Robust increases in severe thunderstorm environments in response to greenhouse forcing [1]

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[1] Noah S. Diffenbaugh, Martin Sherer, and Robert J. Trapp (2013)

Outline

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II. Methods
    A. CMIP5 RCP8.5
    B. NDSEV
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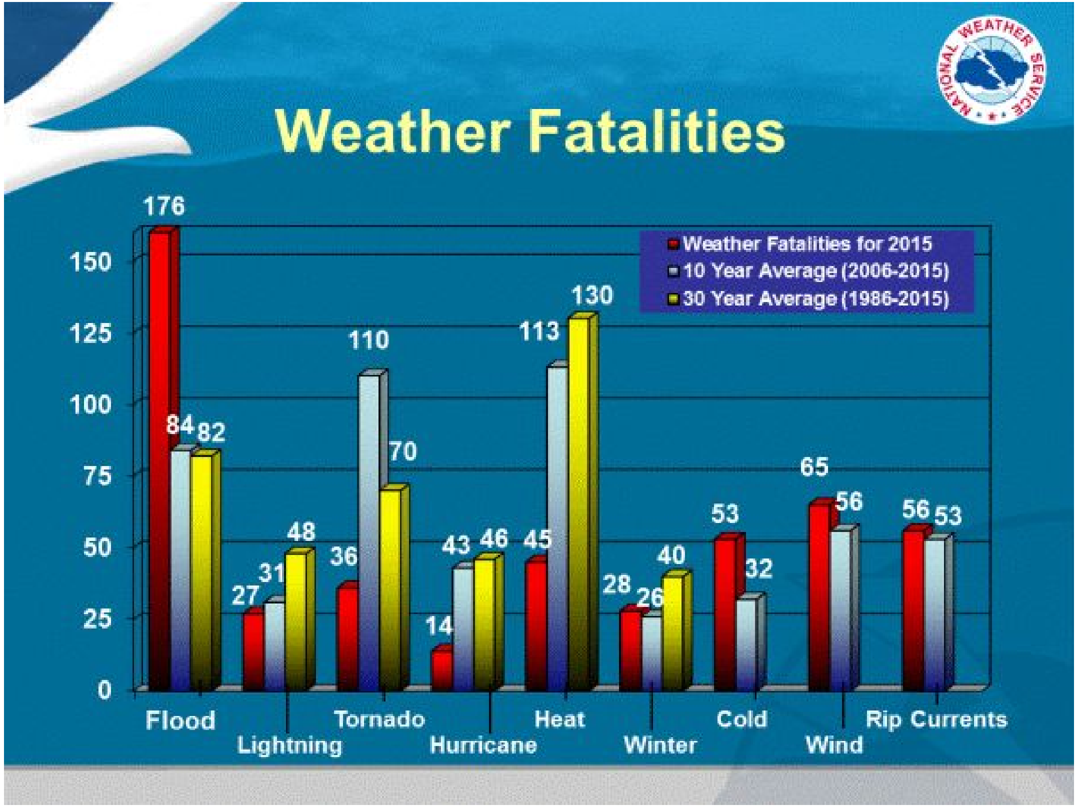
_Introduction_______

- Severe weather = flooding, lightning, tornadoes, wind
- 10 year average of 281/yr
  - April 27, 2011 = 317 deaths in one day



Introduction

- Severe thunderstorms are a primary cause of loss of property and life
  - Tornadic thunderstorms = most intense weather on the planet
- Increases/decreases in thunderstorm activity empirically related to increases/decreases of CAPE and shear (Brooks, et. al. 2003)
- General evaluation of all sorts of severe thunderstorms
  - Hail, tornadoes, and straight-line winds
- Response of severe weather to enhanced greenhouse gas forcing remains uncertain despite numerous studies (Gensini and Mote 2015; Seeley and Romps 2015; Brooks 2013; Trapp, et. al. 2007)

Reasons for the uncertainty

1. No *long term* record of severe thunderstorm/tornado events:
    a. No regular record keeping until the 1950s
    b. The word “tornado” was banned from operational use by the U.S. Army Signal Corps in late 1880s in order to prevent public panic
    c. Trends in tornado records due to increasing population and number or storm spotters/chasers
2. Theoretical arguments don’t agree with climate model experiments all the time
    a. How much does the large scale environment impact storm development compared to other factors?
3. The “initiation problem”
    a. Climate models are at too coarse a resolution to resolve convective initiation processes

