Some Extreme Value Problems in Climatology

Banff interdisciplinary workshop on extremes,
23rd August 2010
Banff, Canada

Eric Gilleland
E-mail: EricG @ ucar.edu
Research Applications Laboratory,
National Center for Atmospheric Research (NCAR)
Weather and Climate Impacts Assessment Science (WCIAS) Program

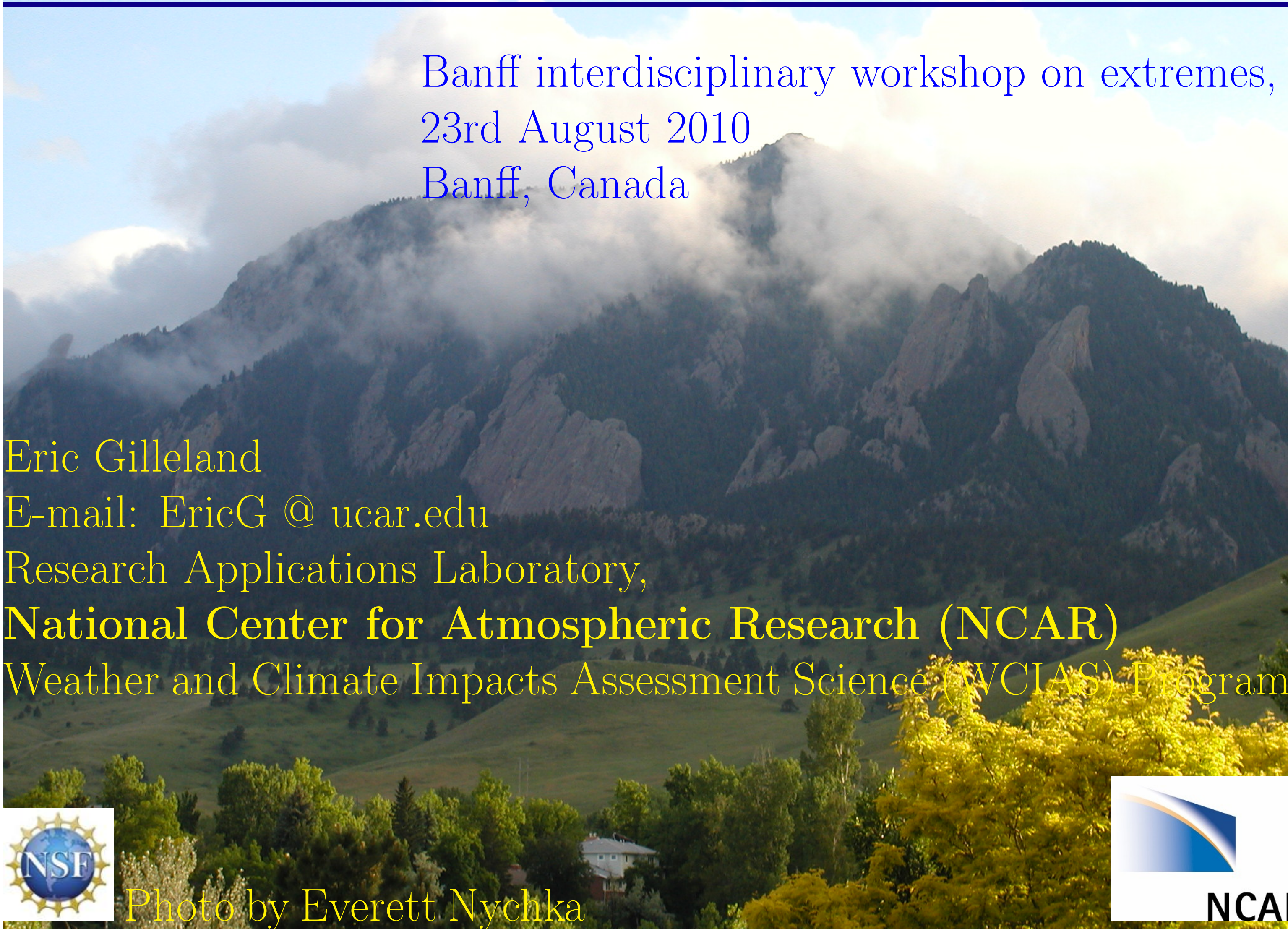
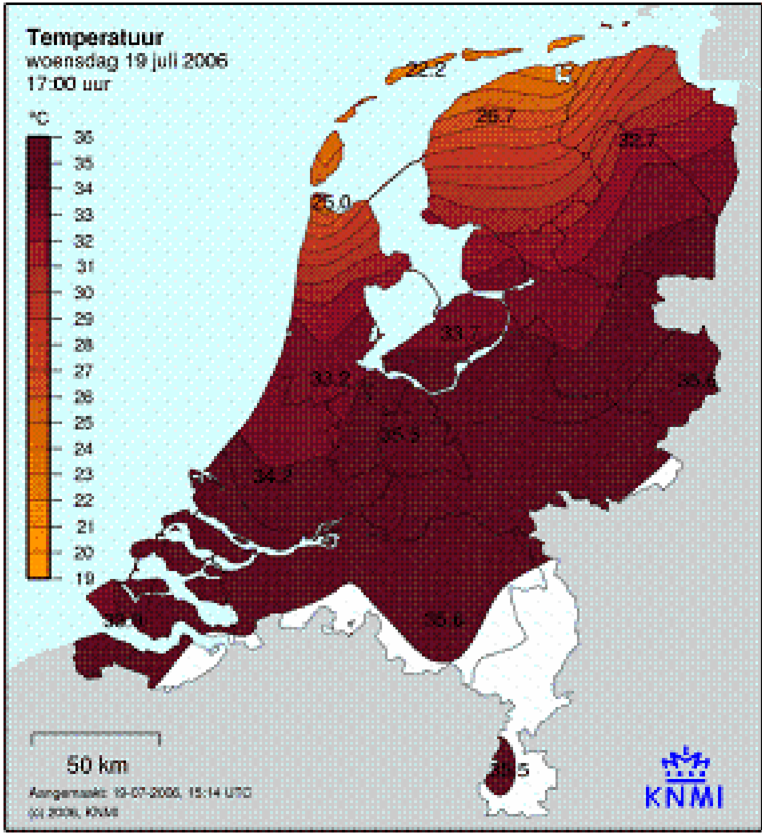


Photo by Everett Nychka

NSF

NCAR

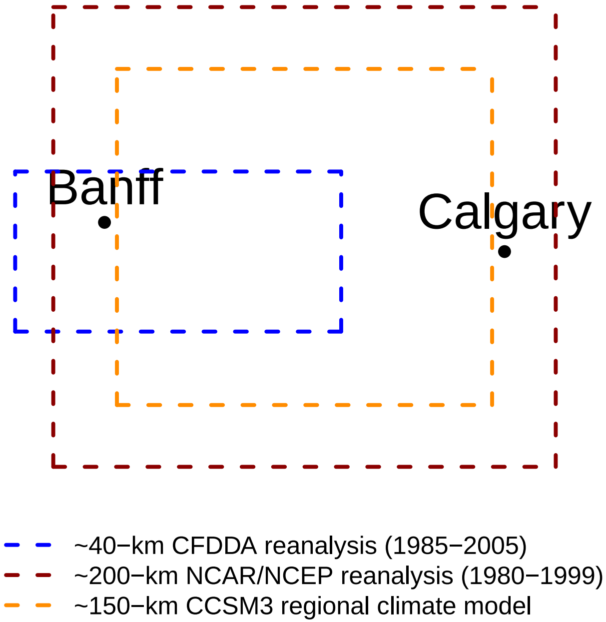
Scale

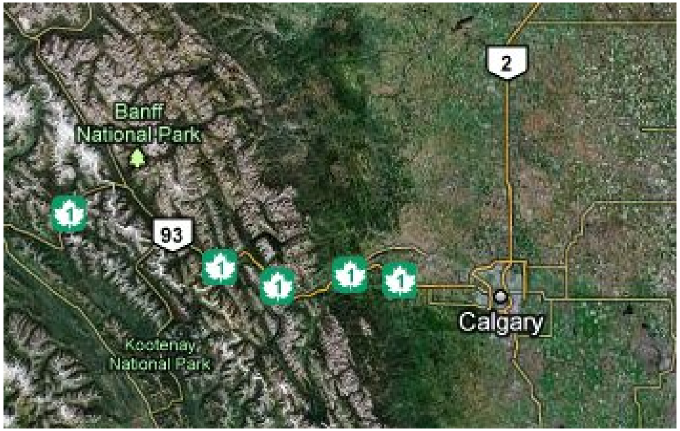


2006 European Heat Wave
(Fig. from KNMI)

F5 Tornado in Elie Manitoba
on Friday, June 22nd, 2007

Resolution


Banff
Calgary
~40−km CFDDA reanalysis (1985−2005)
~200−km NCAR/NCEP reanalysis (1980−1999)
~150−km CCSM3 regional climate model


