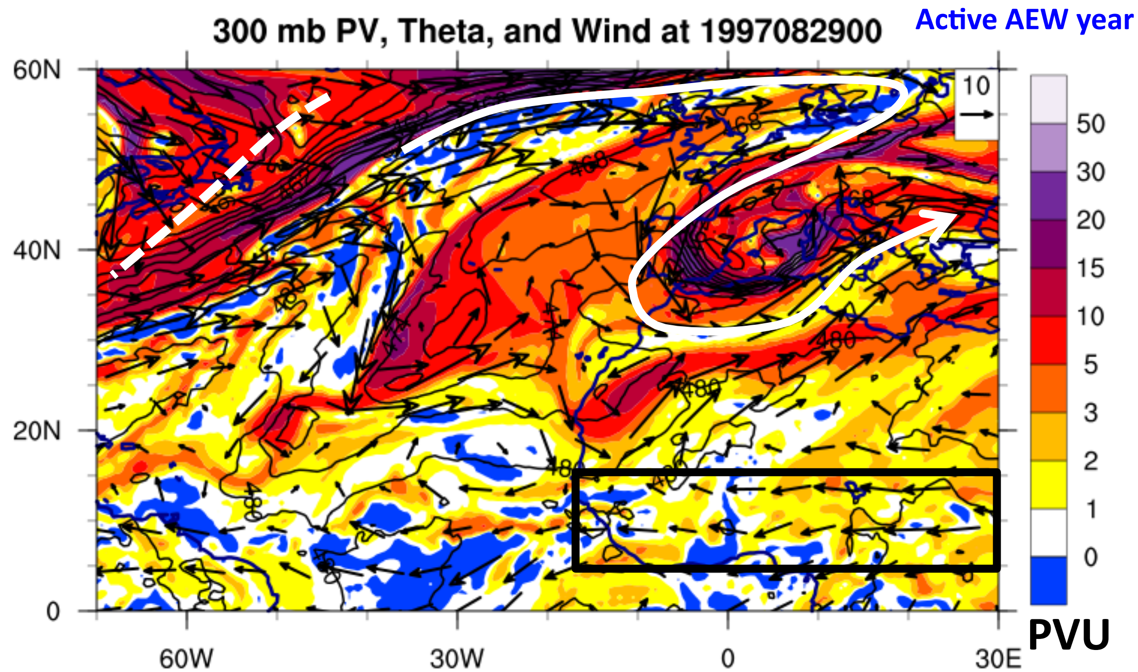




250 mb mean wind (m/s) and total 2–10 day band-pass EKE (×10^3 m^2 s^{-2})

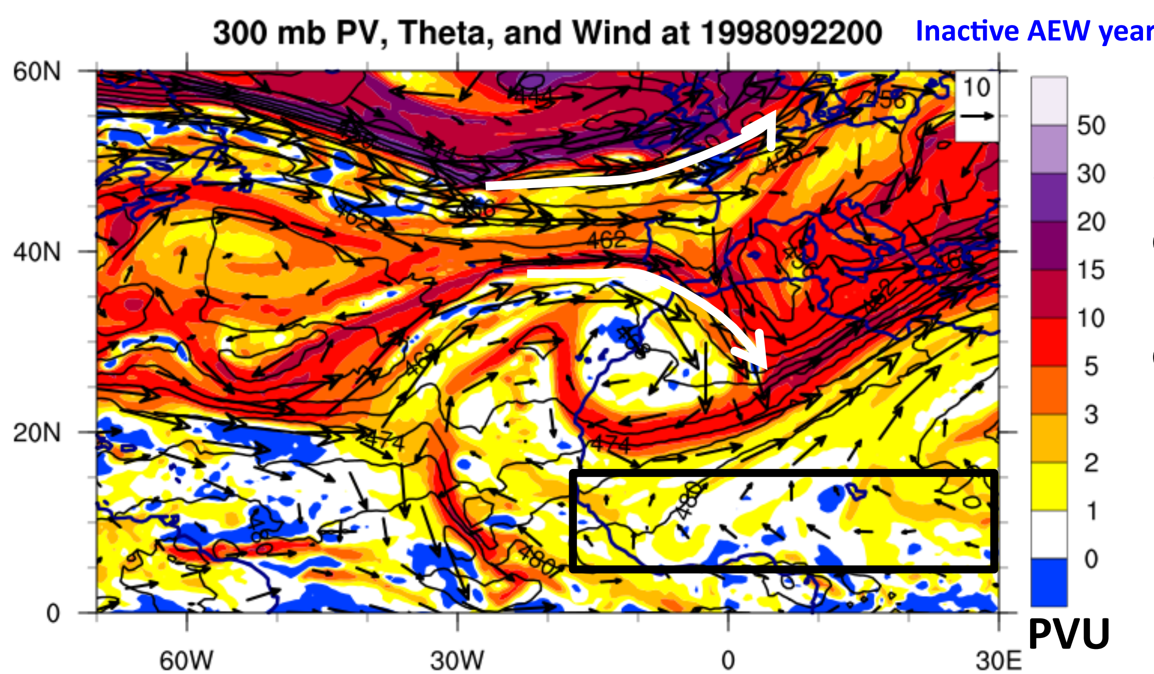
- **Ridging over North America; amplified flow pattern over North Atlantic**
- **Possible link to active convection in eastern North Pacific**

- **Zonal flow pattern from North America to Europe**
- **Inactive convection in eastern North Pacific**



300 mb PV (shaded in PVU), wind (m/s), and θ (K)

- **Deep trough over western North Atlantic facilitates high-latitude anticyclonic wave breaking**
    - **subtropical ridge remains strong**
    - **AEJ provides well-defined waveguide for AEWs**



- **Diffluent jet-exit region over eastern North Atlantic drives midlatitude troughs equatorward over Africa**
    - **subtropical ridge weakens**
    - **AEJ retracts**

Summary

- Assessing variability of AEWs can use different approaches, including:
  - Vortex tracking
  - Eddy kinetic energy
- Interannual variability in AEWs is linked to:
  - the strength of the AEJ/waveguide (e.g., Wu et al. 2012)
  - Organization/intensity of initial convection (e.g., Leroux et al. 2010)
- AEJ strength/waveguide in 1997/1998 is modulated by midlatitude large-scale circulation patterns
  - Note that variability of AEWs and large-scale circulation patterns is reduced in future time slices

Characterization of Drought Using Indices

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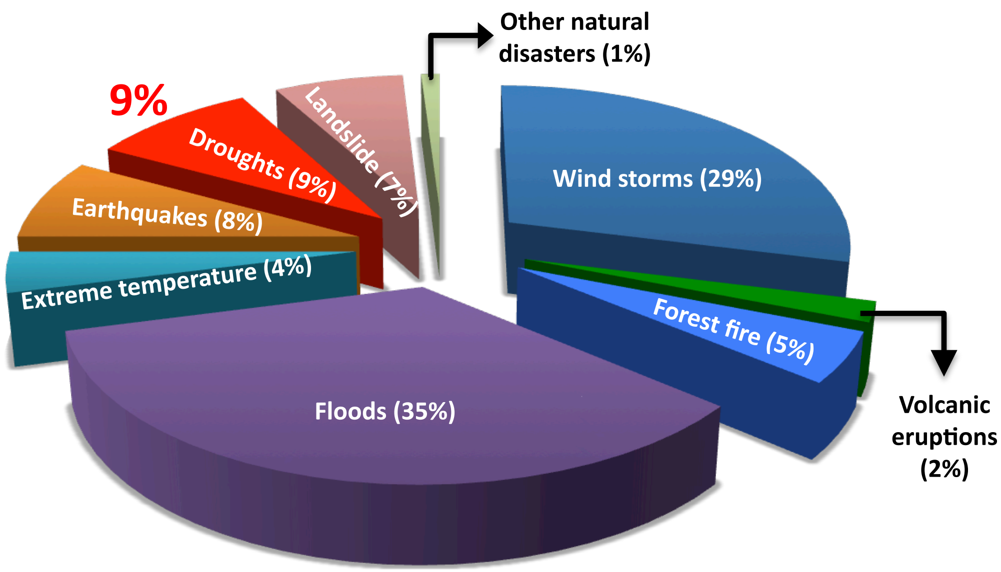
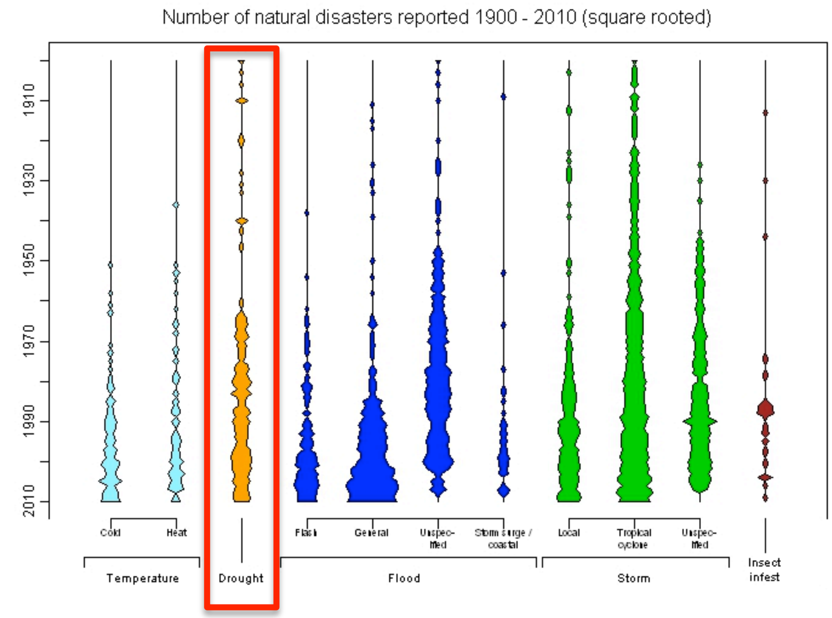
NCAR Earth System Laboratory

13th Annual WRF Users' Workshop
Regional Climate Downscaling Tutorial
29th June, 2012

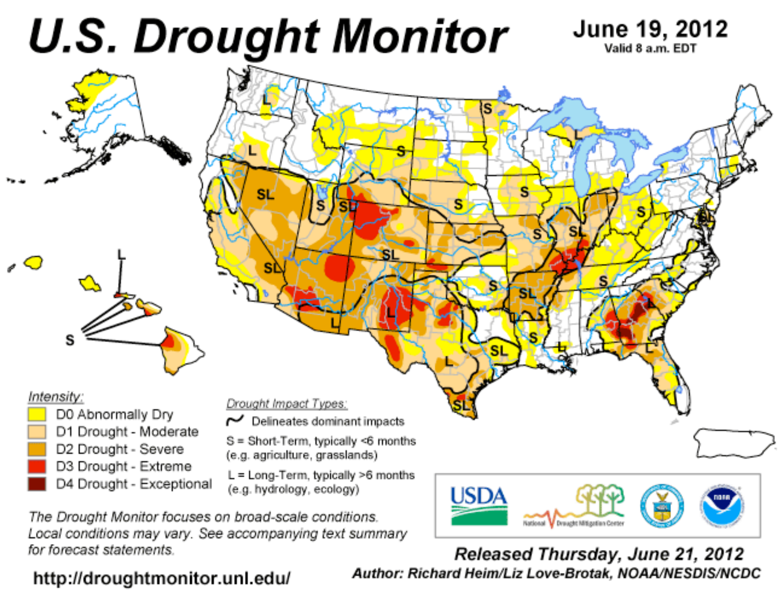
Droughts have been recurrent events in North America



global incidence of natural disasters (1991-2000)



Source: EM-DAT The international disaster data base



Drought Types & Drought Indices

- Meteorological drought: defined on the basis of the degree of dryness (in comparison to some "normal" or average amount) and the duration of the dry spell

  Drought Index*: Standardized precipitation index (SPI), Palmer drought severity index (PDSI), Surface water supply index (SWSI), rainfall anomalies, Foley drought index, effective precipitation*

- Agricultural drought: refers to situations with insufficient soil moisture level to meet the plant needs for water during growing season

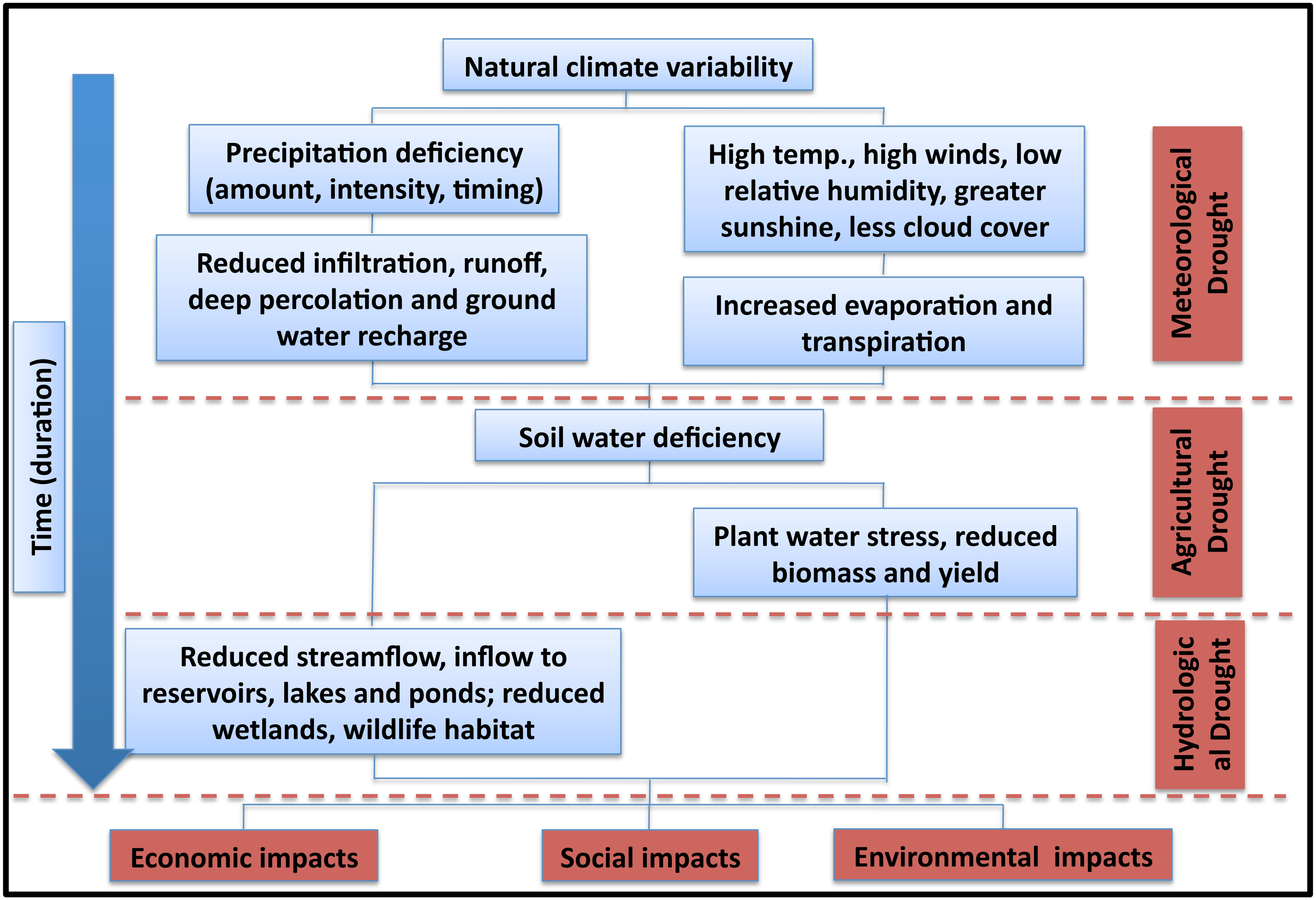
  Drought Index*: Agrohydropotential (AHP), Dry day Sequences, Generalized Hydrologic Model, Crop Moisture Index, Moisture Availability Index*