Reasons for the uncertainty, 2

The expected *decrease* in deep layer atmospheric wind shear (0-6 km) has caused substantial uncertainties across studies

- **Trapp, et. al. (2007, 2009) and others have determined that the increase in CAPE will be able to compensate for the decrease in shear**
- **A lot of emphasis is placed on shear because tornadic storms, the most violent storms on the planet, require intense low level wind shear**

Methods

Coupled Model Intercomparison Project, Phase 5 (CMIP5) global climate model (GCM) ensemble historical and RCP8.5 simulations

- **Historical (baseline) = 1970-1999**
- **RCP8.5 = Representative Concentration Pathway 8.5 (present to ~2100)**

Determine number of severe thunderstorm days using NDSEV (Number of Days with Severe Environments)

- **Considers 0-6 km vertical wind shear and convective available potential energy (CAPE) as outlined by Trapp, et. al. 2007, 2009**

CMIP5 GCM

- Designed in response to IPCC (Intergovernmental Panel on Climate Change) Fourth Assessment Report
- 20 modeling groups and over 50 models organized by the Working Group of Coupled Modeling (WGCM) under the World Climate Research Programme (WCRP)
- 10 models were selected for this study (all models with subdaily, 3D variable output so that CAPE and shear could be calculated and compared at 00Z daily [late afternoon/early evening])

CMIP5 GCM, 2

Table S1. CMIP5 models and realizations used in the reported analyses

Model	Realization ID (historical/RCP8.5)	Horizontal grid*	Vertical grid, levels
bcc-csm-1	1	64 × 128	26
CanESM2	1	64 × 128	35
CCSM4	6	192 × 288	26
CSIRO-Mk3-6–0	1	96 × 192	18
FGOALS-g2	1	60 × 128	26
GFDL-CM3	1	90 × 144	48
GFDL-ESM2M	1	90 × 144	24
IPSL-CM5A-LR	1	143 × 144	39
MIROC5	1	128 × 256	40
NorESM1-M	1	96 × 144	26

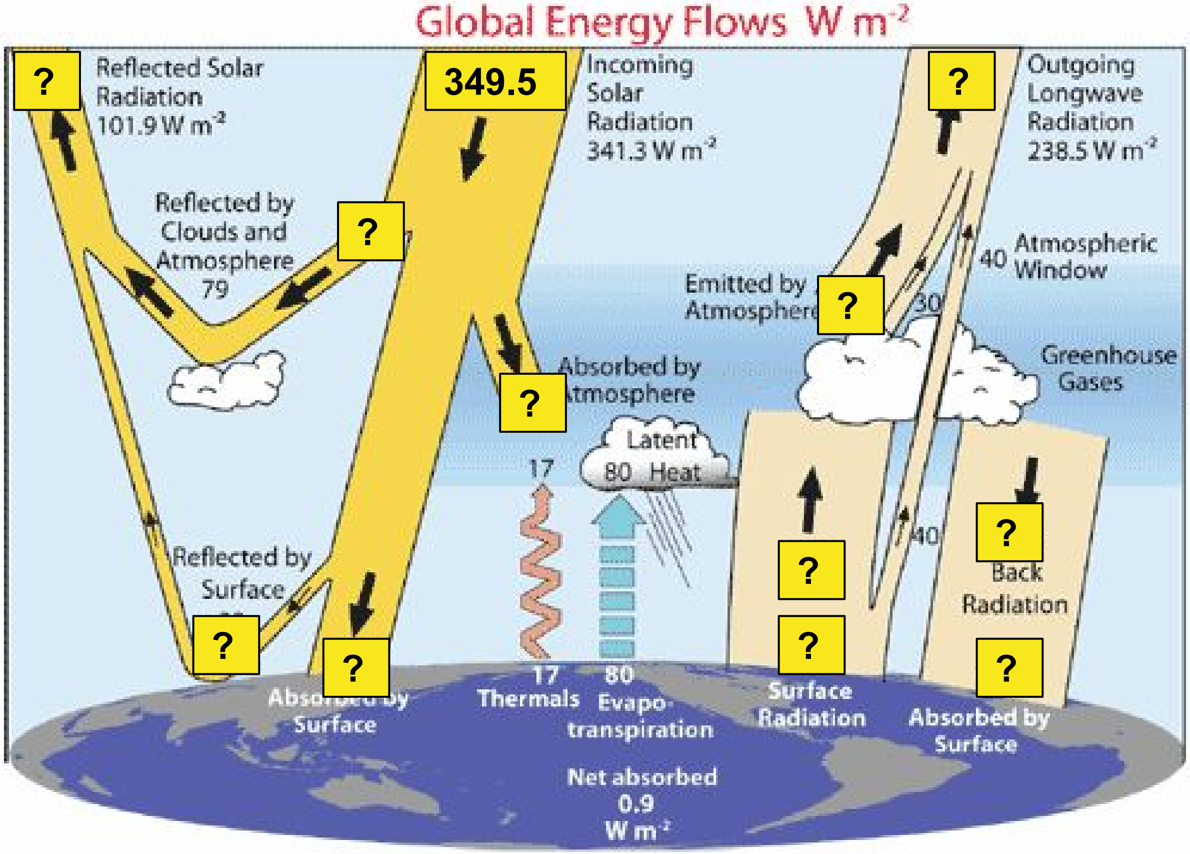
*Lateral points × longitudinal points.