Banff National Park
Kootenay National Park
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2
93
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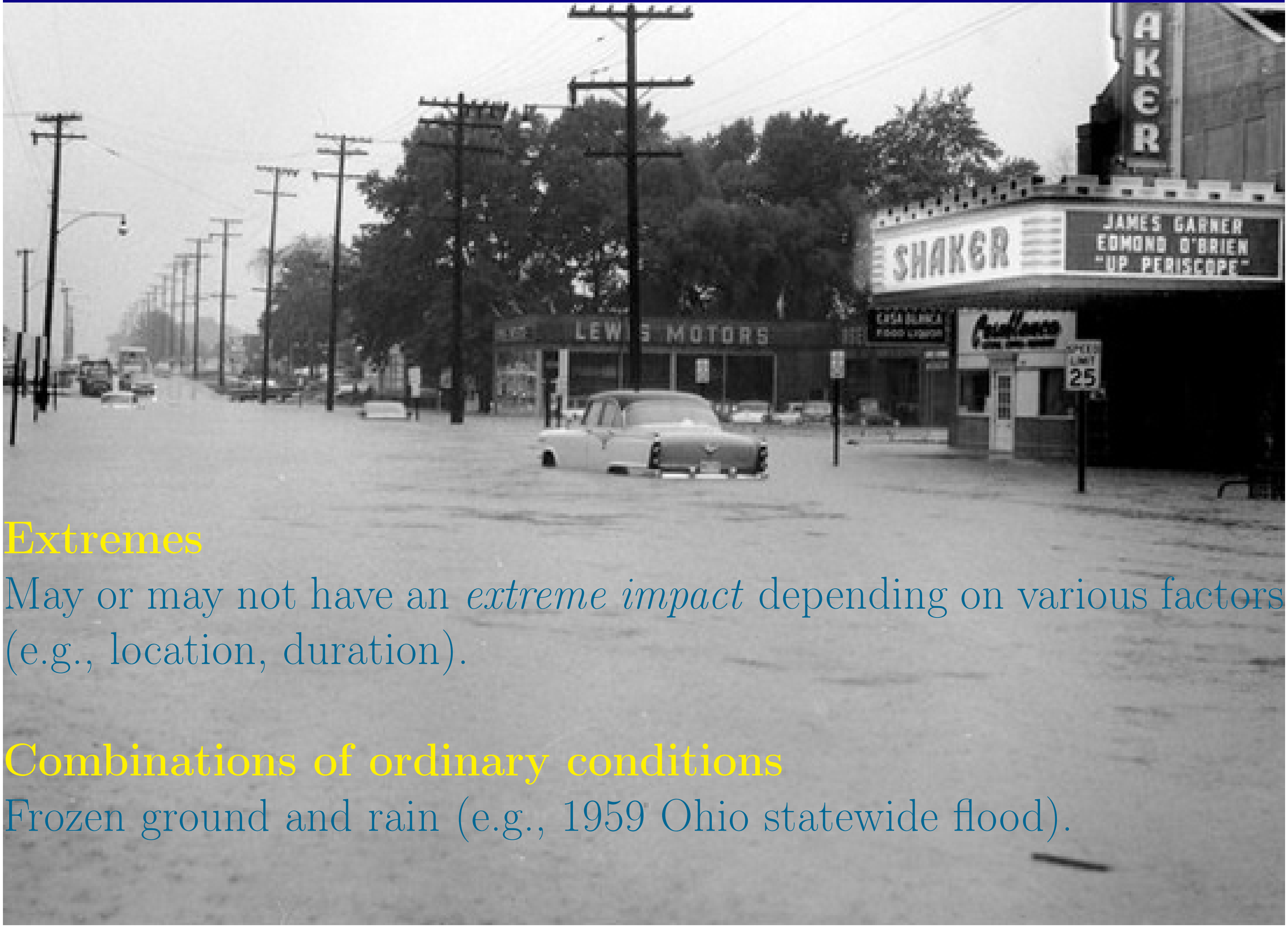
Extremes vs Extreme Impacts

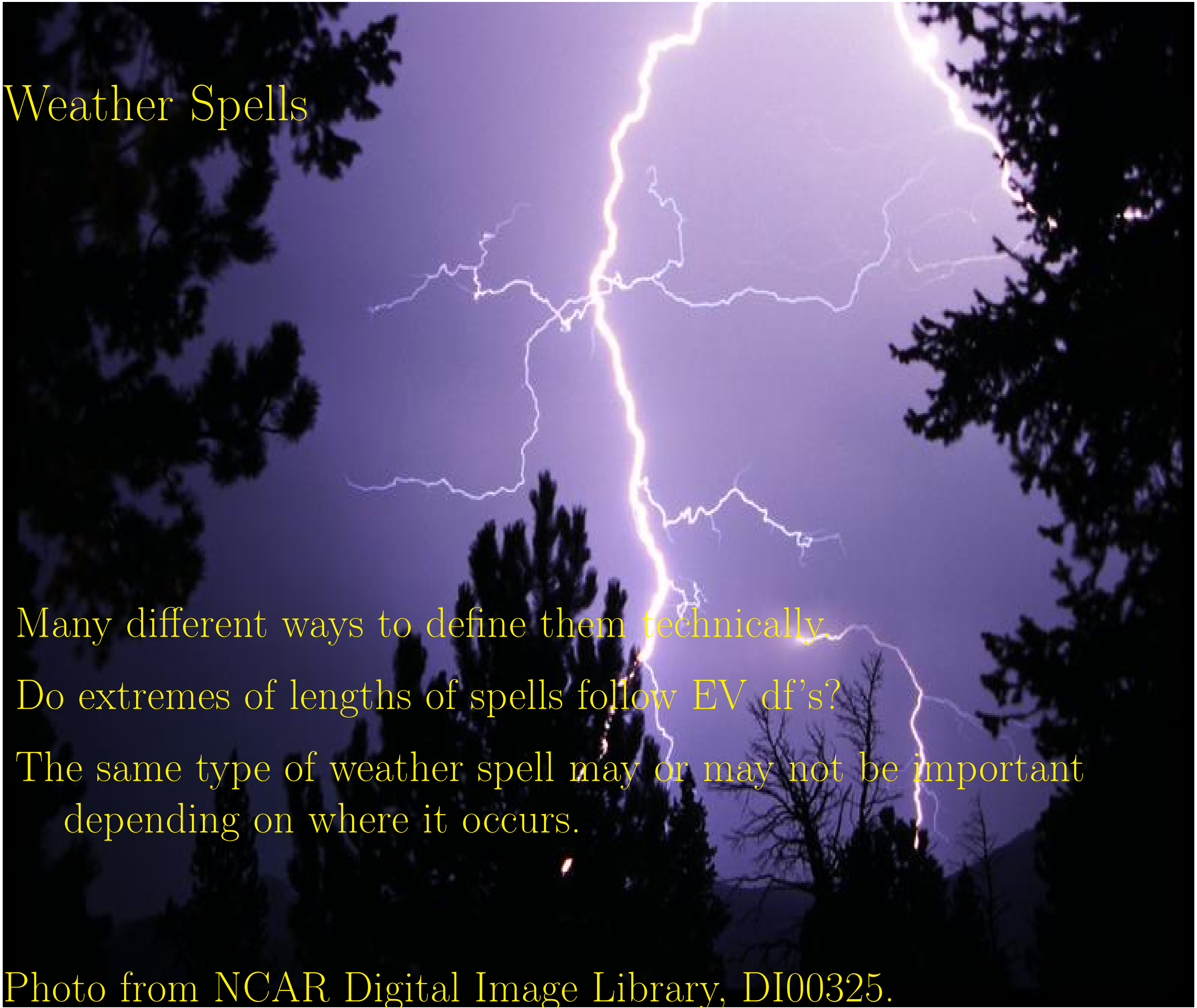


Extremes

May or may not have an *extreme impact* depending on various factors (e.g., location, duration).