- Hydrological drought: occurs after longer period of precipitation deficit that affect surface or subsurface water supply, thus reducing streamflow, groundwater, reservoir and lake levels

  Drought Index*: Standardized runoff index*

- Socioeconomic drought: result of the 3 above droughts

Sequence of drought occurrence



Standardized precipitation index (SPI)

- McKee et al. (1993) developed the SPI for the purpose of defining and monitoring drought
- Input: only precipitation (monthly/ weekly)
- Definition: SPI = standardized precipitation sum over a given period (various time-scales; 3-, 6-, 9-, 12- and 24-months so on)
- Thom (1966) -> Gamma distribution fits cumulative precipitation well

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \qquad \text{for } x>0$$

$\alpha > 0$	α is a shape parameter
$\beta > 0$	β is a scale parameter
$x > 0$	x is the precipitation amount

$$\Gamma(\alpha) = \int_0^{\infty} y^{\alpha-1} e^{-y} dy$$

$\Gamma(\alpha)$ is the gamma function

Standardized precipitation index (SPI)

- Thom (1966): Parameters are determined based on maximum likelihood method

$$\hat{\alpha} = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \qquad \hat{\beta} = \frac{\bar{x}}{\hat{\alpha}} \quad \text{where} \quad A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n}$$

- Estimated parameters are then used to calculate cumulative probability distribution (CDF) for a specific precipitation event, which has been observed on a defined time scale (e.g. month)

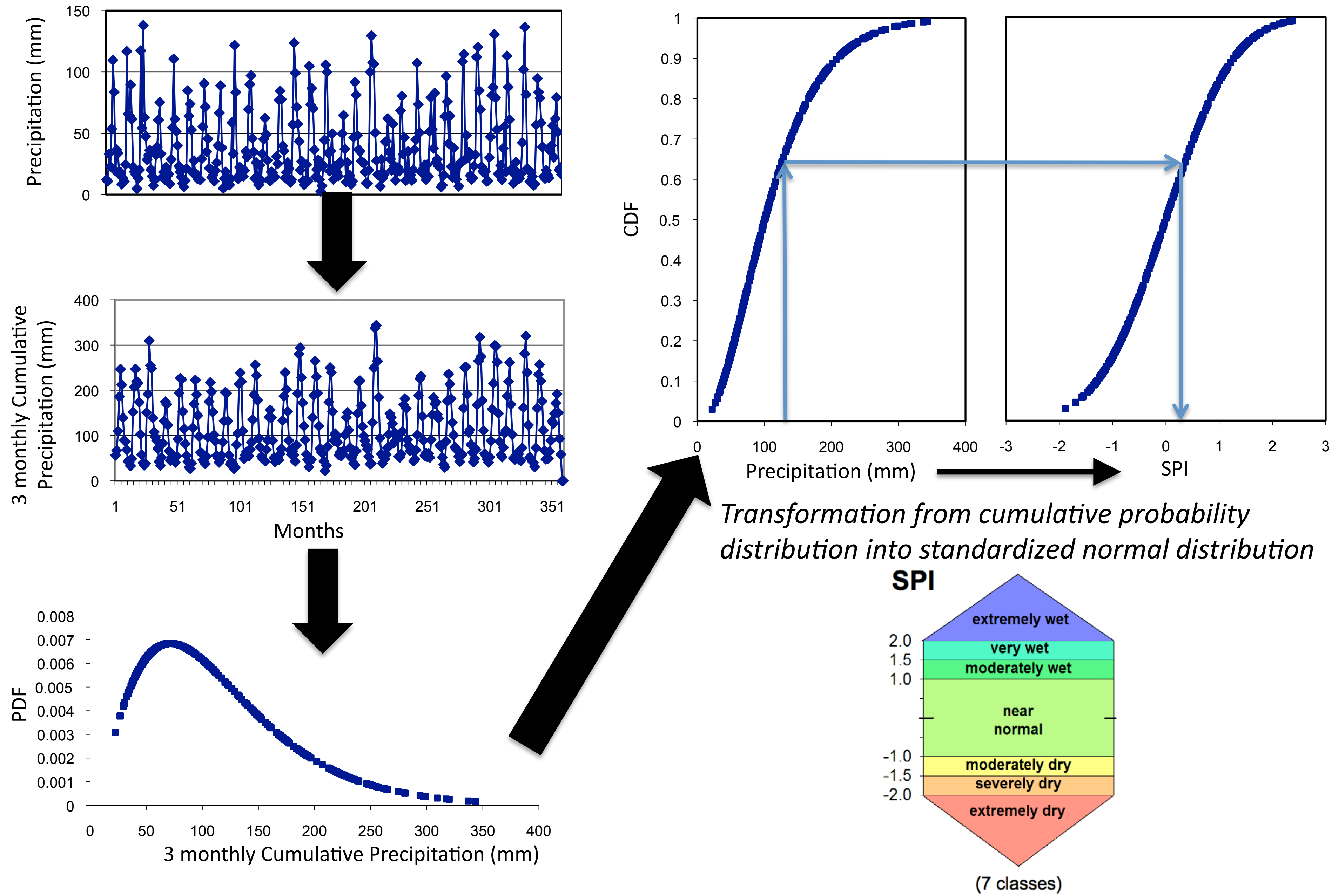
$$G(x) = \int_0^x g(x)dx = \frac{1}{\hat{\beta}^{\hat{\alpha}}\Gamma(\hat{\alpha})}\int_0^x x^{\hat{\alpha}-1} e^{-x/\hat{\beta}} dx$$

- Since Gamma function is undefined for *x*=0 and a precipitation distribution may contain zeros. Therefore CDF becomes

$$H(x) = q + (1-q)G(x)$$ where *q* is the probability of zero

- CDF (*H*(*x*)) is then transformed into standardized normal distribution with mean of zero and variance of 1, which is the value of SPI

Standardized precipitation index (SPI)

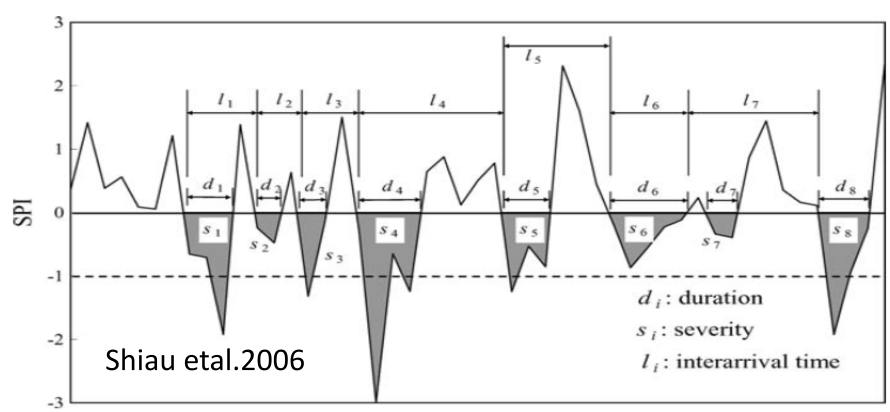


Standardized precipitation index (SPI)

- Drought event define as a continuous period in which SPI is below zero
- The event ends when the SPI becomes positive
- The positive sum of the SPI for all the months within a drought event => drought magnitude

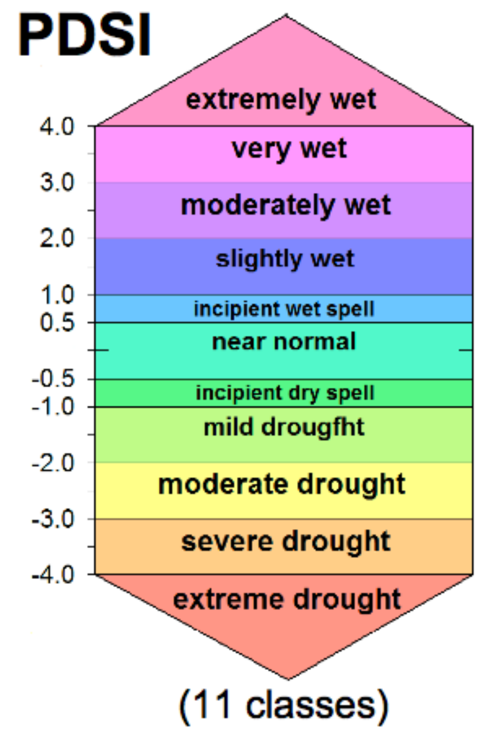
$$S = -\sum_{i=1}^{D} SPI_i$$

Where D is duration & S is severity



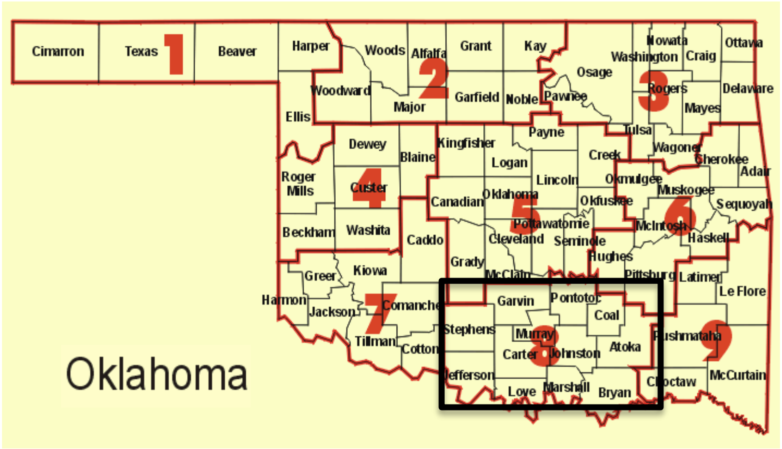
Palmer drought severity index (PDSI)

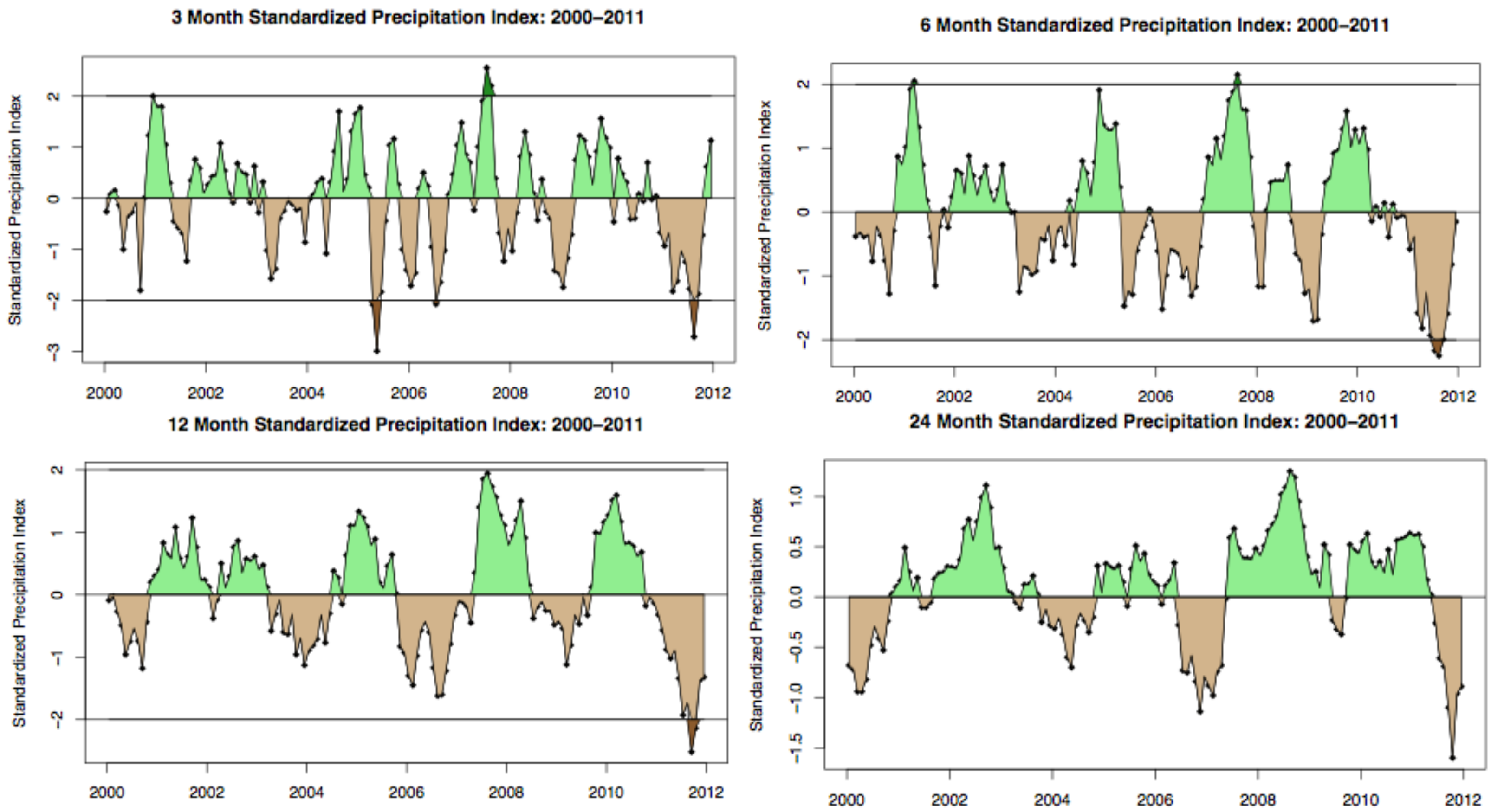
- Palmer (1965) developed the PDSI
- PDSI: based on primitive water balance equation
- Objective: develop a general methodology for evaluating droughts in terms of an index that permits time and space comparisons of drought severity (Palmer 1965)
- Input:
  - precipitation and temperature (monthly/ weekly)
  - available water content
- Most effective in determining mid- to long term droughts
- Not as good with short-term forecasts (i.e., weeks)
- High correlation with SPI at timescales at 6-12 months (Redmont, 2002)
- good proxy of soil moisture condition and streamflow (Dai, 2004)



Case study: Water Decisions for Sustainability of the Arbuckle-Simpson Aquifer

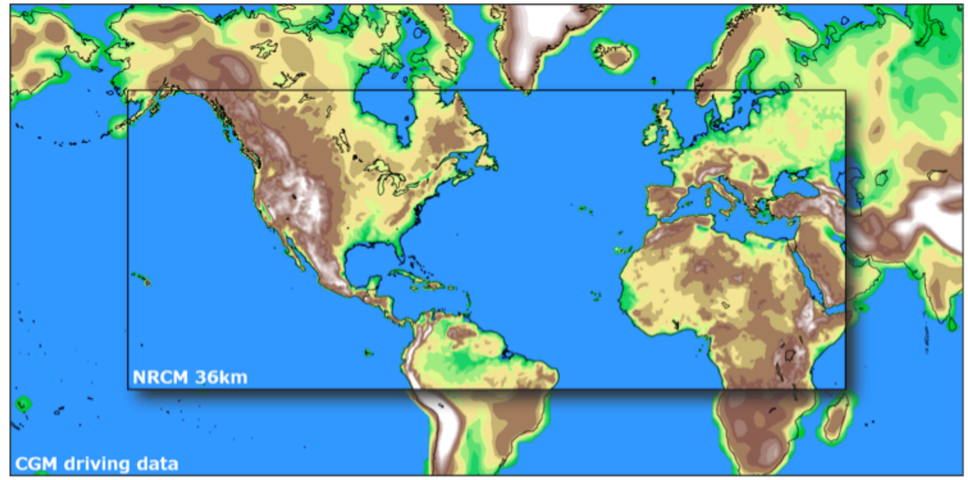
Monthly precipitation data: Cooperative Observer Network (COOP), NCDC