RCP8.5

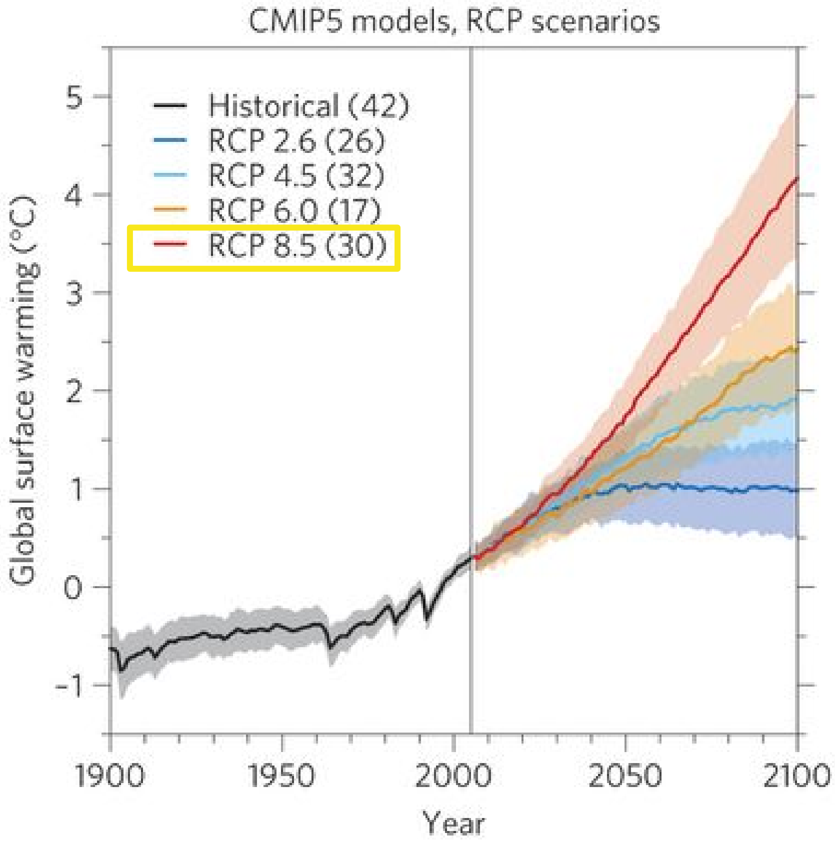
Representative Concentration Pathway 8.5 = ~8.5 W/m² increase in global radiative forcing by 2100 ("business as usual" model)

- **Covers full range of 21st century radiative forcing possibilities along the path to +8.5 W/m²**
- **Analyzing 2070-2099 allows for study of high [radiative] forcing environment**
- **Analyzing earlier periods allows for study of lower levels of forcing**
- **Greenhouse gas concentrations: >1370 CO_2-equivalent by late-21st century**
- **+4.9°C median warming by late 21st century**