Combinations of ordinary conditions

Frozen ground and rain (e.g., 1959 Ohio statewide flood).



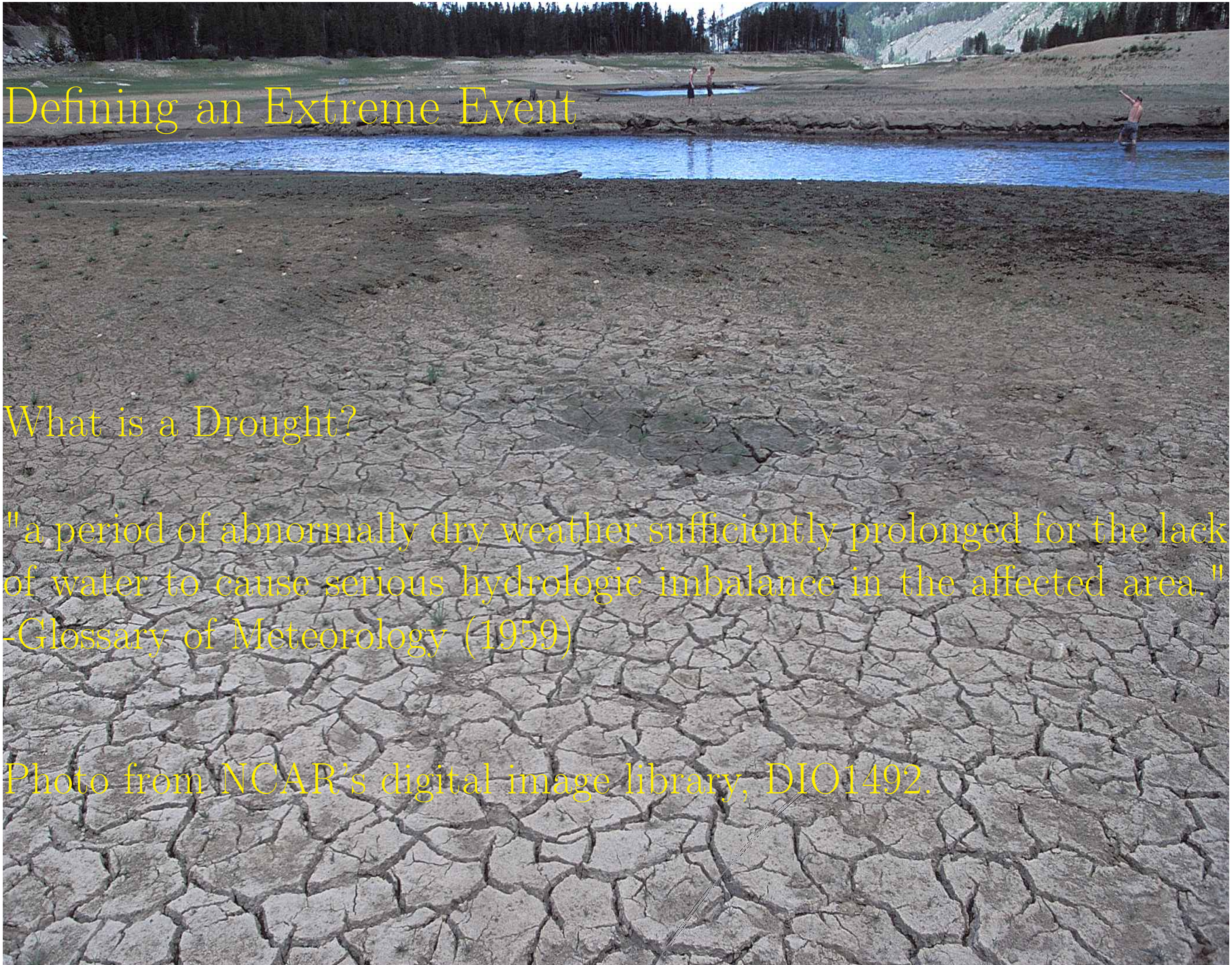
Weather Spells

Many different ways to define them technically.

Do extremes of lengths of spells follow EV df's?

The same type of weather spell may or may not be important depending on where it occurs.

Photo from NCAR Digital Image Library, DI00325.



Defining an Extreme Event

What is a Drought?

"a period of abnormally dry weather sufficiently prolonged for the lack of water to cause serious hydrologic imbalance in the affected area."
-Glossary of Meteorology (1959)

Photo from NCAR's digital image library, DIO1492.

Defining an Extreme Event

What is a Drought?

Meteorological–a measure of departure of precipitation from normal. Due to climatic differences, what might be considered a drought in one location of the country may not be a drought in another location.

Agricultural–refers to a situation where the amount of moisture in the soil no longer meets the needs of a particular crop.

Hydrological–occurs when surface and subsurface water supplies are below normal.

Socioeconomic–refers to the situation that occurs when physical water shortages begin to affect people.

http://www.wrh.noaa.gov/fgz/science/drought.php?wfo=fgz

Droughts

Cebrián and Abaurrea (2006), *J. Hydrometeorology*, **7**, 713–723

- How long is a drought expected to last?
- How severe will it be?
- How often will it occur?

Use Meteorological definition, but note that other factors (e.g., high temperature, wind, low RH, etc.) can make a drought more severe in terms of impacts.

Approach to studying droughts: Marked Poisson Cluster Process
$s(t)$ a stochastic process, which they take to be the previous 12-month accumulated precipitation.

Droughts

Cebrián and Abaurrea (2006), cont.

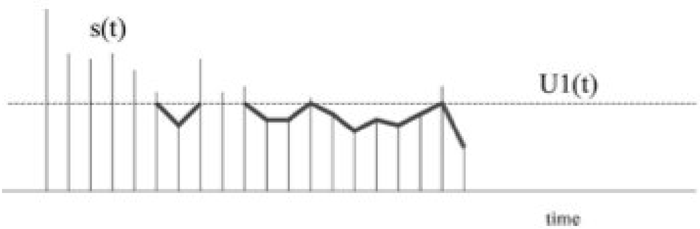


FIG. 1. Dry spell definition.

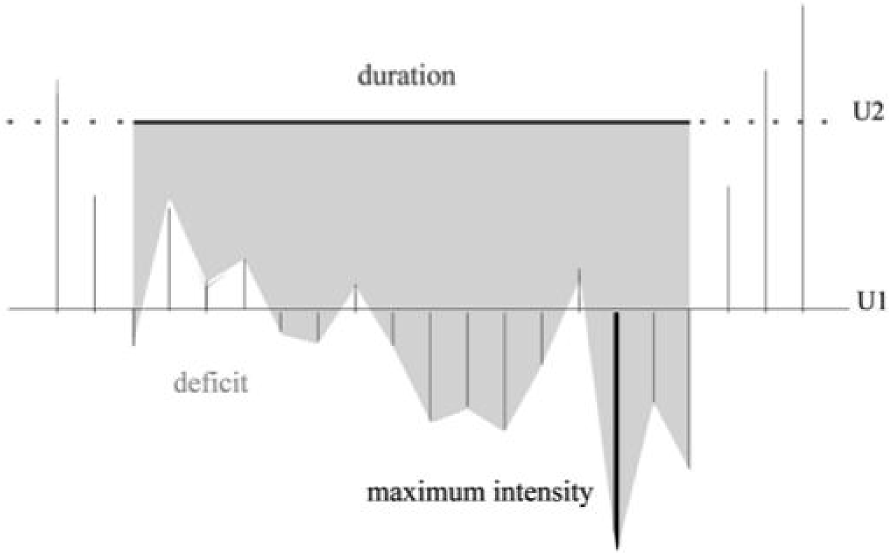


FIG. 2. Definition of the severity variables of a drought.

Criteria to determine drought events: empirical approach based on Ferro and Segers (2003), but include information about intensity of inter-dry spell periods.

Droughts

Groisman and Knight (2008), *J. Climate*, **21**, 1850–1862

Number of rainy days over United States has increased over past 100 years, but opposite trends appear in some regions during past 35–40 years. Can have impacts during warm season (temperature persistently $> 5^o$C).

Count *strings* of days as the number of days where daily precipitation is < 1 mm. Calculate:

1. Number of days in *warm* season,
2. Number of strings of dry days, and
3. String lengths (Focus only on strings of $> X$ days).

$X = 30, 60, 90$.