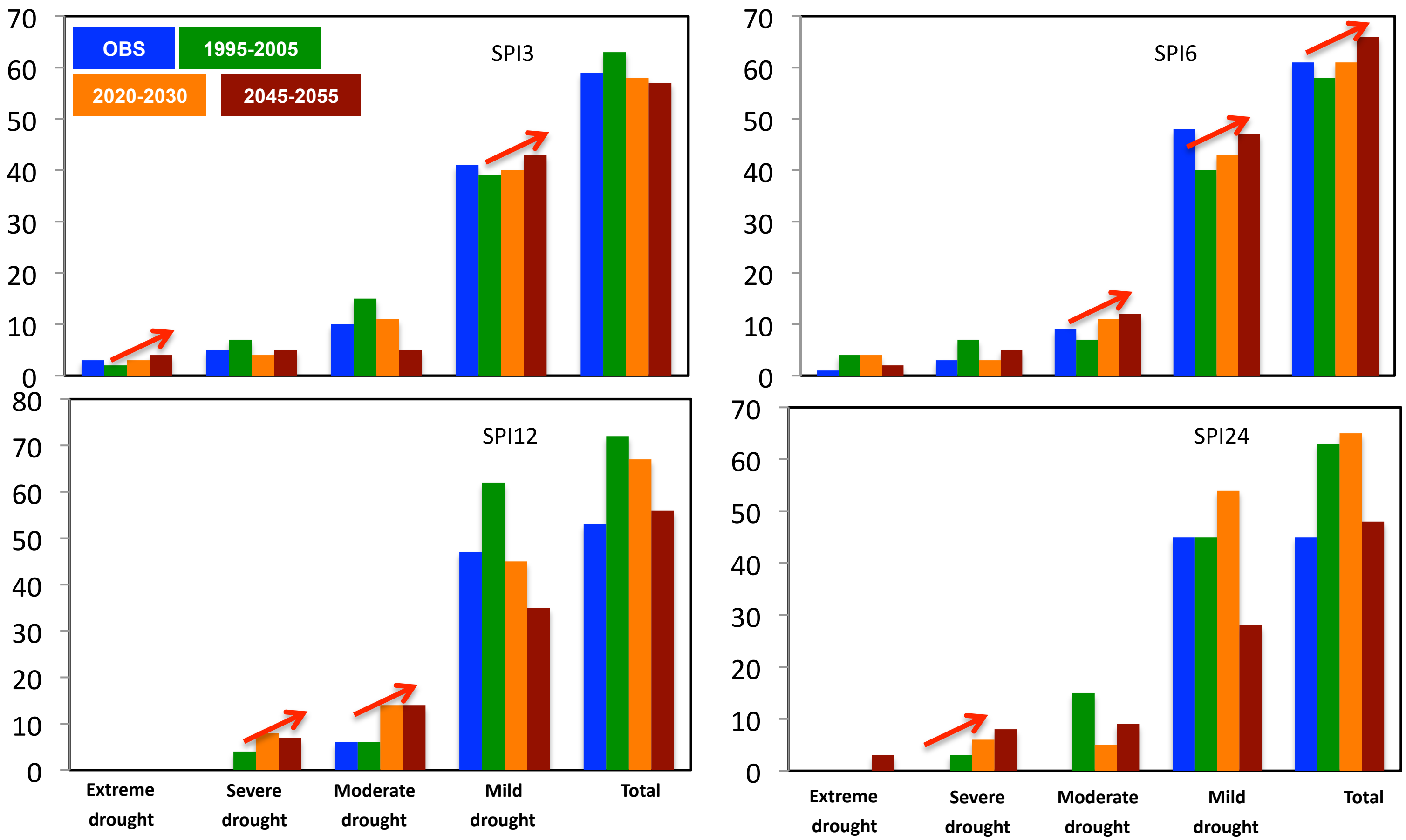




Figures are prepared by Virginia Silvis, Environmental Sustainability, University of Oklahoma

NRCM's Performance & Projection over south-central Oklahoma





Bridging climate information with ecological impacts

Erin L. Towler

PACE Postdoctoral Fellow

MMM/NCAR, Regional Climate Tutorial

June 29th, 2012

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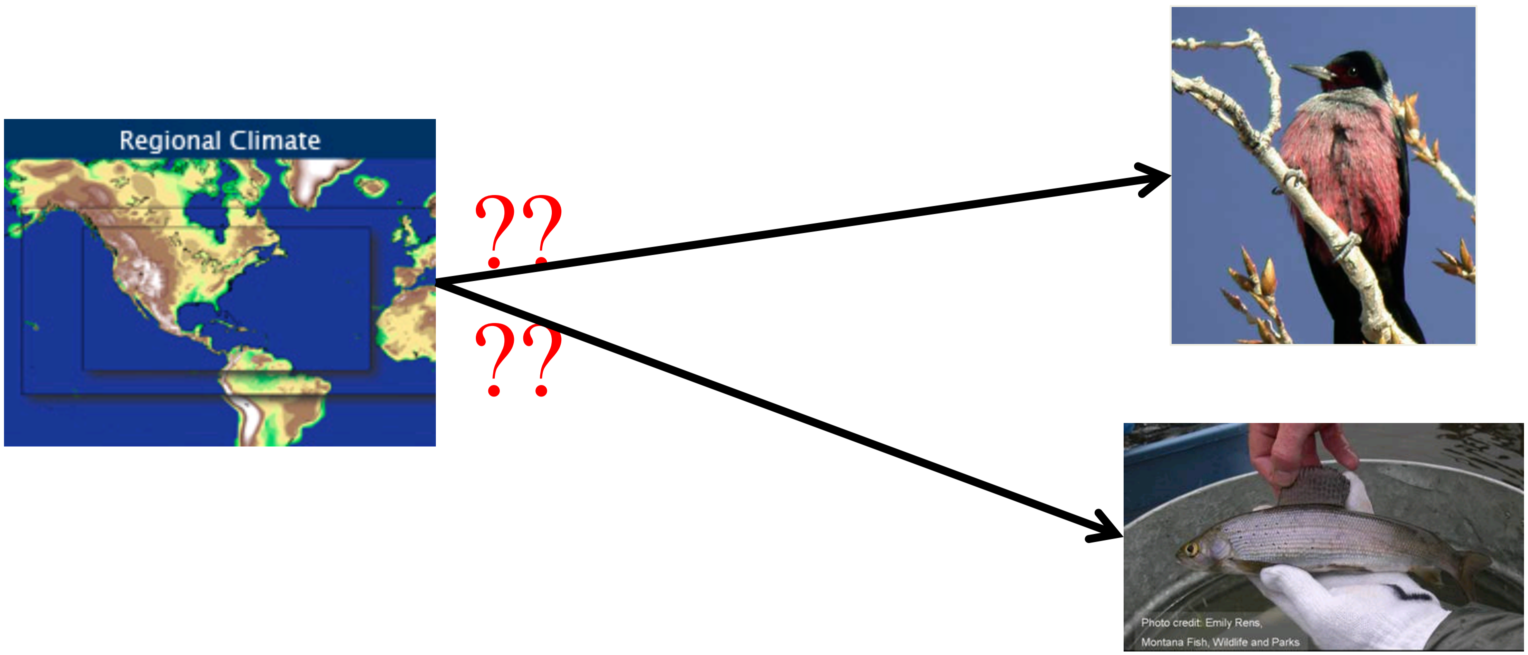
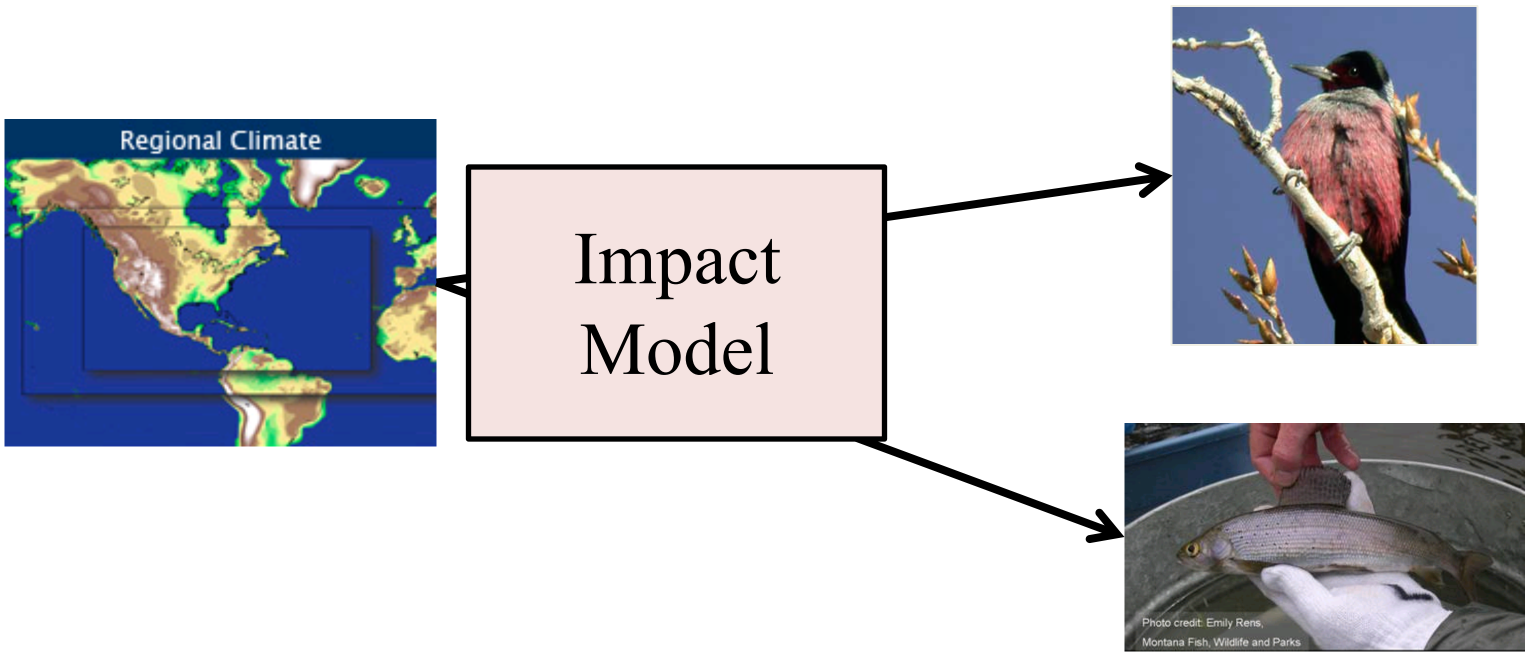
How can we link climate information and ecological impacts?



How can we link climate information and ecological impacts?



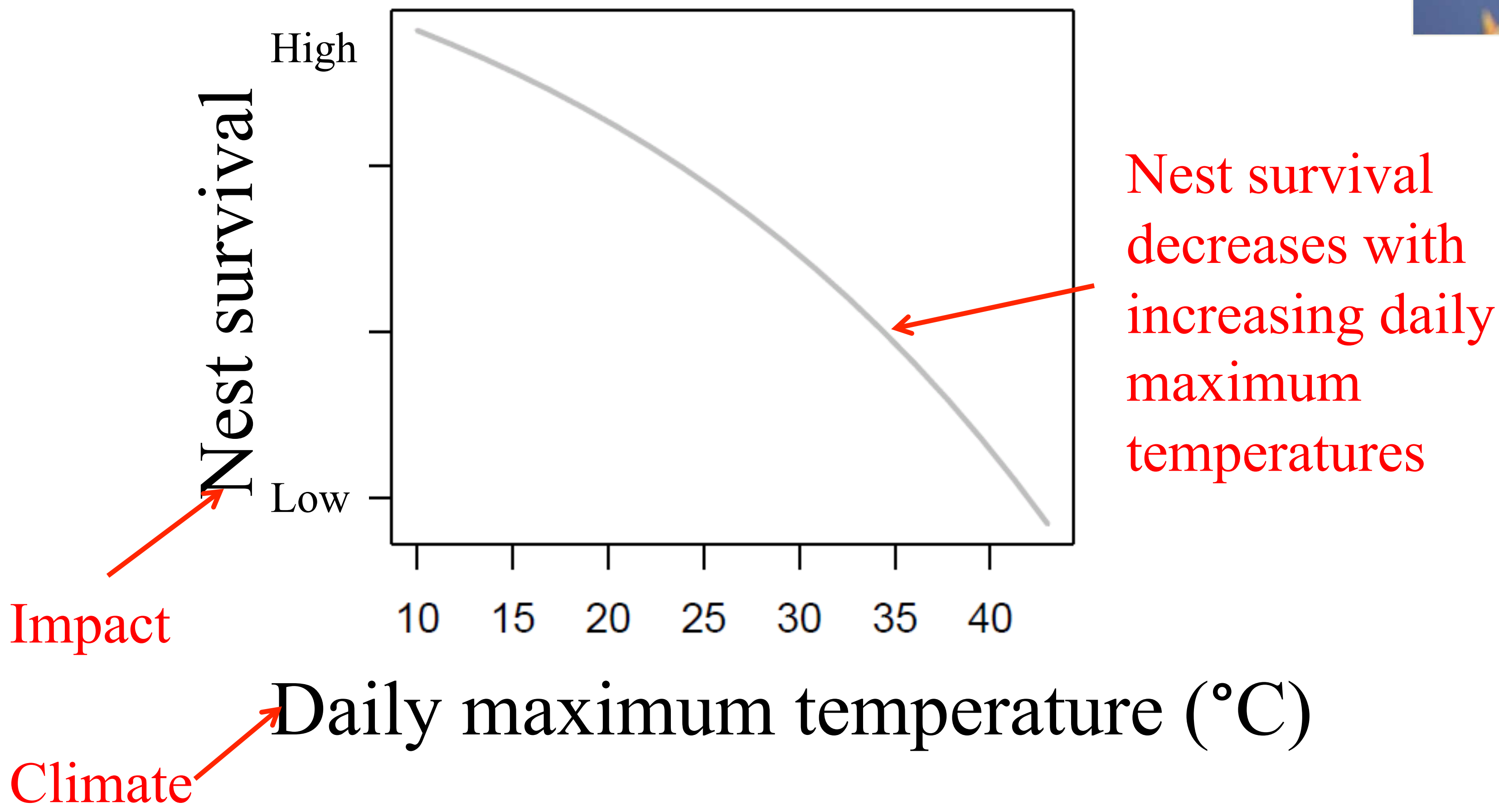
Impact models "translate" climate information into application-relevant information

Demonstrative example:

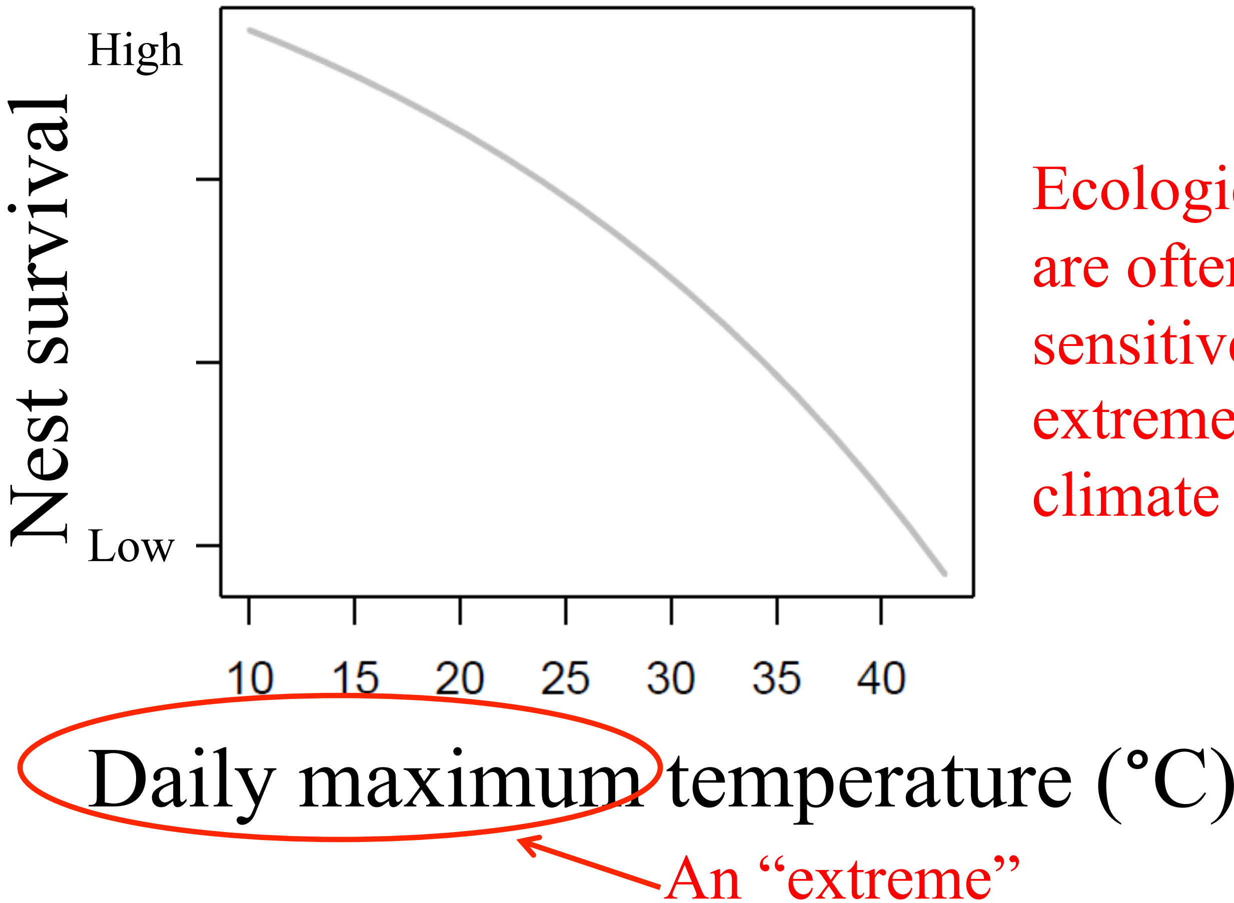
- Collaborated with wildlife biologists to characterize ecological impacts

- Investigated impacts on a species of conservation concern, the Lewis's Woodpecker

Impact model relates nest survival to temperature

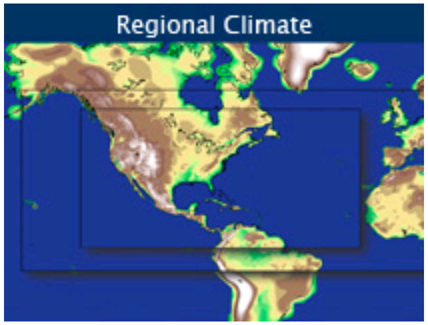


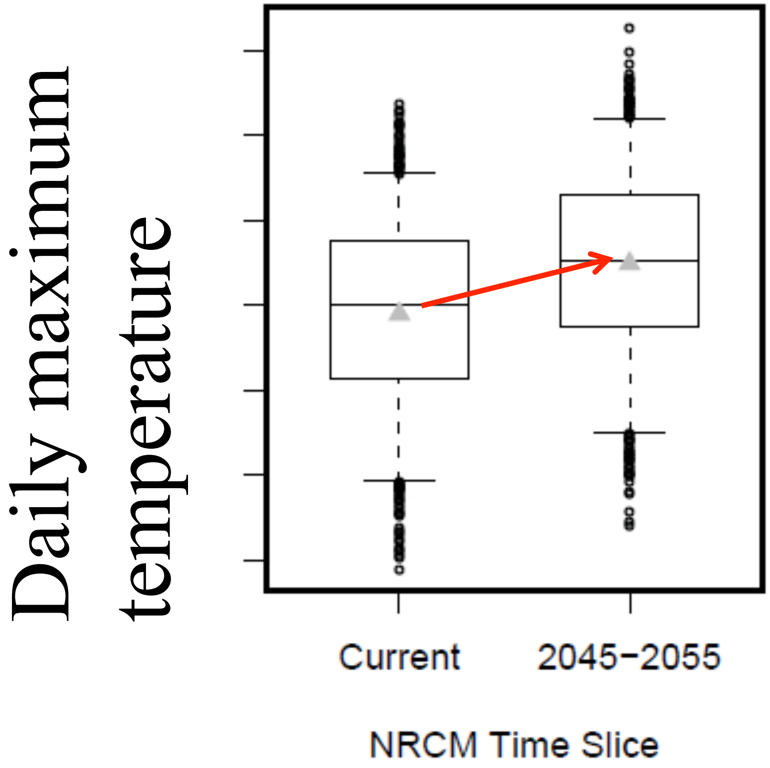
Impact model relates nest survival to temperature



Ecological systems are often more sensitive to weather extremes than to climate averages

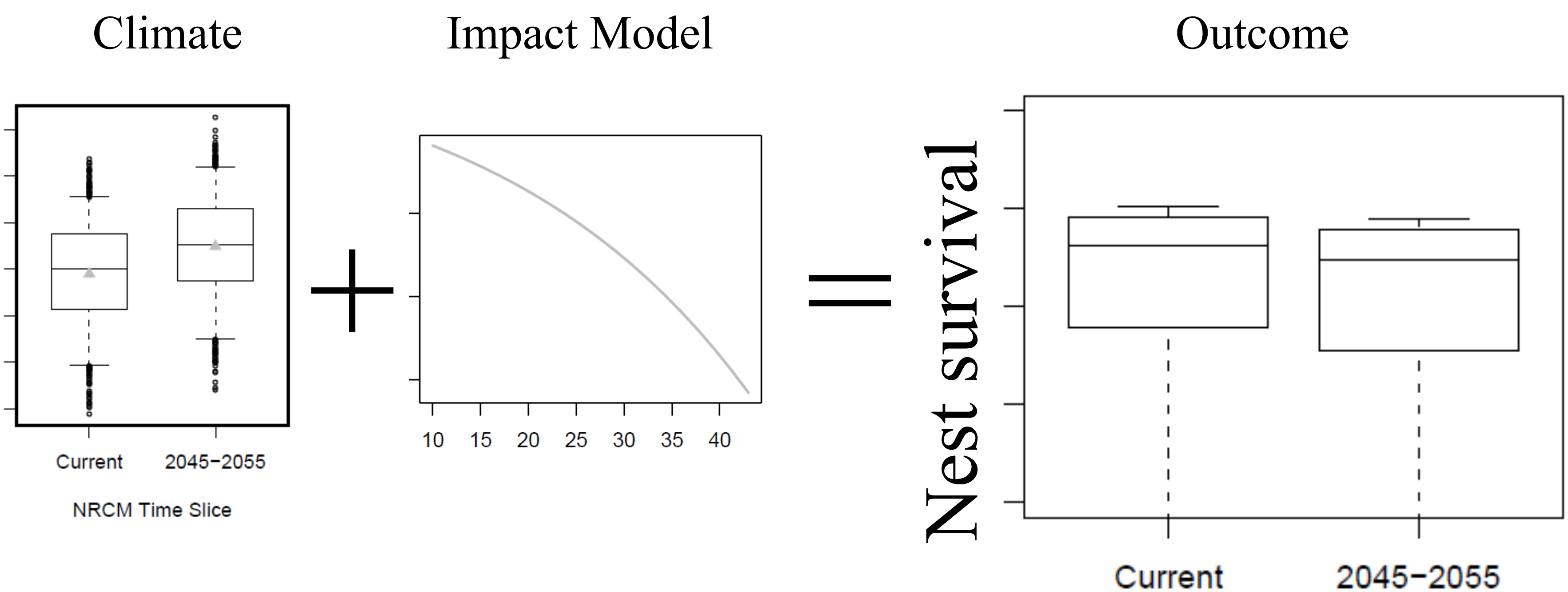
Climate model provides maximum temperatures



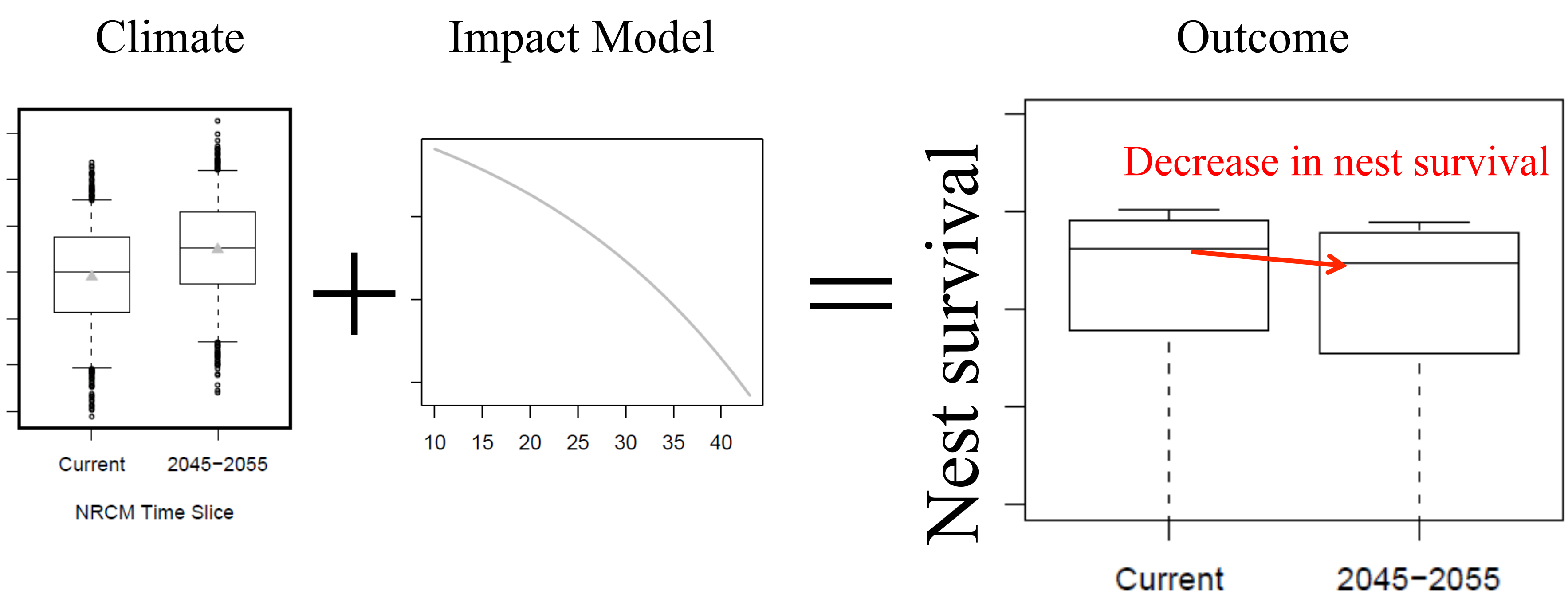


NRCM shows 3 degree increase in daily maximum temperature

Use climate info in conjunction with impact model to quantify outcome

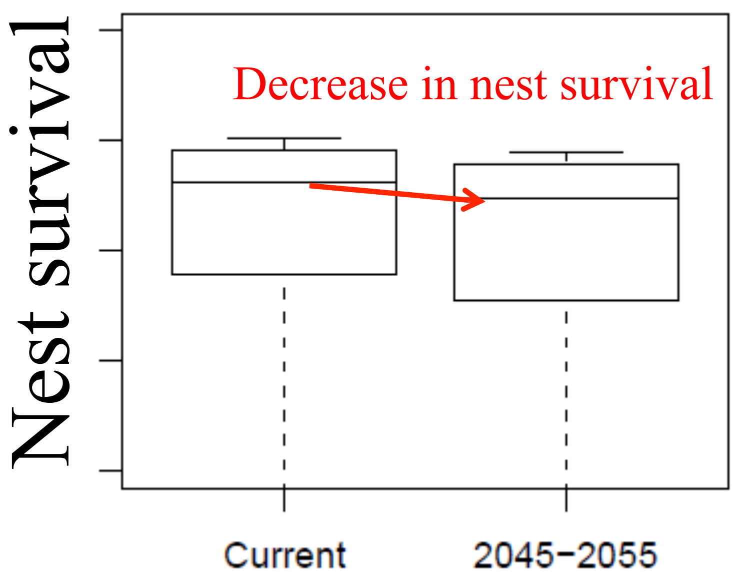


Use climate info in conjunction with impact model to quantify outcome

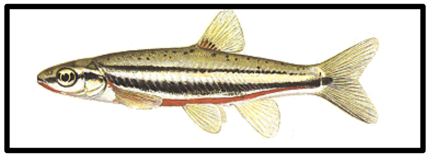


Towler E, Saab V, Sojda R, Dickinson K, Bruyère C, Newlon KR (2012), A risk-based approach to evaluating wildlife demographics for management in a changing climate: A case study of the Lewis's Woodpecker, *Environmental Management* (in review).

Need to "translate" climate information to be decision-relevant



- Nest survival is more relevant to management decisions than raw temperature information.
- Need to consider human dimension of decision making
    - Forthcoming drought ex.



Email Erin with questions: towler@ucar.edu

Applications and use of model data to improve decision making

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Integrated Science Program

NESL

13th Annual WRF Users' Workshop
Regional Climate Downscaling Tutorial
29th June, 2012

NSF

The last mile…And the first?