Global Radiation Balance +8.5 W/m^2



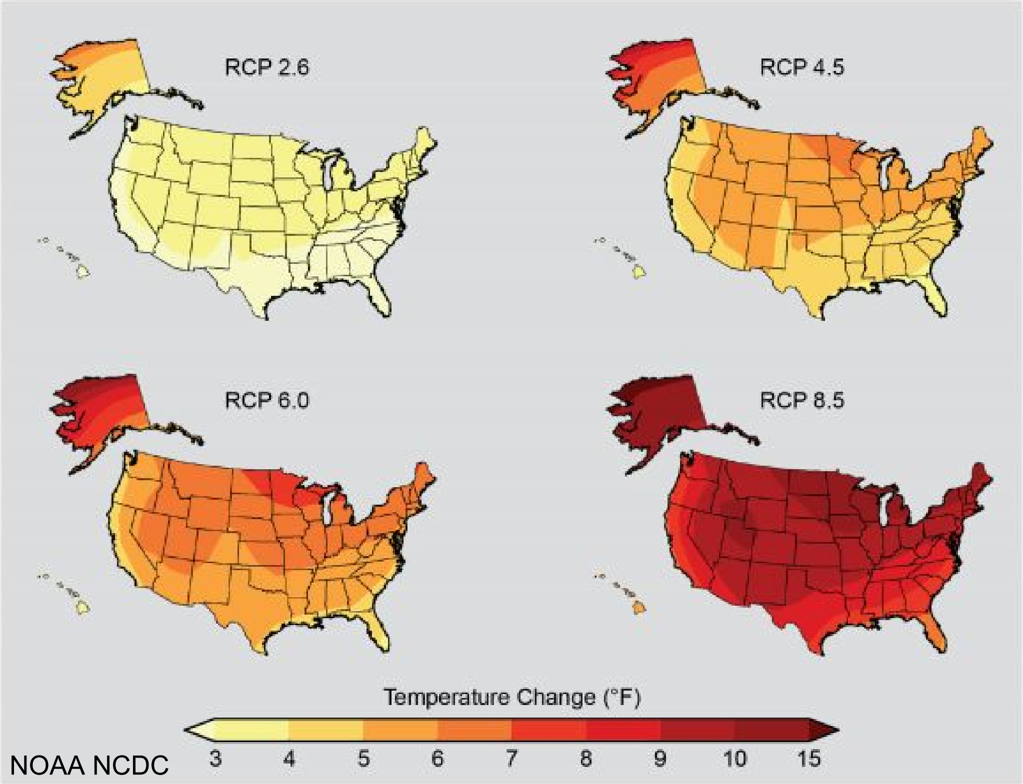
CMIP5 RCP Scenarios



- CMIP5 RCP8.5 covers RCP2.6 - RCP6.0 strength forcing as the temperature and forcing increase to meet RCP8.5 levels
- Different RCP scenarios to simulate different levels of governmental regulations and impacts on environment

CMIP5 RCP Scenarios, 2

- Projected U.S. temperature increases by 2071-2099 using CMIP5 RCP scenarios
- RCP8.5 results in a *global* temperature increase of +4.9°C, but U.S. warms much more than that



_CMIP5 RCP8.5 Output____

- **Differences calculated between 1970-1999 control period and 2070-2099 simulated period**
- **Demonstrates overall seasonal CAPE increases and 0-6 km shear decreases expected by late 21st century**