Droughts

Schubert *et al.* (2010), *J. Climate* (to appear)

U.S. CLIVAR Drought Working Group (DWG) formed in 2006 to coordinate evaluations of existing model simulations, as well as new experiments designed to address outstanding issues about drought variability and predictability. Six modeling groups produced simulations. Primary focus on the role of SST variability on changes in the atmospheric circulation and terrestrial climate.

Droughts

Pegion and Kumar (2010) accepted to *J. Climate*

Investigate modes of SST variability (i.e., PC analysis), and compare with precipitation.

- Increases in precipitation over warmer Atlantic SST's lead to reduction of precipitation over the tropical Pacific warm pool.
- Above reduction produces a *wave train* across the North Pacific into North America. United States is very sensitive to variations in SST's.
- Noted changes in pdf for annual mean precipitation over the great plains region with probability of deficit largest for the cold phase of the Pacific SST mode.

Defining an Extreme Event

What is a Heat Wave?

(e.g., Meehl and Tebaldi, 2004, Science, **305**, 994–997):

- Three-day worst heat event: mean annual 3-day warmest nighttime minima event.
- Threshold excess: The longest period of consecutive days satisfying:
  1. daily maximum temperature above T1 for at least three days,
  2. average daily maximum temperature above T1 for entire period, and
  3. daily maximum temperature above T2 for every day of entire period.

T1 = 97.5th percentile of the df of maximum temperatures in observed and present-day climate simulations. T2 = 81st percentile.

Heat Waves

Karl and Knight (1997), *Bull. Amer. Meteorol. Soc.*, **78** (6), 1107–1119

Analyzing the 1995 Chicago Heat Wave

Temperature and humidity, as indicators of *heat stress* (apparent temperature, T_{ap}).

Median, upper and lower quartiles, maximum, and minimum of hourly T_{ap} for 24-, 48- and 72-hour periods for summers in Chicago.

Heat Waves

Khaliq *et al.* (2005), *Int. J. Climatol.* **25**, 485Ð504

Use HDF–Heat, Duration, Frequency approach, similar to intensity, duration, frequency approach used for precipitation events. using AM series for 1–10 day heat waves:

- Model mean heat wave to its duration by $\mu(D) = aD^b$, with a and b parameters.
- Model growth of heat waves using the GEV df.

Shorter heat waves happening earlier. Worst heat waves June to August.

Weather Spells

Some things to consider

- How should a spell be defined?
  - In terms of impacts? (Varies greatly by region)
  - In terms of perceived impact (e.g., perceived temperature)? (Varies by person)
  - By combinations of variables? (not necessarily extreme)
  - Duration of some persistent event?
  - Can/Should EVT be used for these types of phenomena?
- Often only seasons are examined (e.g., summer for heat waves), but times of seasons may be changing, and spells may also shift in time.
- Large-scale phenomena important, as well as local conditions and characteristics.

Severe Weather

As climate models become increased in resolution, they may resolve some severe weather phenomena, such as hurricanes. However, other types of severe weather may still require higher resolution.

- Use large-scale indicators to analyze conditions ripe for severe weather.
- Use climate models as drivers for finer scale weather models.
- Statistical approach to current trends in observations.
- Other?

Severe Weather: Large-scale indicators

Monaghan *et al.* (2010) accepted to *J. Climate*

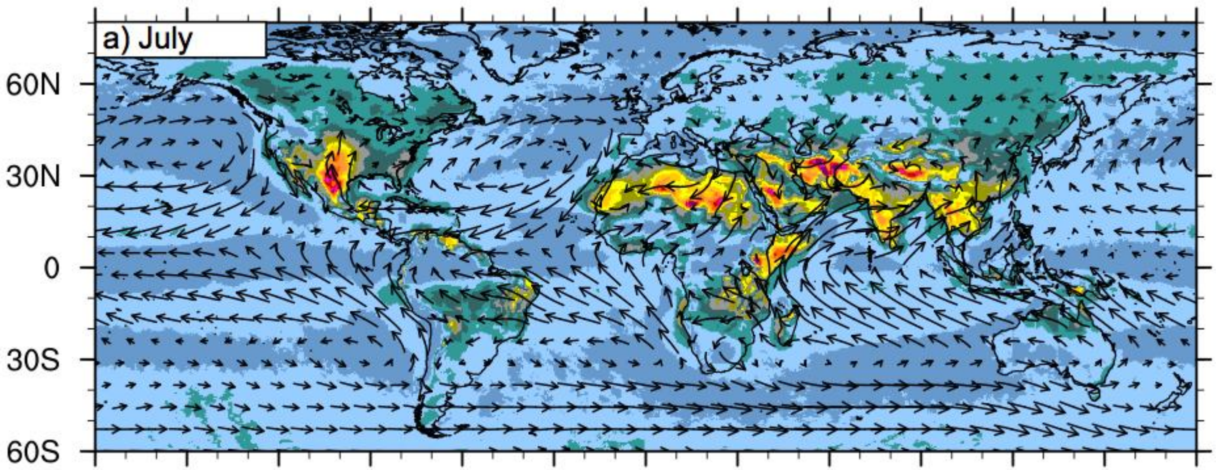
- Nocturnal Low-Level Jets (NLLJ) previously linked to rainfall extremes.
- Used Climate Four Dimensional Data Assimilation (CFDDA) System reanalysis data–based on the 40-km MM5 model (21-year hourly global dataset).
- Realistically simulates vertical, horizontal, and diurnal structure of winds in well-known NLLJ's.
- Realistically simulates diurnal cycle, extremes and spatial structure of rainfall globally compared to satellite-based precipitation data.

Severe Weather: Large-scale indicators

Monaghan *et al.* (2010) accepted to *J. Climate*, cont.

Recent studies show widespread changes in amplitudes of near-surface diurnal heating cycles that in turn play key roles in driving NLLJ's.

Important for future work to address how rainfall extremes may be impacted if trends in diurnal cycles cause the position, magnitude and frequency of NLLJ's to change.



Severe Weather: Large-scale indicators

Monaghan *et al.* (2010) accepted to *J. Climate*, cont.