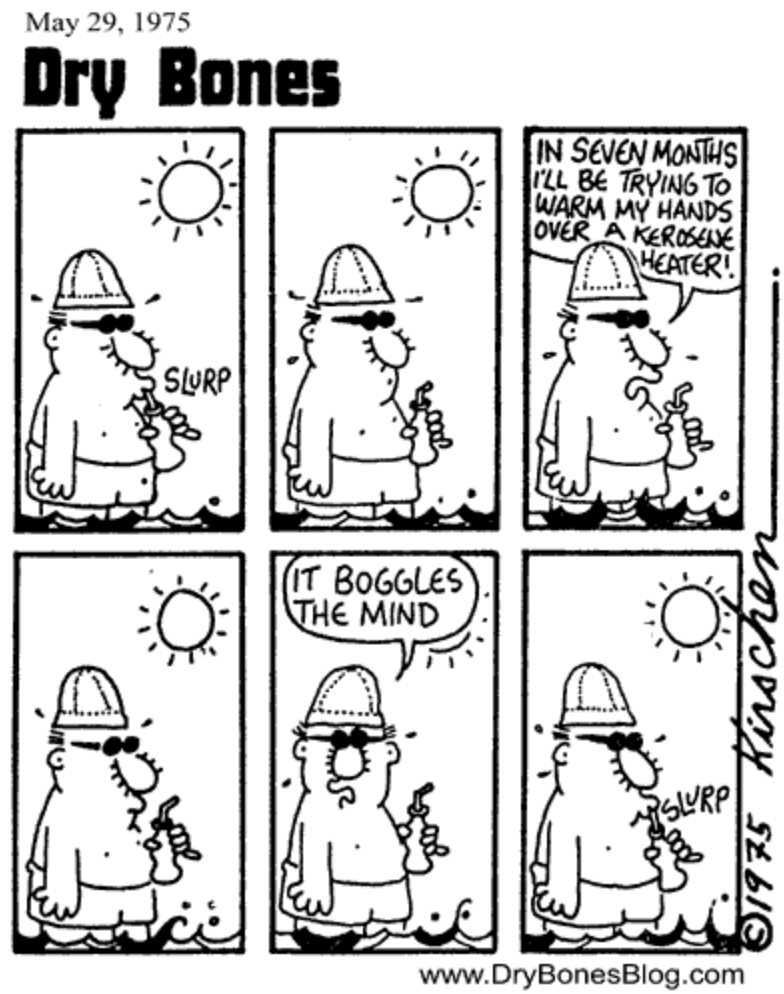
1. High Impact Weather, Extremes, and Societal Impacts

2. Case Study: Interdisciplinary study using downscaled information in the context of drought in south-central Oklahoma

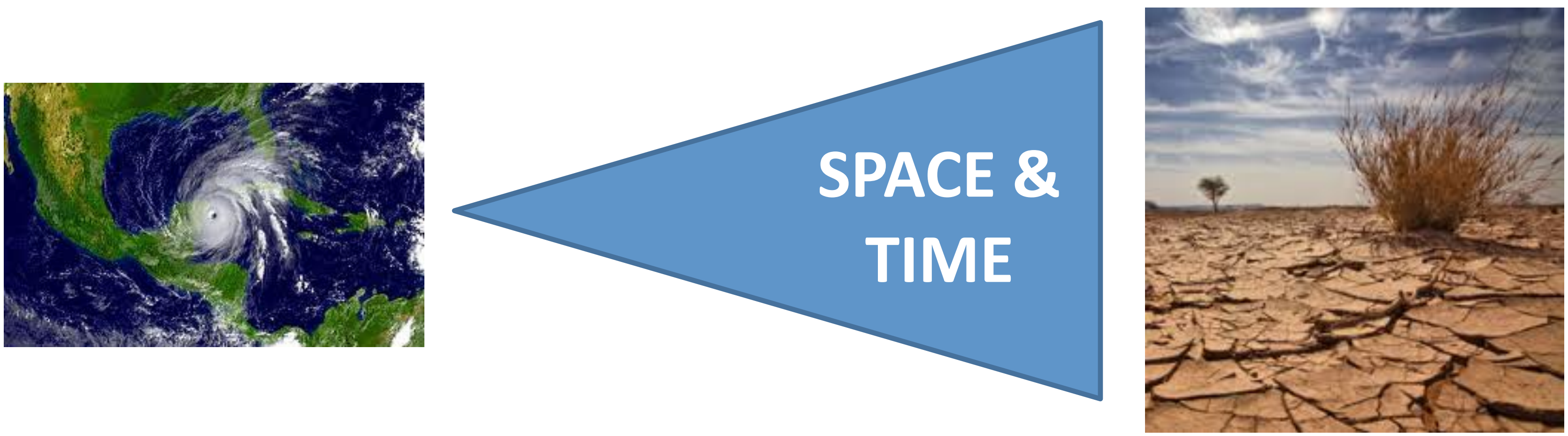
High Impact Weather, Extremes, and Societal Impacts

- Complex interactions between physical and human systems

- Rare at a particular location and time or can cause significant impacts, including:
  - Heat and cold
  - Heavy precipitation and floods; low precipitation and drought
  - Storms and severe weather



High impact weather experienced across time and space scales



Weather and climate information is important for decision makers in many contexts

Information about weather and climate extremes can be particularly important for decisions that keep people safe

Our objectives

We want to provide better information in better ways to ***enhance people's decision-making*** and ***reduce their risk*** to life, property, and harm

"Uh-oh! They're doin' the weather before the news! That's always a bad sign!"

Why downscaled information for decision making?

- ***Is downscaled information relevant***?

  Downscaled model information may be relevant to decision makers because at a more "human scale"
- ***Is downscaled information appropriate***?
  Caution about how downscaled information is used
  - For what purpose?
  - What are the assumptions and expectations?

Challenges with downscaled information for communication and decision making

- Work with interdisciplinary research teams so know the limitations of downscaled information
- Assess how well the model is doing with respect to the area of interest
- Models provide insight, not necessarily answers

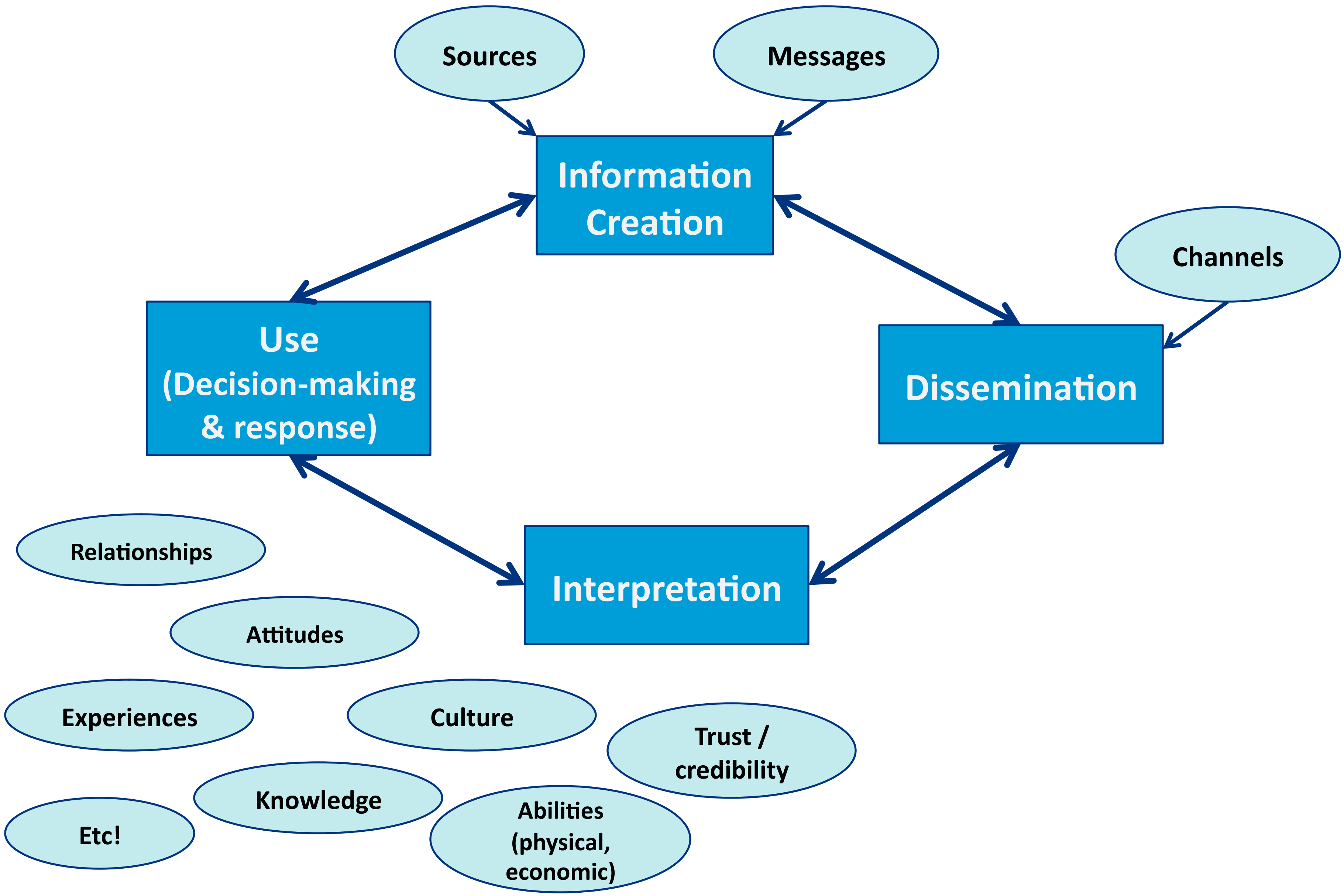
Broader challenges

- Why don't people *understand and use* weather and climate information?

  … the way we think they should?

- Are there gaps between the weather and climate information we generate and that received and used?

From model to use



Types of decision makers

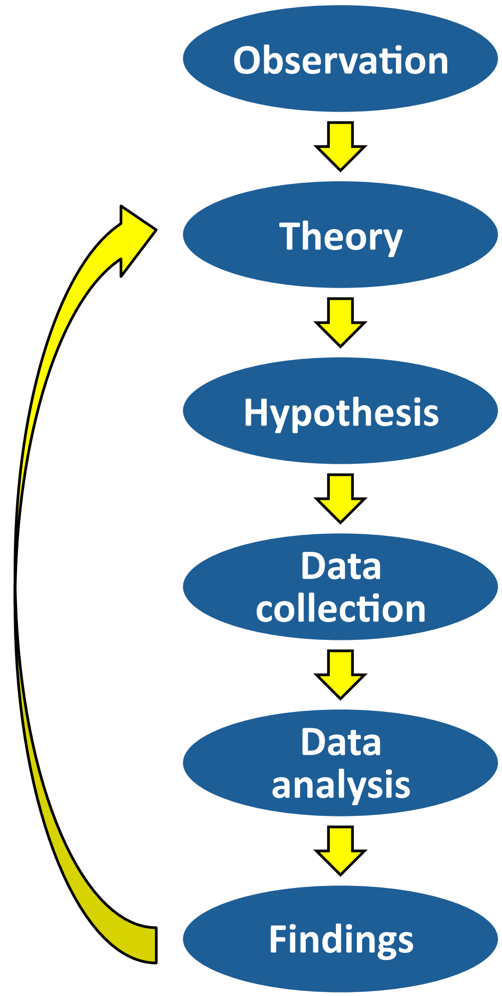
- International public policy
- Federal public policy
- State / regional public policy
- Local public policy
- Private sector
- Individual
  - Your family, neighbors, hikers etc.

Types of decisions

- **Risk management**: How to reduce risk from extreme weather impacts
- **Adaptation**: How to adapt to extreme weather in a changing climate
- **Other factors**: How does extreme weather interact with other factors in decision making?
  - Vulnerability (i.e., individuals and communities)
  - Resource management (i.e., public institutions)
  - Private sector (i.e., insurance agencies, energy companies)

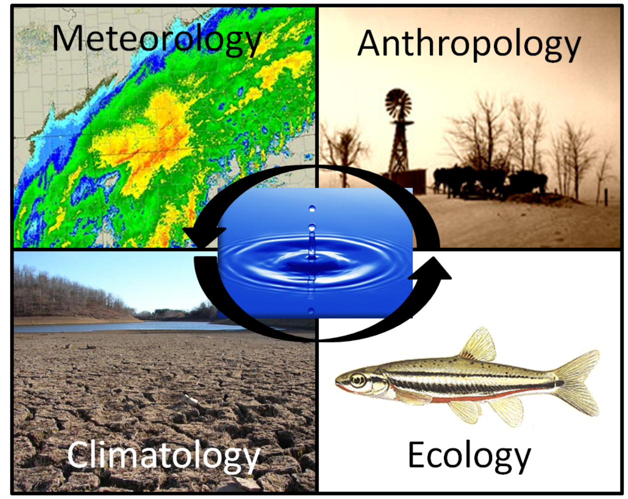
Interdisciplinary work integrates the social sciences

- The study and understanding of ***human cognition***, ***culture*** & ***behavior***
- Social scientists follow the scientific method
  - Theories, hypotheses, research questions,
  - Data collection instruments, sampling, error
  - Reliability (are we consistent?) validity (are we measuring what we think we're measuring?)

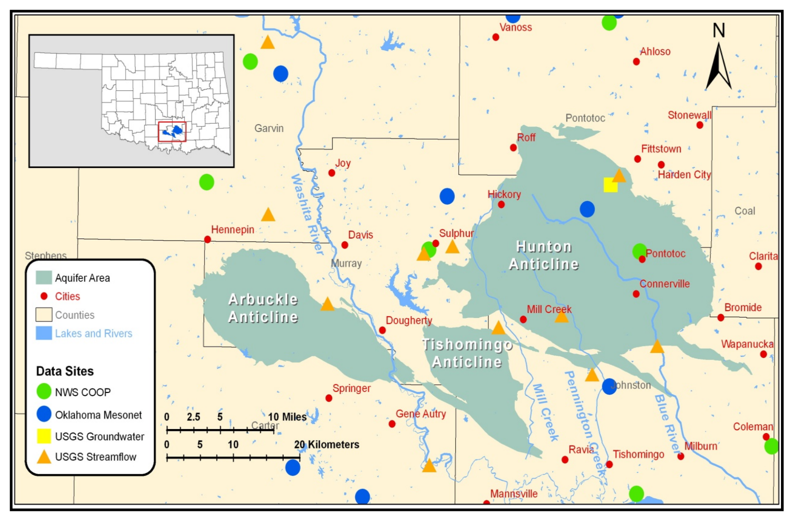


Case study: Water Decisions for Sustainability of the Arbuckle-Simpson Aquifer

Research Question: How do stakeholders perceive drought risks across weather and climate scales given



1) diverse cultural beliefs,
2) valued ecosystem services,
3) past drought experience, and
4) uncertainties in climate projections?



Funded by the NOAA Climate Program Office

Risk perception

- Subjective judgments
  - "To categorize something as a risk implies values" (Boholm 2003)
- How people identify and understand risks motivates their decisions; for example
  - Driving through flooded areas
  - Conflict over resource management

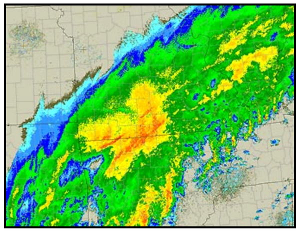
Stakeholder interviews

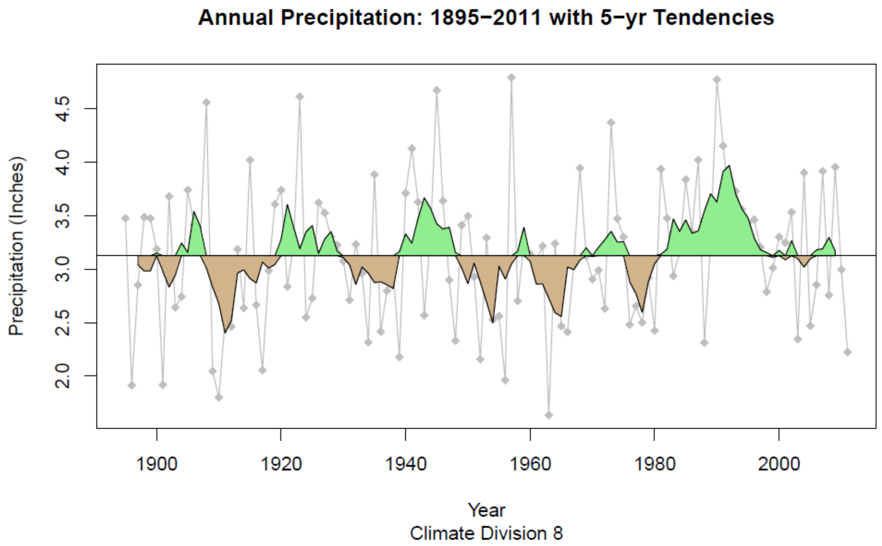
- Decision makers and managers

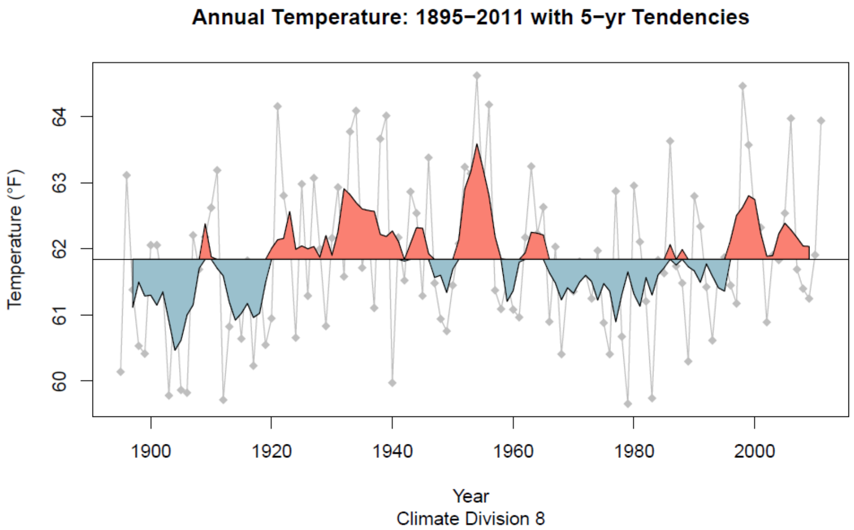
  (i.e., Oklahoma Water Resources Board, cities of Ada, Sulphur, and Tishmingo)
- Community leaders
- Industry association members (i.e., ranching, farming, mining)
- Engaged citizens (i.e., Citizens for the Protection of the Arbuckle-Simpson Aquifer (CPASA))
- Chickasaw Nation