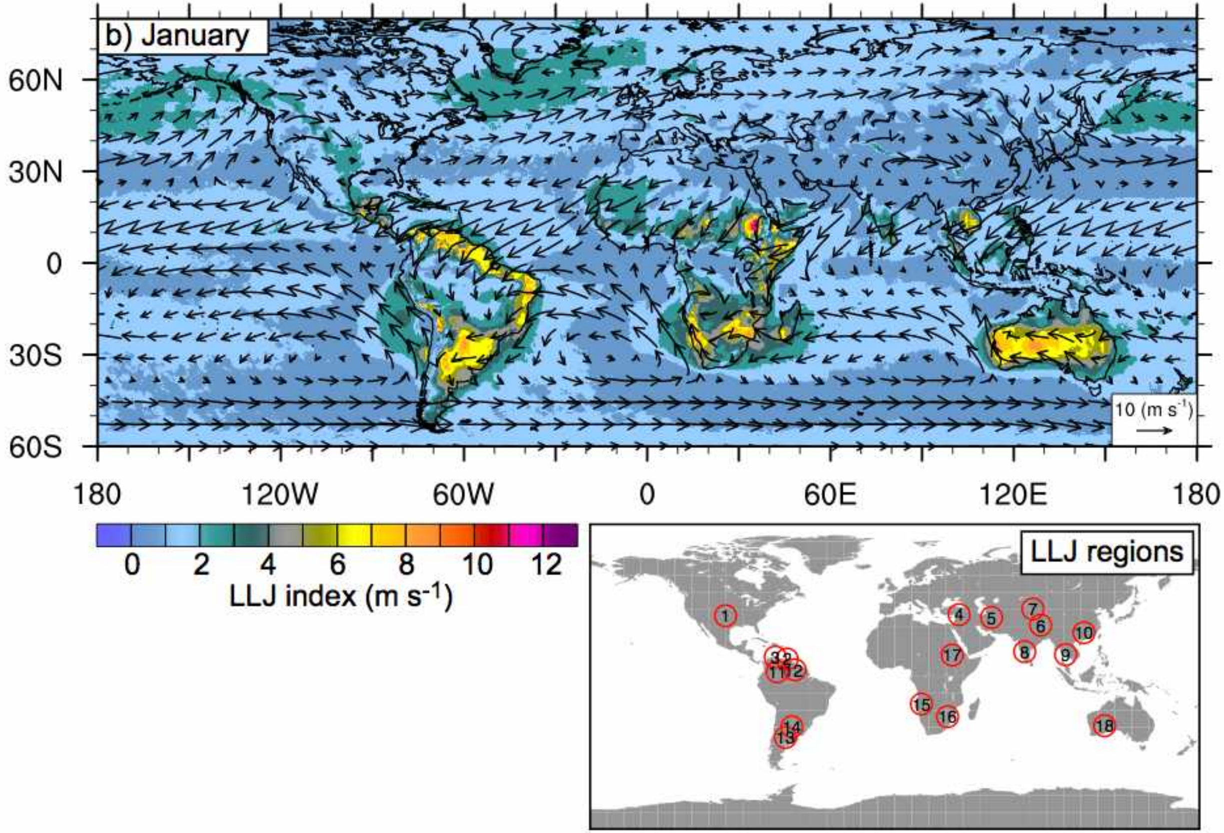
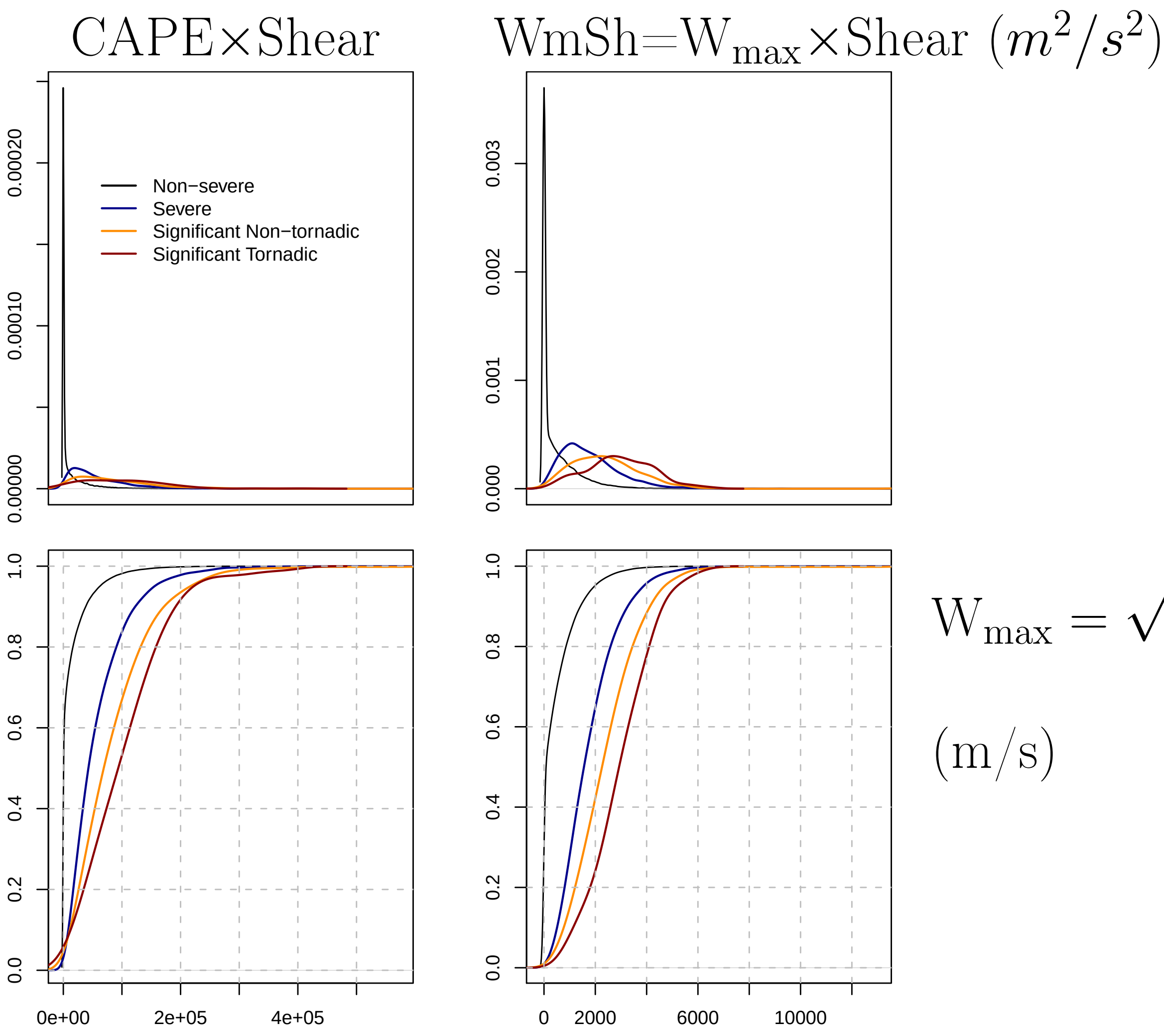


FIG. 4. Mean NLLJ index (shaded) at 0000 LST for 1985-2005 for (a) July and (b) January. The mean 500-m-AGL winds (arrows) are plotted atop the NLLJ index at approximately every twentieth grid point (~10 deg). Numbered boxes in the inset correspond to NLLJs examined in this study, whose characteristics are summarized in Table 1.

Large-scale indicators for Severe weather

Non-severe	hail < 1.9 cm. (3/4 in.) diameter winds < 55 kts. no tornado
Severe	Hail ≥ 1.9 cm. diameter winds ≤ 55 kts. and < 65 kts. or tornado
Significant Non-tornadic	Hail ≥ 5.07 cm. (2 in.) diameter Winds ≥ 65 kts.
Significant Tornadic	Same as sig. tornadic with F2 (or greater) tornado.

Large-scale indicators for Severe weather



$$W_{max} = \sqrt{2 \cdot \text{CAPE}}$$

(m/s)

CAPE (W_{max}) and 0-6 km shear data, or indeed, output

NCAR/NCEP reanalysis data are on a $1.875^o \times 1.915^o$ lon-lat grid with over 17 thousand points covering the globe, and temporal spacing every 6 hours for 42 years (1958-1999). Further details about the reanalysis data can be found in Brooks *et al.* (2003), *Atmos. Res.*, **67–68**, 73–94.

Current climate output from the CCSM3 model for 756 grid points at $1.4^o \times 1.4^o$ resolution over the United States, with temporal spacing of 6 hourly points for 20 years from 1980-1999.

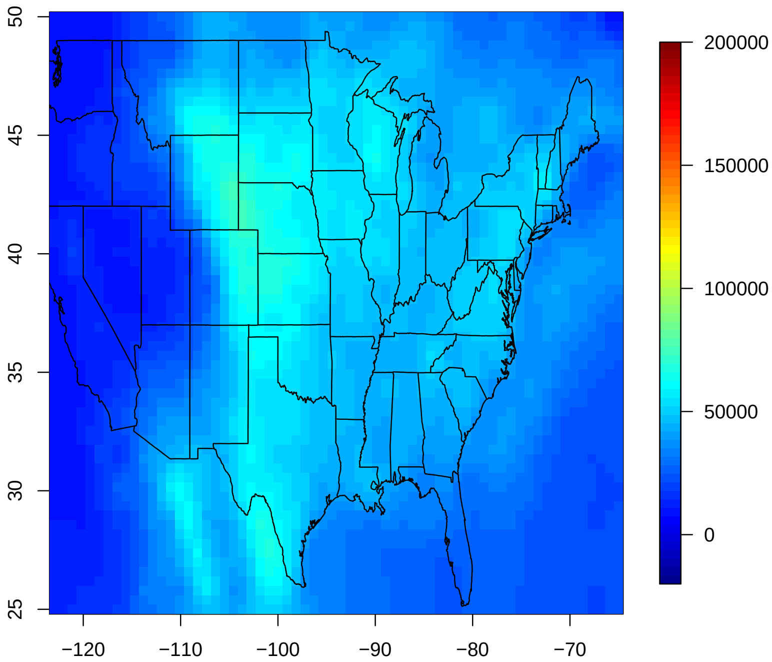
Goals/Questions

Societal Impacts

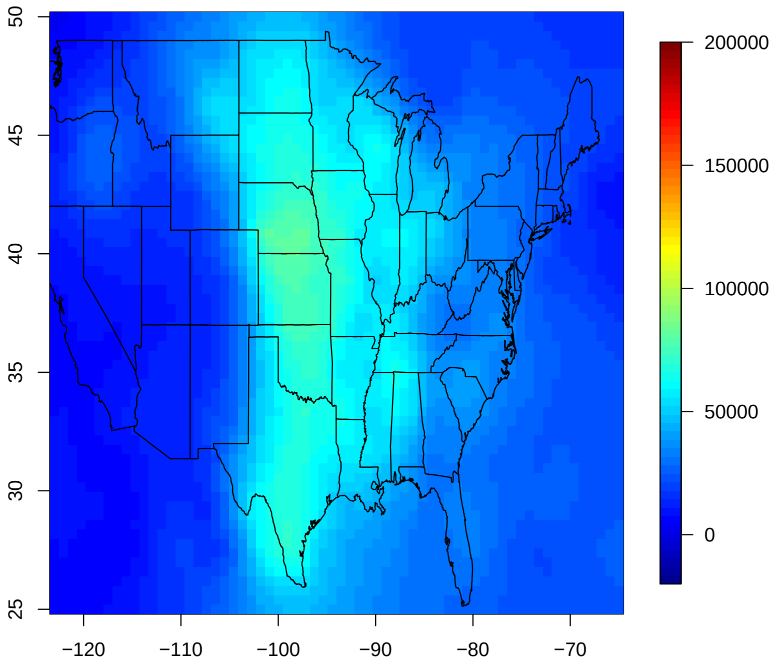
- What can be said about severe weather under a changing climate?
  - Will such events happen more/less frequently?
  - Will they be more/less intense?
- How well does the climate model output characterize the large-scale indicators? How can this be verified?

CCSM3 vs. NCAR/NCEP reanalysis

Median AM cape*shear CCSM3 (1980−1999)



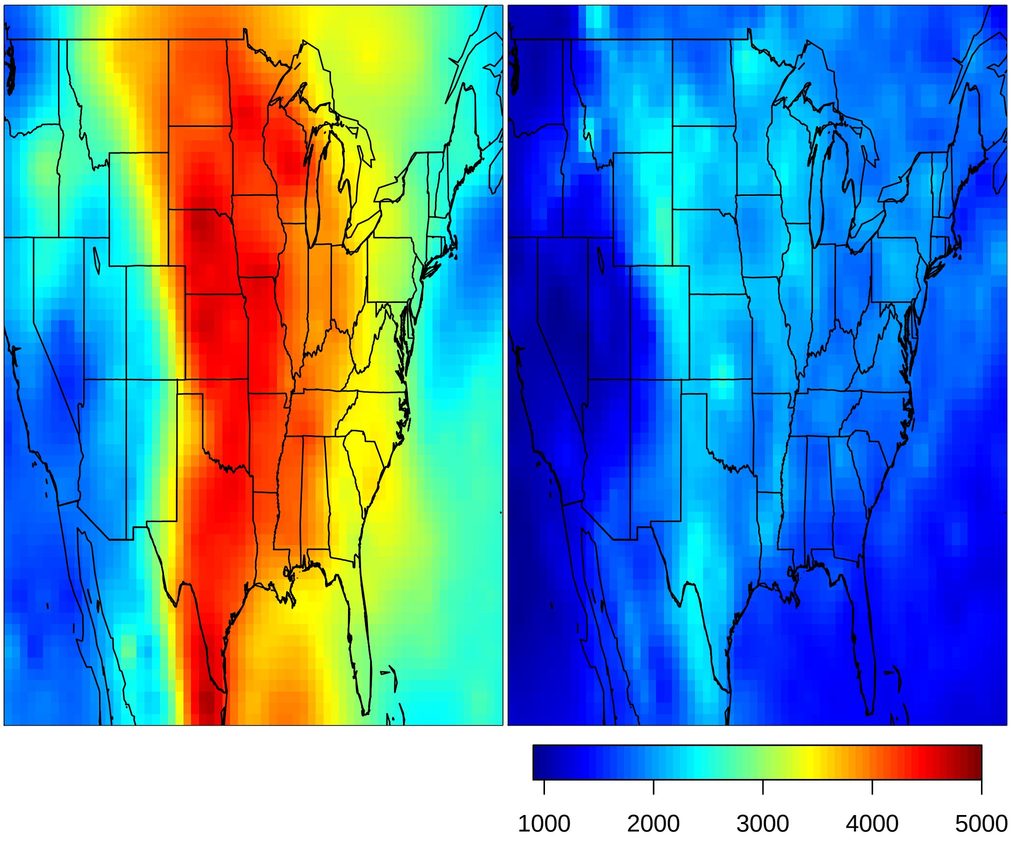
Median AM cape*shear reanalysis (1980−1999)