Interview Questions:

Meteorological memories

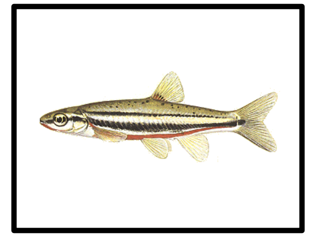


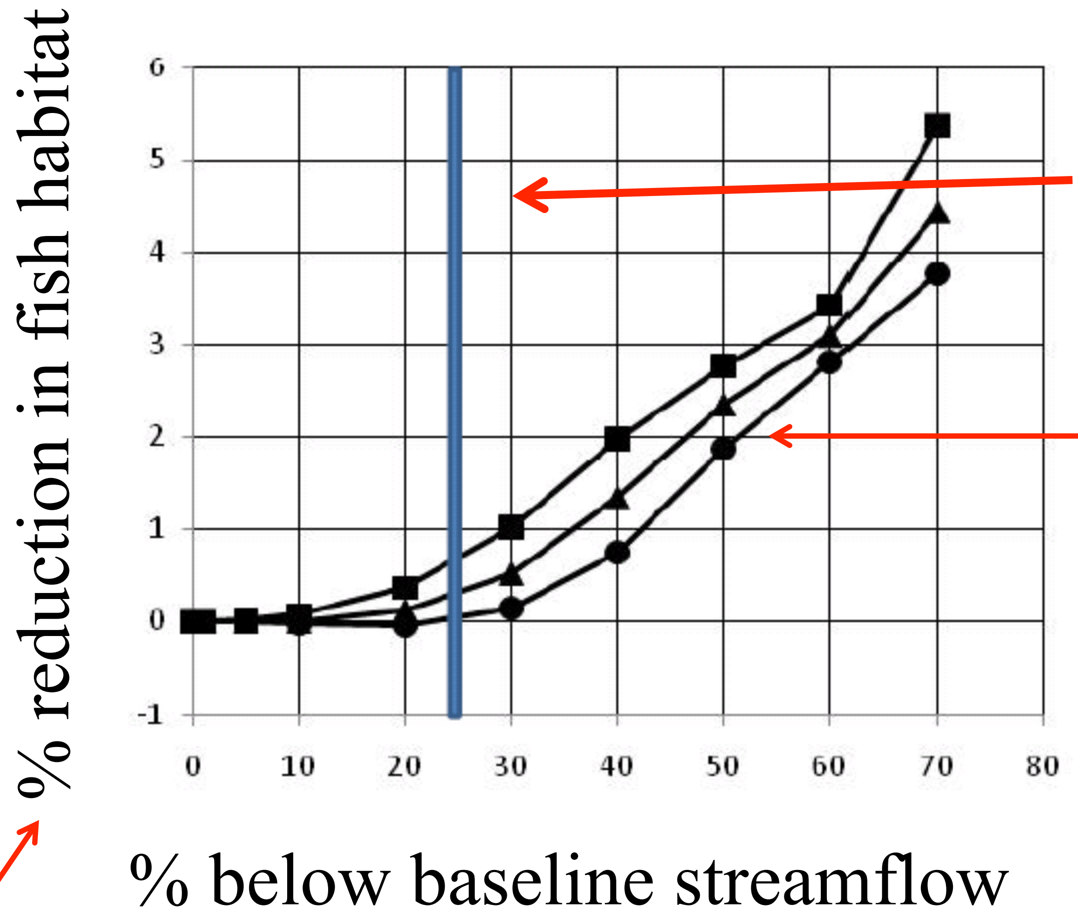




10. [EXPERIENCE] **Have you experienced drought(s) in the past?** [YES/NO]
    a. **If yes, WHEN was the worst drought?**
    b. **WHY was it bad?** [OPEN ENDED. PROMPT: impacts, severity, drought duration, drought frequency]
    c. **Other droughts? WHEN? Why were they bad?** [OPEN ENDED. PROMPT: impacts, severity, drought duration, drought frequency]

Water shortages negatively impacts services, e.g., fish habitat





Critical threshold for fish

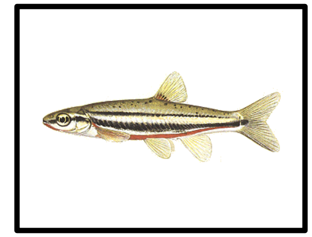
Impact model

How often is this expected in the future?

Impact

Hydro-climate

Interview Questions:
Valued ecosystem services



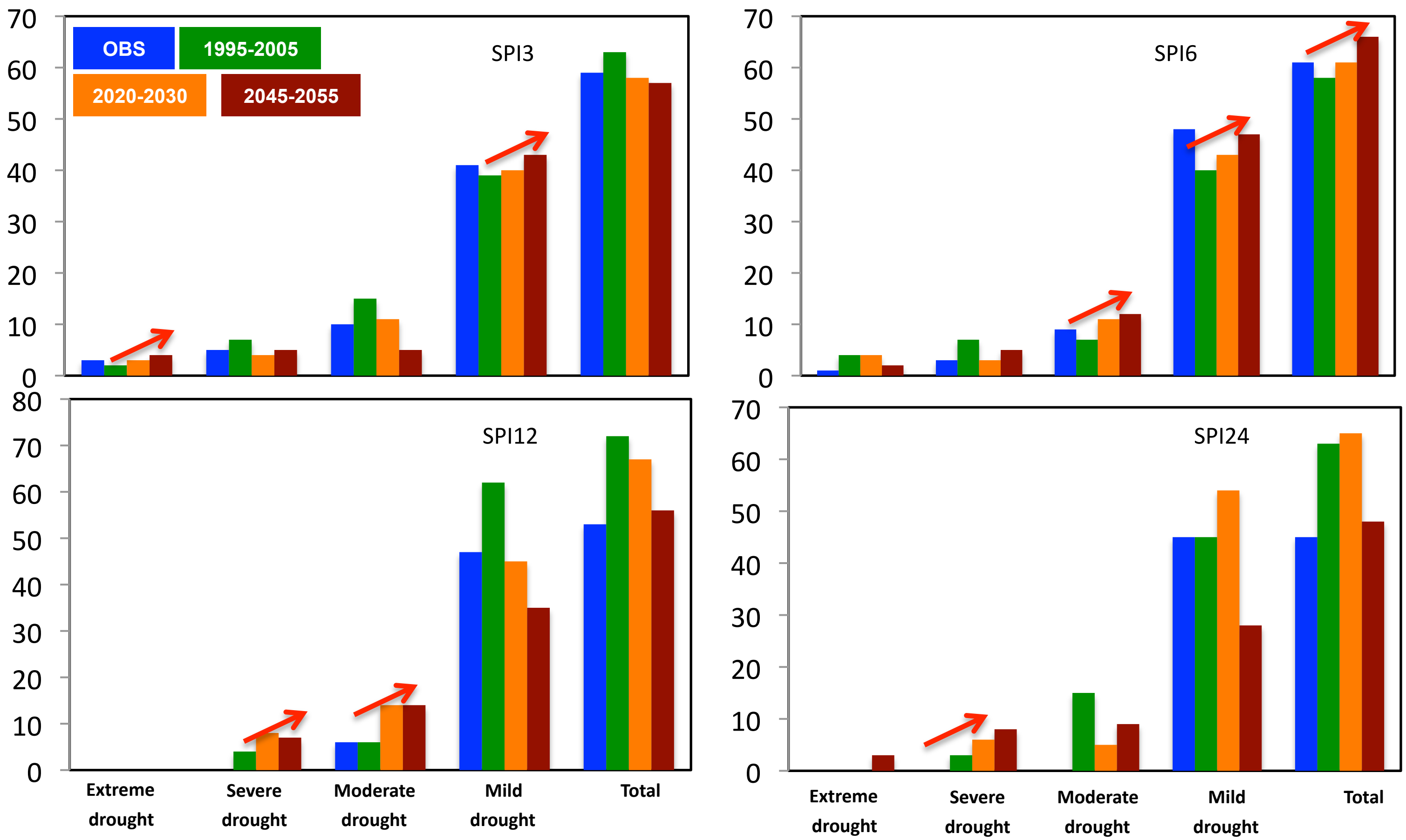
5. [ECO. SERVICES] **How important to you are the following activities related to water in this area:**
   a. **Recreational activities:**
      i. **Please explain** [OPEN ENDED. PROMPT: fishing, swimming, boating]
      ii. **Please evaluate:**

Not Very Important		Somewhat Important		Very Important	Don't know
☐	☐	☐	☐	☐	☐

6. [ECO. SERVICES] **How important do you think the state of the local environment is to maintaining these water-related activities**:

Not Very Important		Somewhat Important		Very Important	Don't know
☐	☐	☐	☐	☐	☐

NRCM's Performance & Projection over south-central Oklahoma



Interview Questions:
Future expectations and drought

11. [EXPECTATIONS] **Do you expect dry periods to increase or decrease in the future?** [INCREASE/DECREASE]
    a. **Why is that your expectation?** [OPEN ENDED]
    b. **Will it be drier/less dry in summer or winter or both?** [OPEN ENDED]

12. [EXPECTATIONS] **Do you agree or disagree that in the future water supplies in this area ...**
    a. **Will be adequate for human and environmental needs even if we don't enforce limits on current water use**
       i. **Please explain** [OPEN ENDED]
       ii. **Please evaluate:**

Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree	Don't know
☐	☐	☐	☐	☐	☐

What we need for effective communication and decision making

- Improving communication and usability of weather and climate information requires
  - Understanding how intended audiences ***perceive, interpret, and use information*** (i.e., drought projections)
  - Applying findings to improve development, provision, and ***communication of information*** (i.e., for effective drought planning)

Thank you!

Heather Lazrus **hlazrus@ucar.edu**

Mesoscale and Microscale Meteorology/

Integrated Science Program

NCAR

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

APPLICATIONS AND USE OF MODEL DATA

ATMOSPHERIC CHEMISTRY / AIR QUALITY

Gabriele Pfister

Atmospheric Chemistry Division

In collaboration with

Mary Barth, Cindy Bruyere, James Done, Greg Holland,
Jean-Francois Lamarque, Stacy Walters

Climate and atmospheric composition/air quality

- **Climate and weather impact atmospheric chemistry/composition**
- **Atmospheric chemistry/composition impacts climate and weather**
- **Weather and climate influence air quality**

Examine feedbacks between

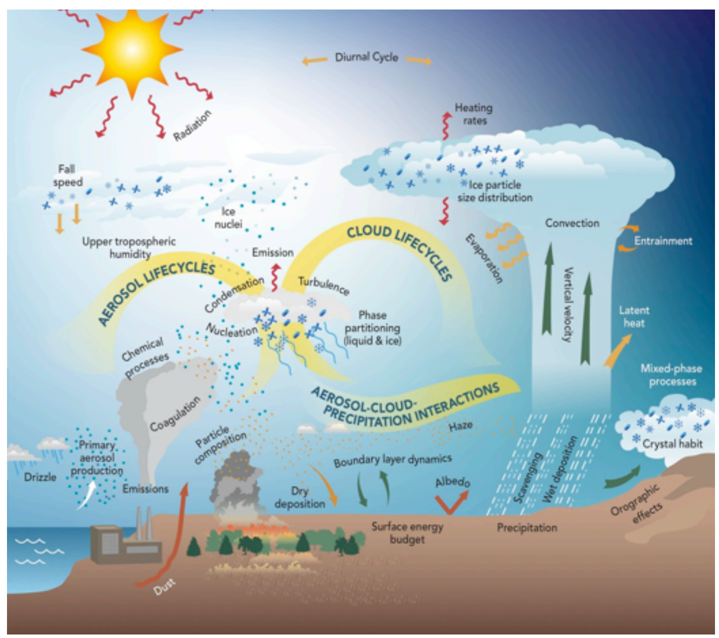
atmospheric composition and climate

Climate and atmospheric composition/air quality

Examples:

- Emissions, chemical processes as well as climate & weather control ozone and methane
  -> ozone and methane in turn are important climate forcing agents.

- Impact of emissions of short-lived climate forcers (and precursors) on climate
  -> e.g. tropospheric aerosols and their effects on climate by changing radiation and clouds through direct and indirect effects



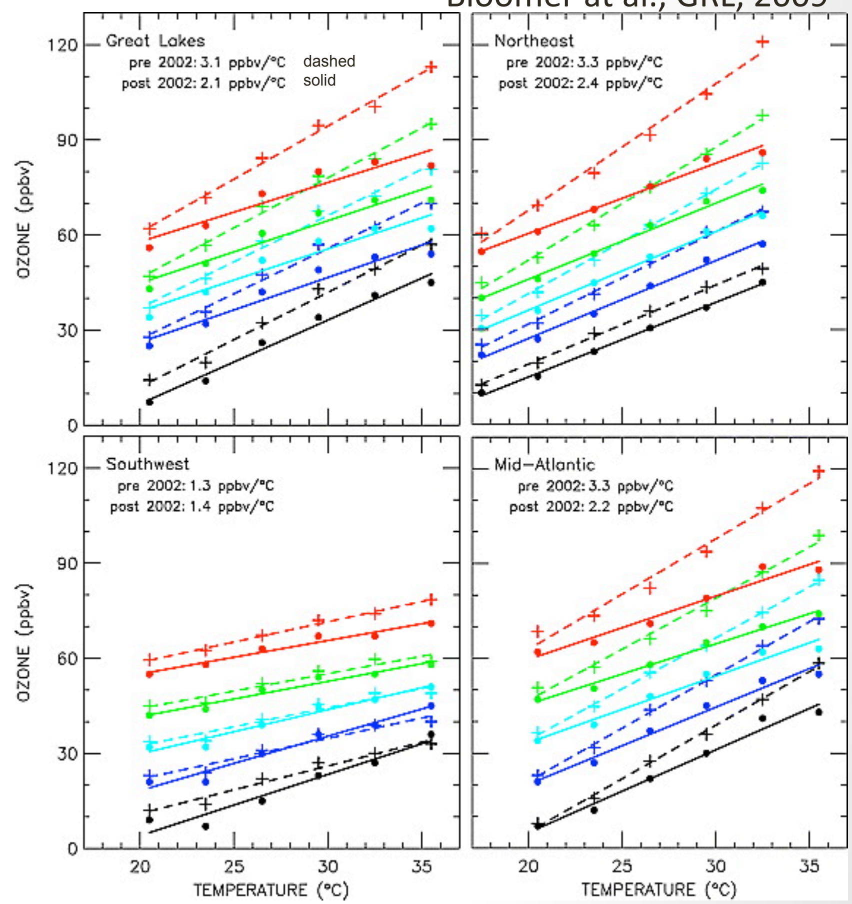
Source: ASR

Climate and atmospheric composition/air quality

Examples:

- How is air quality evolving under a future climate and future emission scenarios?
  (e.g. correlation between T and ozone)
- Boundary layer meteorology strongly impacts surface concentrations of trace gases and aerosols and their evolution.
- Changes in future weather patterns influence air quality (e.g, a future climate with more frequent stagnation events or heat waves could lead to increased air pollution episodes)

Bloomer at al., GRL, 2009



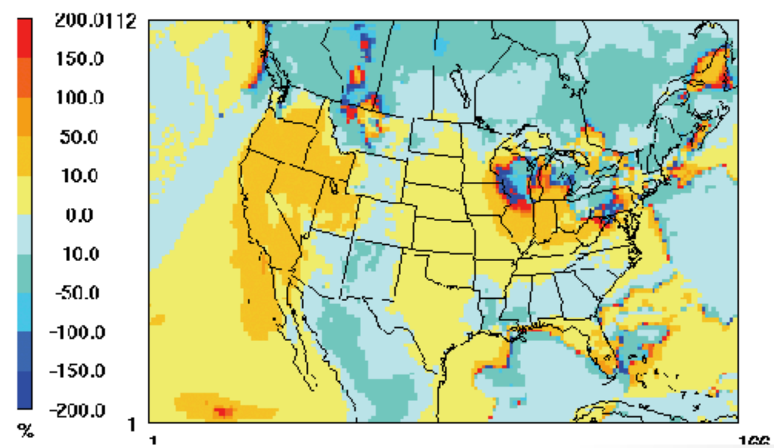
Observed relationship between temperature and ozone
Colors are different percentiles (95th, 75th, 50th, 25th, 5th)

Climate and atmospheric composition/air quality

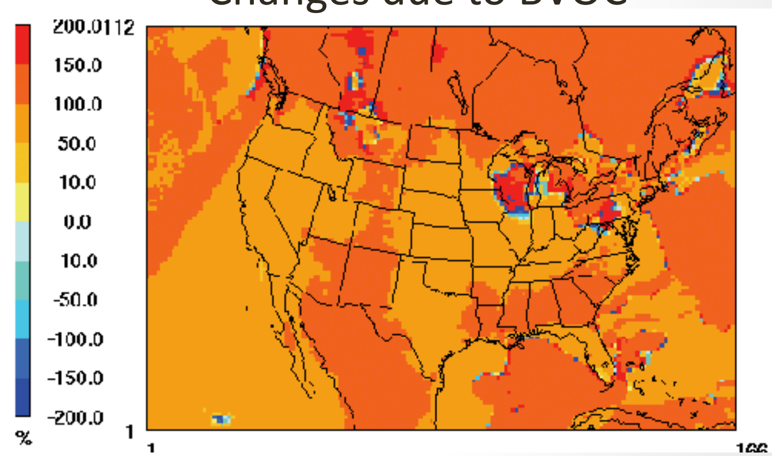
Examples:

- Climate and weather impact the type and state of vegetation
  - ➔ control biogenic emissions
  - ➔ impact on ozone, SOA, etc.
  - ➔ feedback on climate and weather

Changes due to Climate



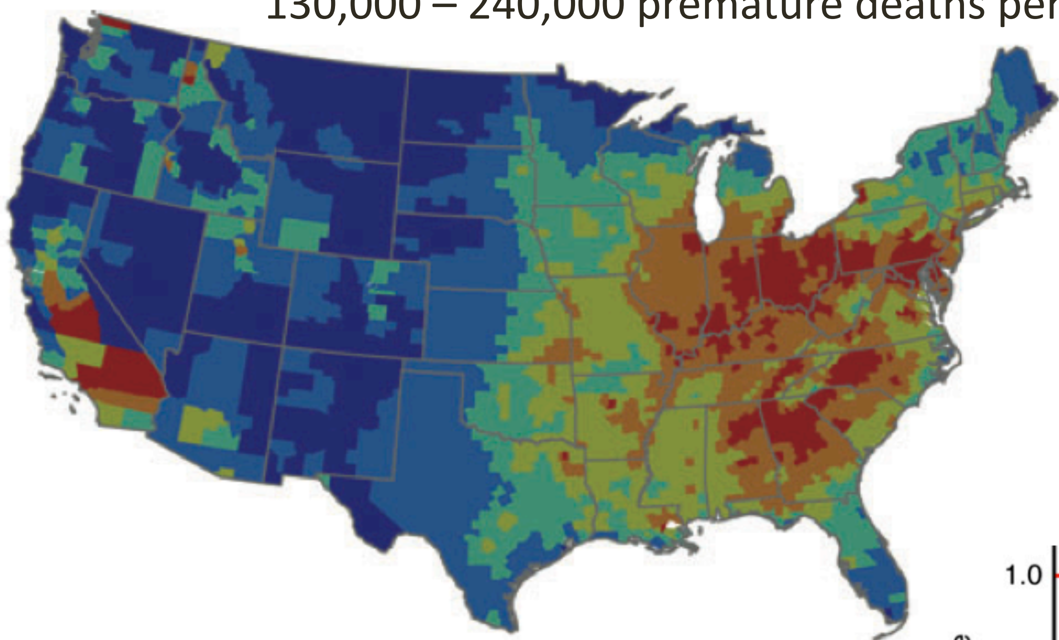
Changes due to BVOC

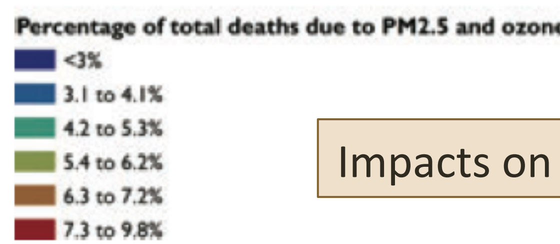


Rel. Change in 24-hour PM2.5
(2051 to 2001) Zhang et al., 2008

Societal Relevance

130,000 – 240,000 premature deaths per year are attributable to PM2.5 and ozone (Fann et al., Risk Analysis, 2011)



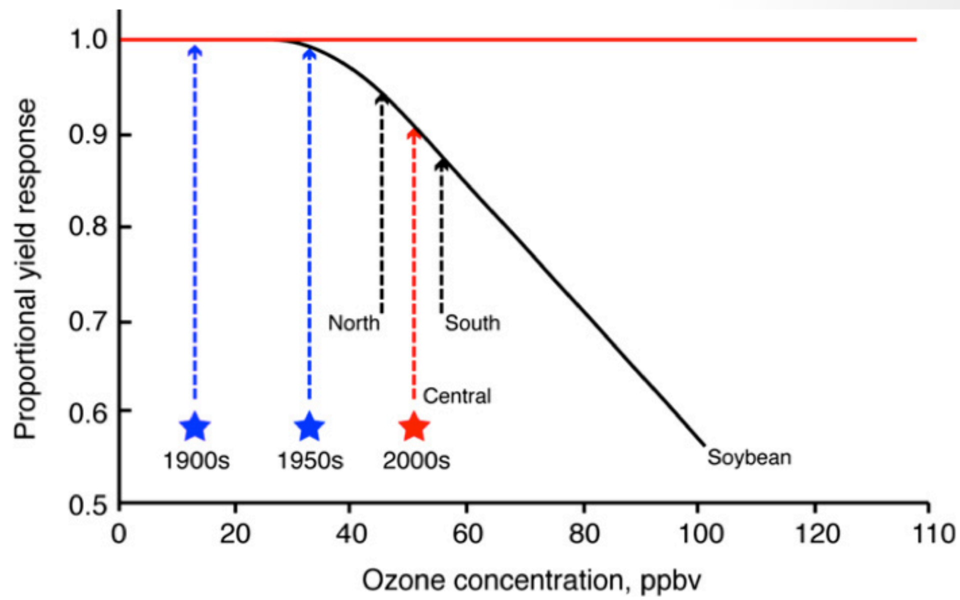


Impacts on Health

Impacts on Vegetation Growth

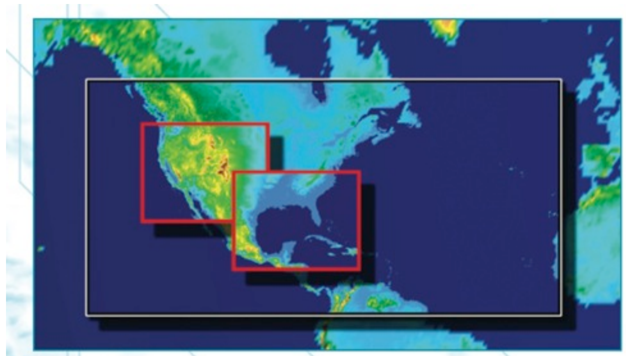
Fig. 7. Relationship between relative yield of soybean as a function of concentration (after Heagle, 1989) and measured surface O_3 concentrations over the past century (from Volz and Kley (1988) and Staehelin et al. (1994)) and in the current study over the three regions defined by "North," "Central" and "South" (see text for further details).

from Fishman et al., Atm. Env. (2010)



WRF-Chem in Climate Runs

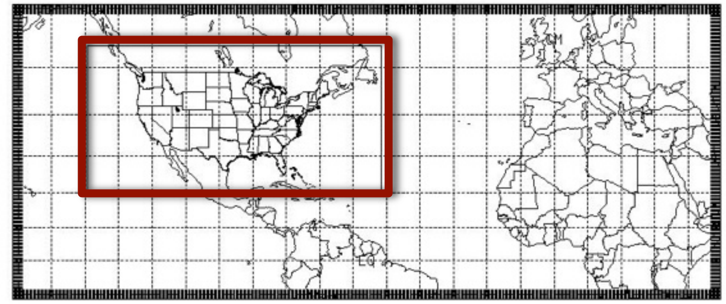
Physical Climate: WRF forced by CESM setup ("NRCM")



Physical and *Chemical* Climate - WRF-Chem forced by CESM/CAM-Chem ("NRCM-Chem")

- Which chemical mechanisms and which aerosol scheme?
- Anthropogenic emissions?
- Fire emissions?
- Biogenic Emissions?
- Chemical initial and boundary conditions?
- Stratospheric Ozone?
- What type of output?
- Evaluation?

ACD/MMM NRCM-Chem Simulation Example



- **Basic Setup:**

12 x 12 km^2 for contiguous U.S. (~ 700 x 350)

Time Periods: 1995-2005 2025-2035 2045-2055

Meteorological IC and BC: NRCM 36 x 36 km^2 output
Chemical IC and BC: CAM-Chem global climate simulations for ACCMIP

Physics: CAM-5 Physics (incorporated into WRF-Chem by PNNL)

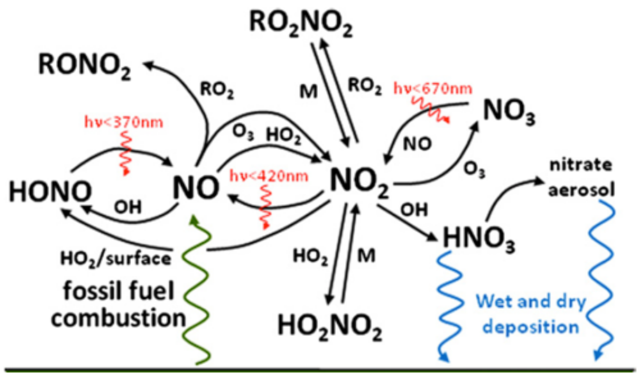
Chemistry: Reduced hydrocarbon scheme (Howeling et al., 1998)

Aerosols: Modal MAM aerosol scheme (SOA, direct and indirect effect)

Sensitivity runs with meteorology only and coupled to chemistry
➔ impacts of feedbacks between atmospheric composition and climate

WRF-Chem – Chemical/Aerosol Scheme

Accurate representation of chemical processes *vs* computing requirements



Number of Species added with, e.g.:

GOCART simple	*lumped aerosols only, no gas phase chemistry*	19
MOZCART	*MOZART gas phase, lumped GOCART aerosols*	96
RACM/SORG	*RACM gas phase, model aerosol*	93
CBMZ/MOZAIC	*CBMZ gas phase, 8 size bin aerosols*	230

☒ Reduced Hydrocarbon Chemistry and MAM aerosol with SOA (73 species) (same scheme also included in CAM-Chem/CESM)

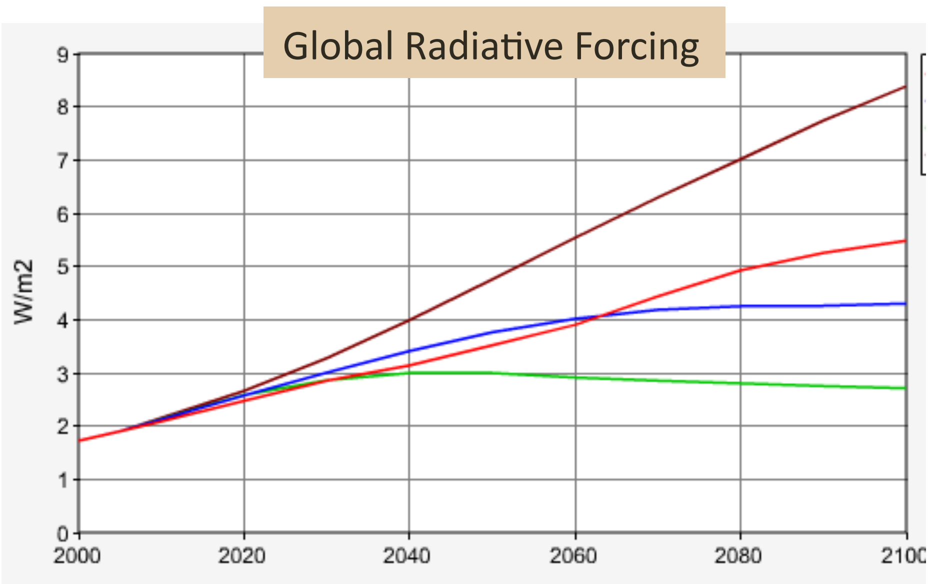
Anthropogenic Emissions

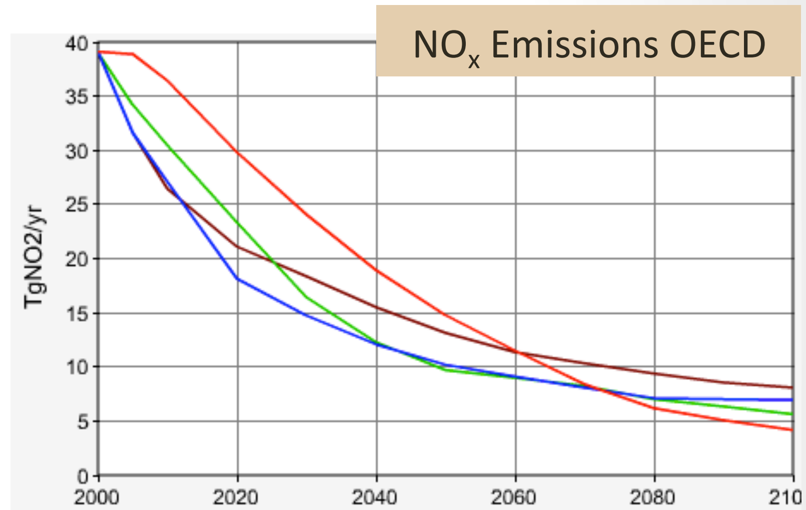
-> **<u>High resolution</u>** emission inventories for present & future for all gas and aerosol species

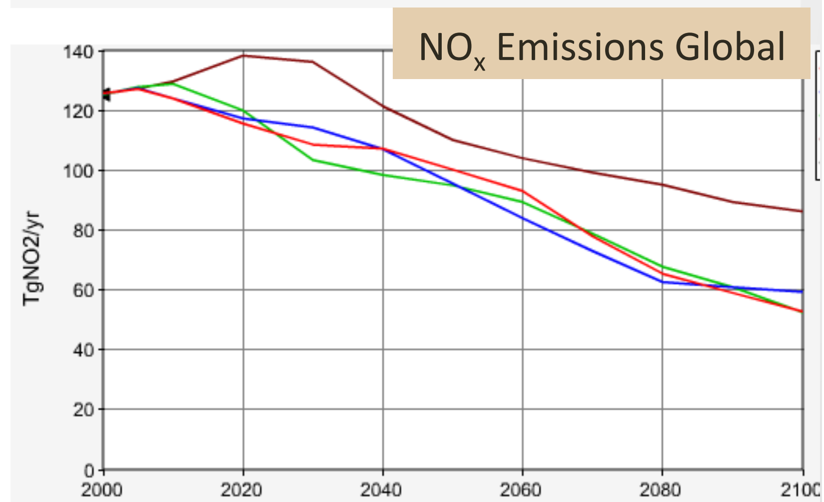
Decide: • Future Scenario? RCP? Which?