CCSM3 vs. NCAR/NCEP reanalysis

GEV-estimated 20-year Return Levels

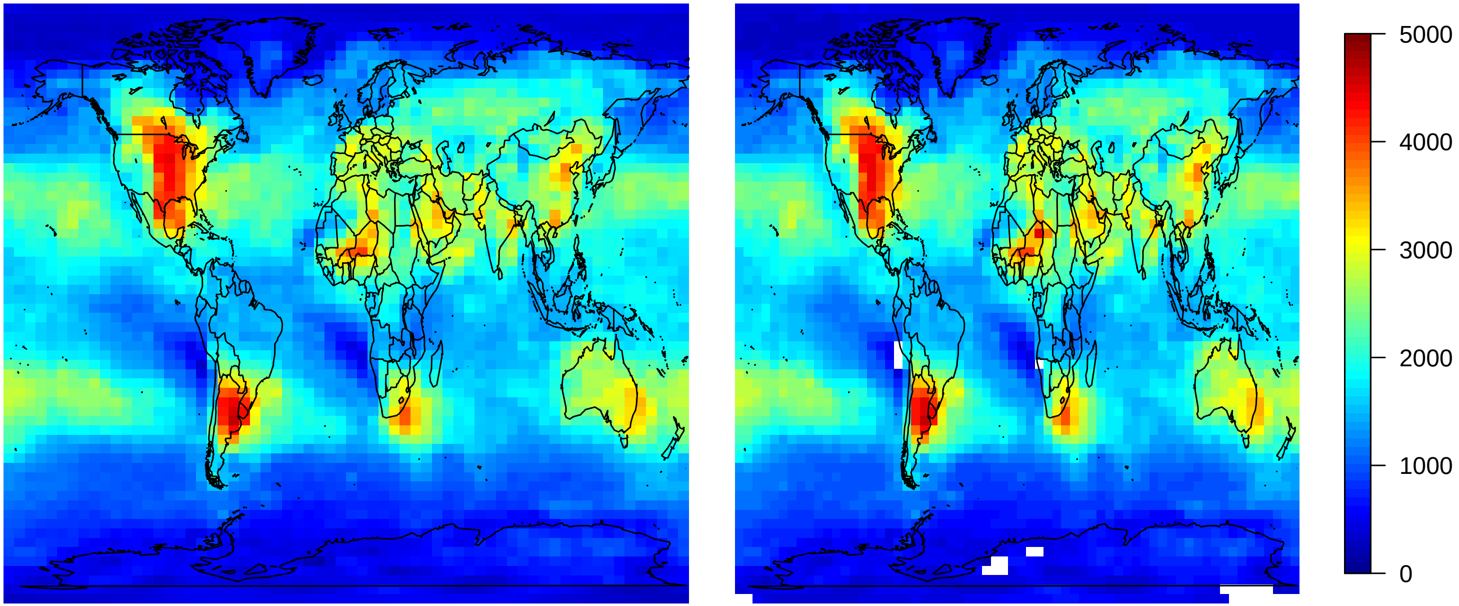
Reanalysis CCSM3



Large-scale indicators for Severe weather

WmSh=W_{max} × Shear

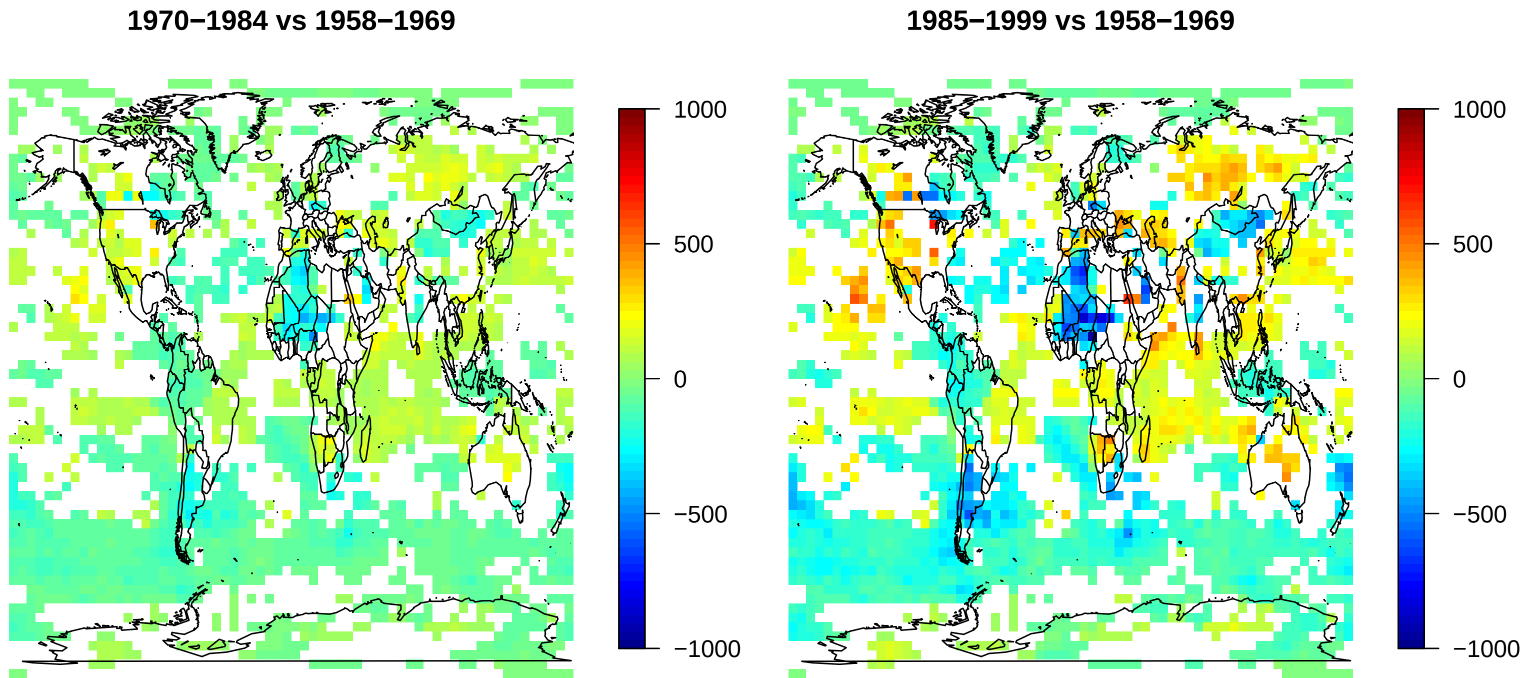
AM Reanalysis (95-th quantile) 20-yr GEV return level



Lower quartile of differences (GEV − Data) is only about −10 m/s, upper quartile of differences is only about 50 m/s.

Large-scale indicators for Severe weather

$\text{GEV}(\mu(t) = \mu_0 + \mu_1 t, \sigma, \xi)$,
$t = 0$ (1958–1969), $t = 1$ (1970–1984), $t = 2$ (1985–1999).
20-year return levels (i.e., 95-th percentile, m/s).



Min. diff. from $t = 0$ to $t = 2$ is ≈ -1500 m/s, max. is ≈ 800 m/s.
25th percentile of diff's is ≈ -200 m/s, 75th percentile is ≈ 150 m/s.

Large-scale indicators for Severe weather

Threshold excess modeling

Industrial Mathematical and Statistical Modeling (IMSM) Workshop for Graduate Students. Center for Research in Scientific Computation, Raleigh, North Carolina and the Statistical and Applied Mathematical Sciences Institute (SAMSI), Research Triangle Park, North Carolina, 20-28 July 2009.

Paper accepted to *Environmetrics*:

Heaton, M.J., M. Katzfuss, S. Ramachandar, K. Pedings, Y. Li, E. Gilleland, E. Mannshardt-Shamseldin, and R.L. Smith, 2009. Spatio-temporal models for extreme weather using large-scale indicators.

Large-scale indicators for Severe weather

Hierarchical Bayesian models applied to daily maximum $W_{max} \times$shear. Three models of increasing complexity explored, and compared to individual fits via MLE. Thresholds set at 95-th percentile for each grid. Region of higher scale, and bounded upper-tail shape parameters identified. All models vary according to this region.

- Model 1: GPD with (ln) scale and shape parameter varying by region.
- Model 2: GPD with Gaussian process for the (ln) scale parameter, and shape parameter varies according to region.
- Model 3: Point Process with temporal trend for location parameter, trivariate Gaussian process for location and (ln) scale parameters, and shape parameter varying according to region as in other two models.

Large-scale indicators for Severe weather

Three models of increasing complexity applied to threshold excesses (over the 95-th quantile of *daily* maximum WmSh).

Model 1

$y_{td}(\boldsymbol{s}_l)|\psi_{u(\boldsymbol{s}_l)}(\boldsymbol{s}_l), \xi(\boldsymbol{s}_l) \overset{\text{iid}}{\sim} \text{GPD}(\psi_{u(\boldsymbol{s}_l)}(\boldsymbol{s}_l), \xi(\boldsymbol{s}_l))$, where

$$\ln(\psi_{u(\boldsymbol{s}_l)}(\boldsymbol{s}_l)) = \alpha_\psi + \mathbf{1}_{\boldsymbol{s}_l \in \mathcal{A}_\psi} \delta_\psi,$$

and

$$\xi(\boldsymbol{s}_l) = \alpha_\xi + \mathbf{1}_{\boldsymbol{s}_l \in \mathcal{A}_\xi} \delta_\xi,$$

with $\mathcal{A}_x$ somewhat arbitrarily chosen regions representing areas of exceptional values of these parameters as estimated via MLE at individual locations (this roughly translates to the "*tornado alley*"). Priors for these parameters are taken as $\alpha_\psi \sim N(5.5, 1)$, $\delta_\psi \sim N(0, 1)$, $\alpha_\xi \sim N(0, 0.2^2)$, $\delta_\xi \sim N(0, 0.2^2)$.

Model 2

$y_{td}(\boldsymbol{s}_l)|\psi_{u(\boldsymbol{s}_l)}(\boldsymbol{s}_l), \xi(\boldsymbol{s}_l) \overset{\text{iid}}{\sim} \text{GPD}(\psi_{u(\boldsymbol{s}_l)}(\boldsymbol{s}_l), \xi(\boldsymbol{s}_l))$, where

$$\ln(\psi_{u(\boldsymbol{s}_l)}(\boldsymbol{s}_l)) \sim GP((\mu_\psi, \tau^2_\psi, \phi_\psi),$$

and

$$\xi(\boldsymbol{s}_l) = \alpha_\xi + \mathbf{1}_{\boldsymbol{s}_l \in \mathcal{A}_\xi} \delta_\xi,$$

with $\text{Cov}(\ln(\psi(\boldsymbol{s}_l)), \ln(\psi(\boldsymbol{s}_k))) = \tau^2 \exp\{-\phi_\psi \|\boldsymbol{s}_l - \boldsymbol{s}_k\|\}$, and $\| \cdot \|$ the spherical distance in miles. Priors are the same as model 2, with additional priors for $\mu_\psi \sim \text{Unif}(-\infty, \infty)$, $\tau^2_\psi \sim \text{IG}(2.1, 3)$, and $\phi_\psi \sim \text{Unif}(0.001, 0.1)$.

Model 3

$$x_{td}(\boldsymbol{s}_l)|x_{td}(\boldsymbol{s}_l) > u(\boldsymbol{s}_l), \beta_0(\boldsymbol{s}_l), \beta_1(\boldsymbol{s}_l), \sigma(\boldsymbol{s}_l), \xi(\boldsymbol{s}_l) \overset{\text{iid}}{\sim} \text{PP}(\beta_0(\boldsymbol{s}_l) + \beta_1(\boldsymbol{s}_l)t, \sigma(\boldsymbol{s}_l), \xi(\boldsymbol{s}_l)),$$

where

$$(\beta_0(\boldsymbol{s}_l), \beta_1(\boldsymbol{s}_l), \ln(\sigma(\boldsymbol{s}_l)))^T \sim \text{GP}_3(\boldsymbol{\mu}_{M_3}, \phi_{M_3}, \boldsymbol{\Gamma}),$$

and

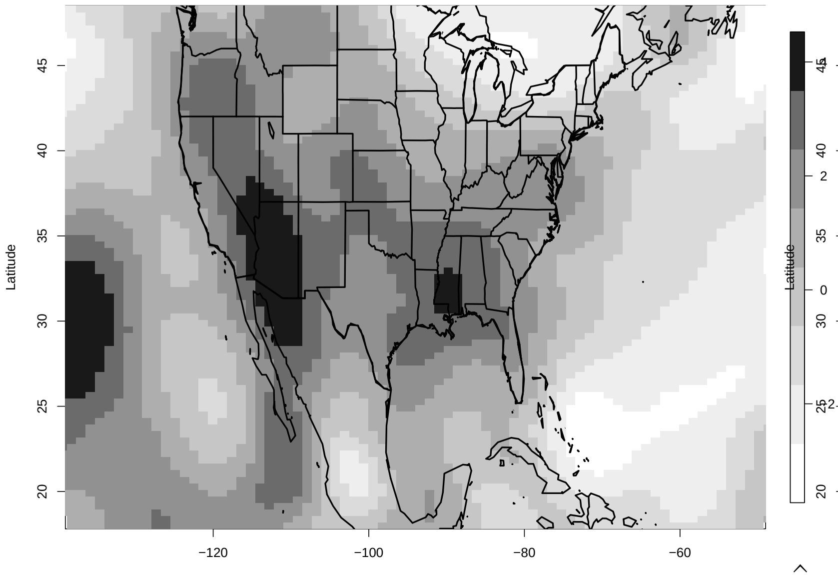
$$\xi(\boldsymbol{s}_l) = \alpha_\xi + \mathbf{1}_{\boldsymbol{s}_l \in \mathcal{A}_\xi} \delta_\xi,$$

with GP_3 a trivariate Gaussian process induced via coregionalization (Gelfand *et al.* 2004), $\boldsymbol{\mu}_{M_3} = (\mu_{\beta_0}, \mu_{\beta_1}, \mu_\sigma)^T$, $\phi_{M_3} = (\phi_1, \phi_2, \phi_3)^T$, and $\boldsymbol{\Gamma}$ is a 3×3 lower triangular matrix with entries γ_{ij}.

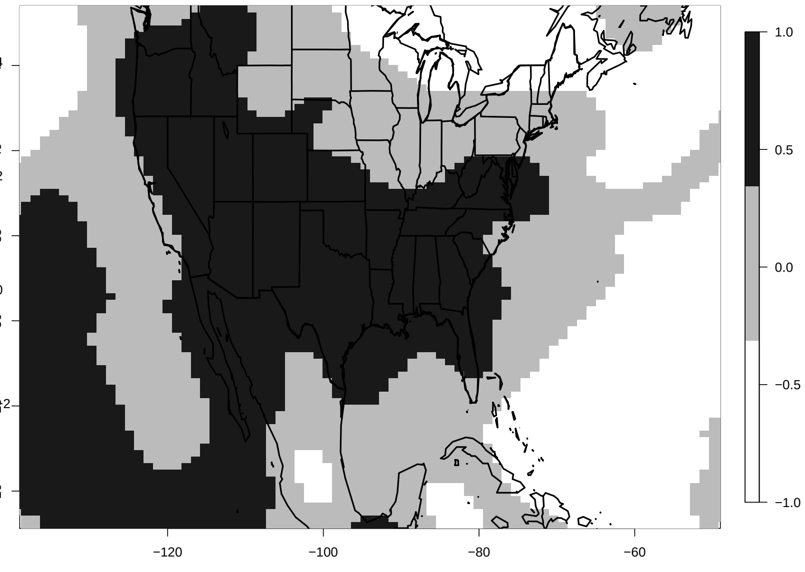
Large-scale indicators for Severe weather

Model 3 is best according to DIC (also most useful).

$\hat{\beta}_1$ Values



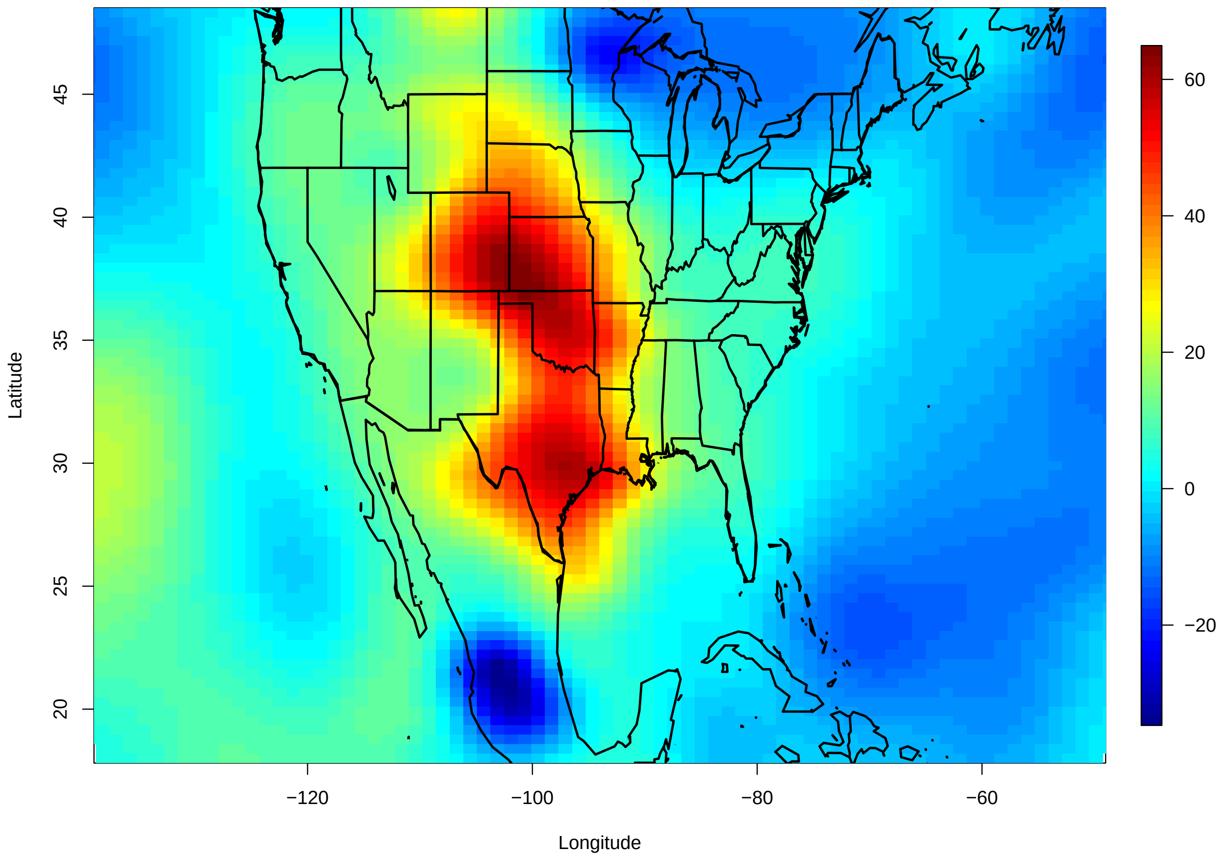
Statistical Significance



Is there practical significance with $\hat{\beta}_1$ ranging only from about -4 to 4 (e.g., 4×42 years is only 168 m/s difference *in location parameter*)?

Large-scale indicators for Severe weather

Twenty-year return level differences as calculated from the posterior means of Model 3 for 1999 vs 1958. Practical significance?



Discussion

- How should extreme events be defined? Deadliness? Perception-based? Statistically? Economically? Other?
- What is the relationship between changes in the mean and changes in extremes? What about variability? Higher order moments?
- If climate models project the df of atmospheric variables, then do they accurately portray the df's? Enough so that functionals of interest, such as extrema, are correctly characterized?
- If climate models only project the mean, then can anything be said about extremes?
- How can it be determined if small changes in high values of large-scale indicators lead to a shift in the df of severe weather conditional on the indicators?

Discussion

- How do we verify climate models, especially for inferring about extremes?
- Extremes are often largely dependent on local conditions (e.g., topography, surface conditions, atmospheric phenomena, etc.), as well as larger scale processes.
- Can a *metric* for climate change pertaining to extremes be developed that makes sense, and provides reasonably accurate information?
- How can uncertainty be characterized? Is there too much uncertainty to make inferences about extremes?
- How can spatial structure be taken into account for extremes?
- Many extreme events, and especially extreme impact events, result from multivariate processes. How can this be addressed?