Change in Radiative Forcing ≠ Change in Air Quality

RCP 2.6
RCP 4.5
RCP 6.0
RCP 8.5







RCP source: http://www.iiasa.ac.at

Anthropogenic Emissions

-> **<u>High resolution</u>** emission inventories for present & future for all gas and aerosol species

Decide:

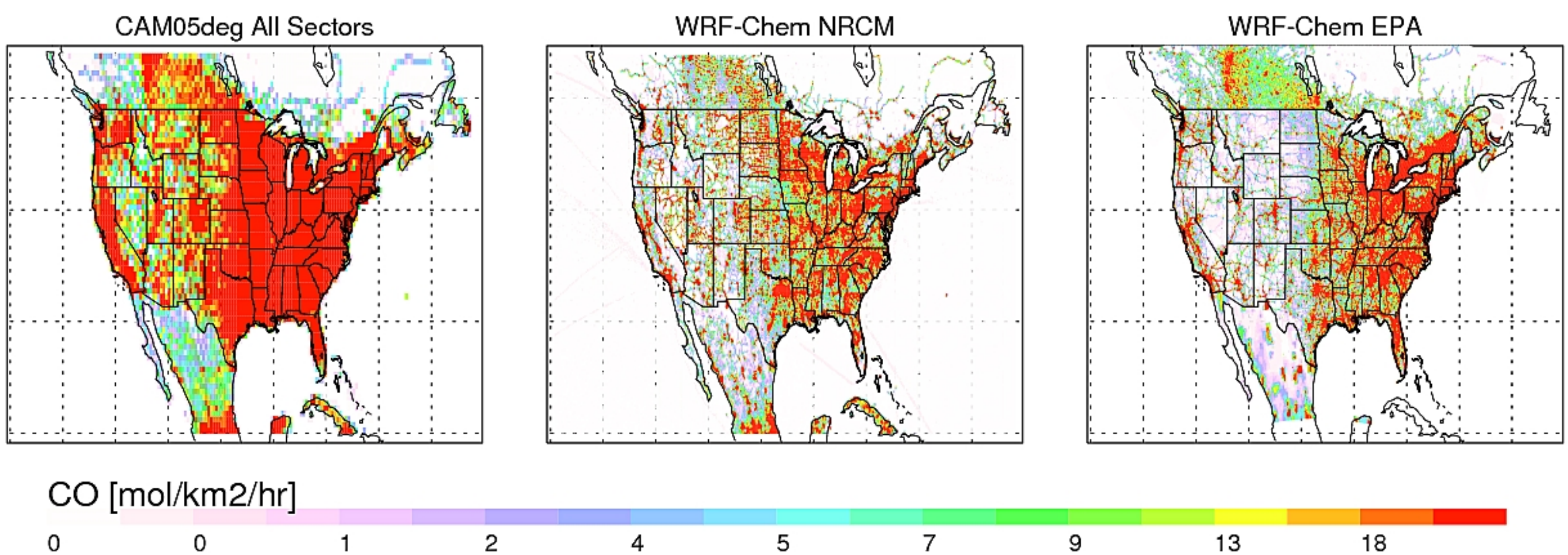
- Future Scenario? RCP? Which?
- Seasonal and diurnal variability?
- Inter-annual variability?
- Spatial distribution for future scenario?
- Emissions from aircraft? Ships?

Anthropogenic Emissions

-> **<u>High resolution</u>** emission inventories for present & future for all gas and aerosol species

Decide:
- Future Scenario? RCP? Which?
- Seasonal and diurnal variability?
- Inter-annual variability?
- Spatial distribution for future scenario?
- Emissions from aircraft? Ships?

☒ CAM-Chem RCP 0.5 °x 0.5° -> scaled on sector basis to distribution of EDGAR 0.1° x 0.1°
RCP 8.5 for future years

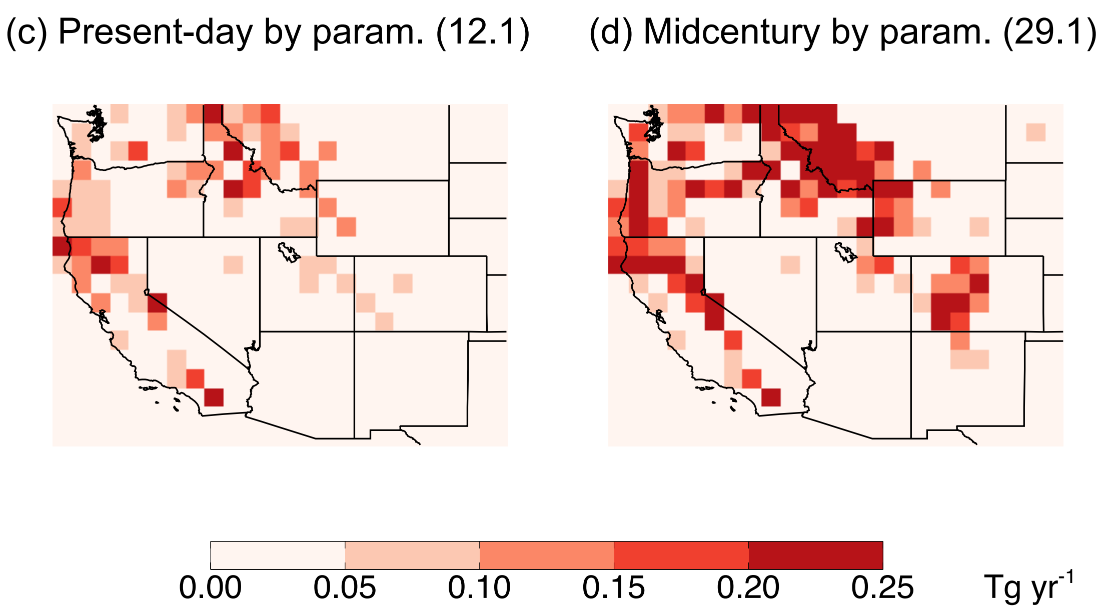


Fire Emissions

- How to define future emission scenarios ?
- Constant fire emissions for present and future?
- Daily/monthly/seasonal?
- Feedback on land cover?

☒ Daily climatology from NCAR Fire Model FINN (2002-2010) for present and future

"Interactive" Way: Predictions - Regression analysis of meteorological variables and fire parameters for current and past years



Projected Annual Total Biomass Burned (Xu et al., submitted to JGR)

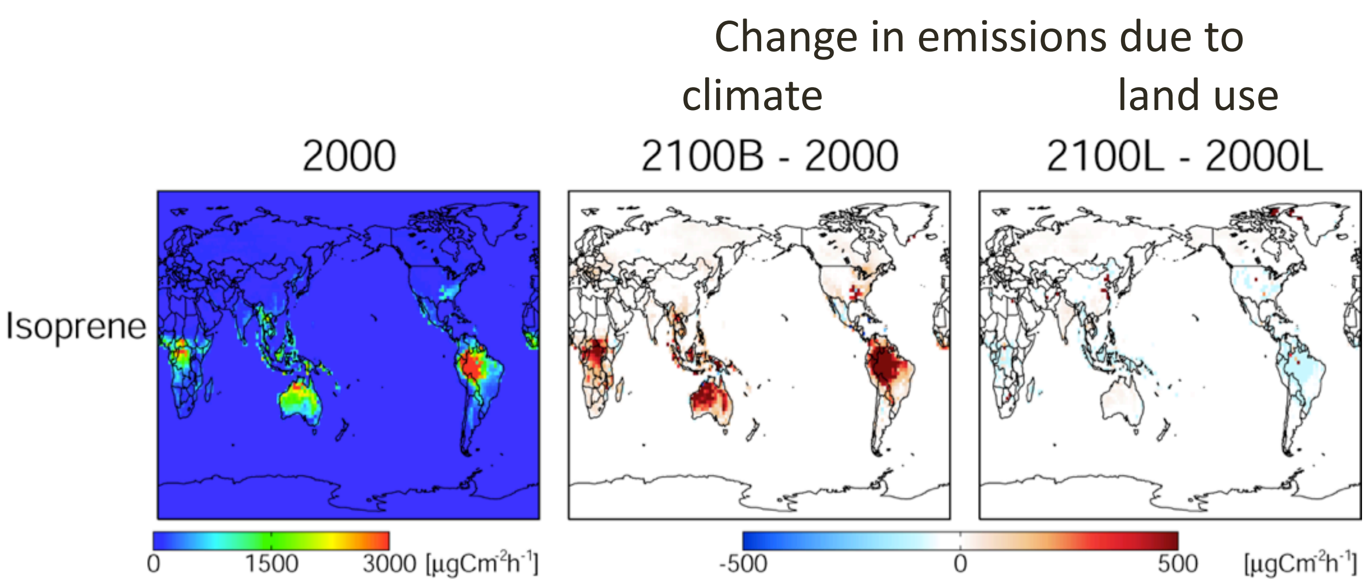
Biogenic Emissions and Land Cover

Currently in WRF-Chem: MEGAN biogenic emissions calculated online with dependence on solar radiation, temperature, etc.. **But**: uses it's own land cover and not the one in WRF.

Future changes in biogenic emissions expected because of changes in meteorology AND Changes in land cover.

☒ No change in land cover; limit to impact of climate on biogenic emissions

<u>Desirable</u>: Meteorology, biogenic emissions and deposition linked to land model as e.g. in CAM-Chem (Heald et al., 2008 and Lamarque et al., 2011)

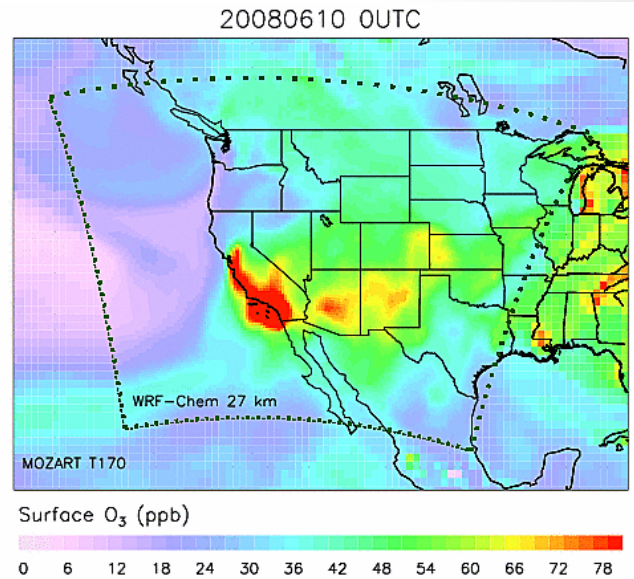


(from Heald et al., 2008)

Initial and Boundary Conditions

Need chemical IC and BC for time period of consideration for all long-lived (≥hours) gas and aerosol species

- Mapping of species needed?
- Frequency of Update?
- Reflect trend in atmospheric composition resulting from emission/climate changes from rest of world?



☒ CAM-Chem monthly mean
Note: meteorology not compatible with CESM

Other Consideration:

- Stratosphere – Upper boundary conditions for present and future?
- Initial Conditions. E.g importance of well represented aerosols in IC – risk to "kick off" climate in wrong direction?

"Climate predictions over decadal time scales are expected to depend crucially on both initial conditions and the changing radiative forcing (Cox and Stephenson, 2007)"

Runtime and Output

- Chemical variables add significant amount of runtime and output
  Writing output accounts for large part of runtime
  Meteorological/chemical time step
  Chemistry input files require additional disk space

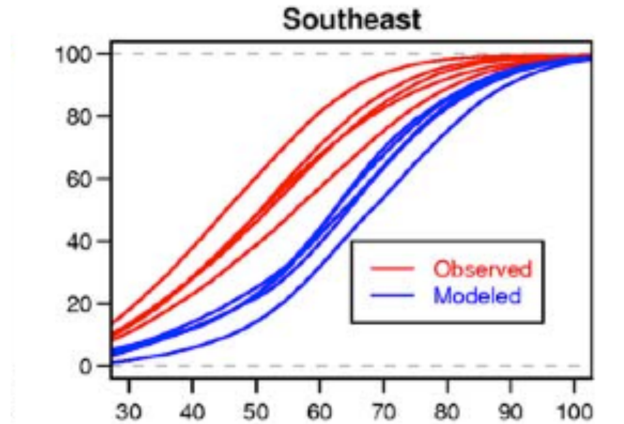
- AQ Health Standards are based on hourly information (e.g. 8-hour average ozone and hourly ozone NAAQS)

- In Air Quality the main focus is on surface and on criteria pollutants, but for interpretation we need 3D information & other species.

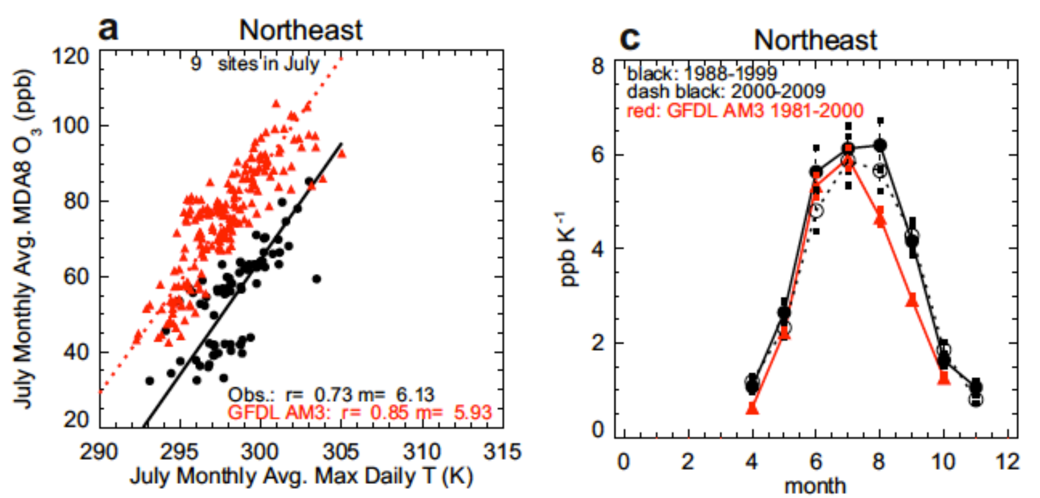
Hourly surface fields of main pollutants and meteorological parameters & 6-hour (average) 3D fields (code modifications needed)

Evaluation and Analysis

- Climatological Year ≠ Actual Year
- Evaluate with statistics for present time observations and climatologies
- Evaluate relationships and feedbacks
- Statistical Downscaling/Tail of distribution
  (What can we learn from physical climate applications?)
- Evaluation of dynamical, physical & chemical field!



Observed (red) and modeled (blue) cumulative distribution of MDA8 ozone for May-Sep 1999-2003. Nolte et al., JGR 2008



Relationships between monthly regional averages of MDA8 O3 (ppb) and of daily Tmax (K) for individual years (black) and from the GFDL AM3 model (red). Rasmussen et al., Atmos. Environ. 2012