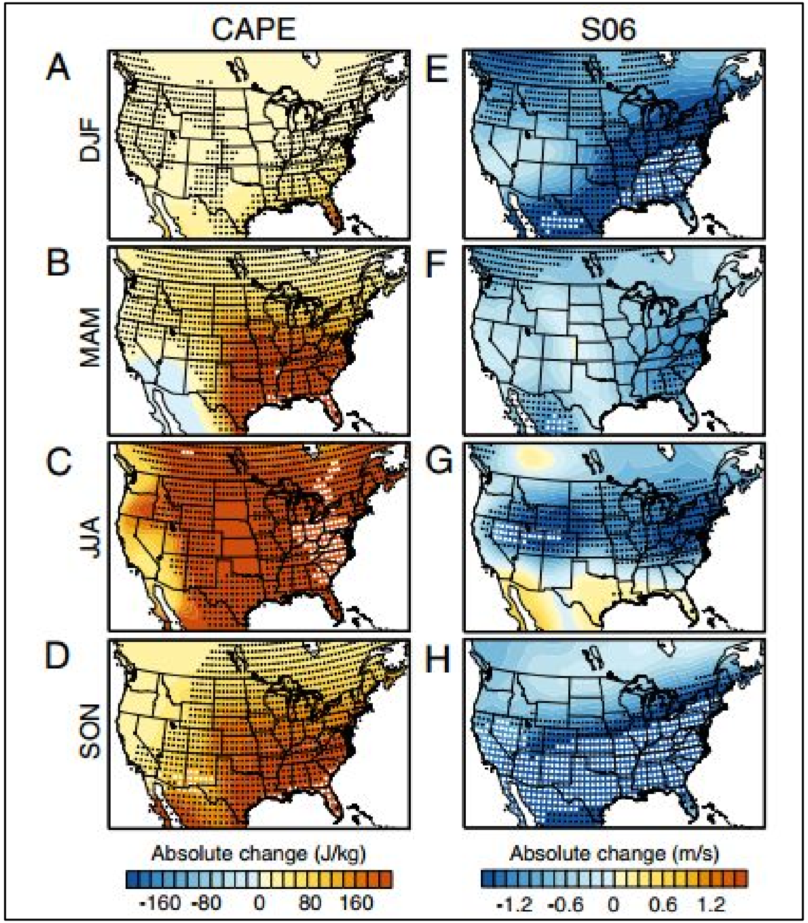
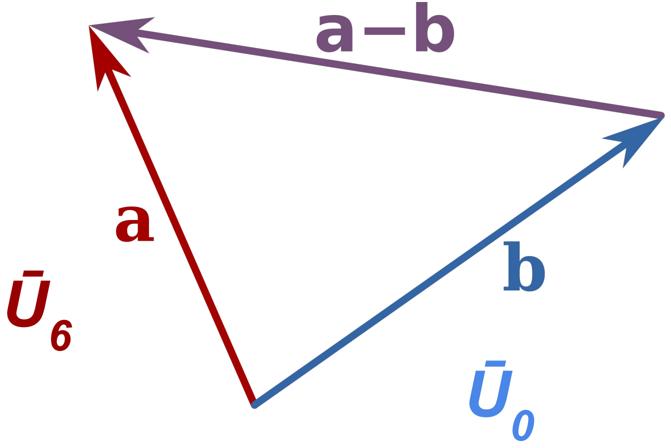
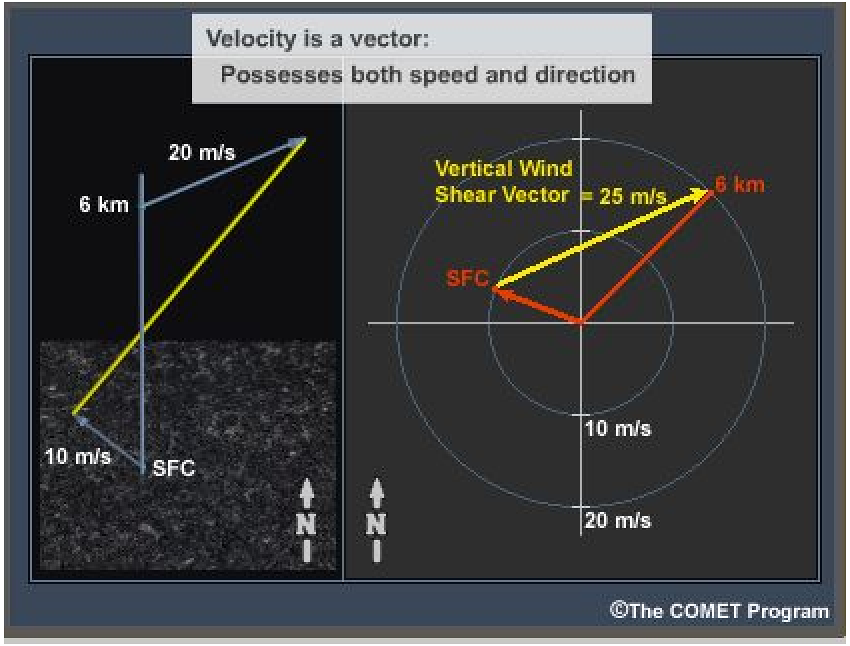


Fig. 2. Response of CAPE and wind shear in the late 21st century period of RCP8.5 during the winter (DJF), spring (MAM), summer (JJA), and autumn (SON) seasons. Differences are calculated as in Fig. 1, *Left*. (*A–D*) CAPE. (*E–H*) The magnitude of the vector difference of the horizontal wind at 6 km and the lowest model level (S06).

0-6 km Vertical Wind Shear

6 km horizontal wind minus model surface wind (referred to as 0-6 km shear but surface not always at 0 km)





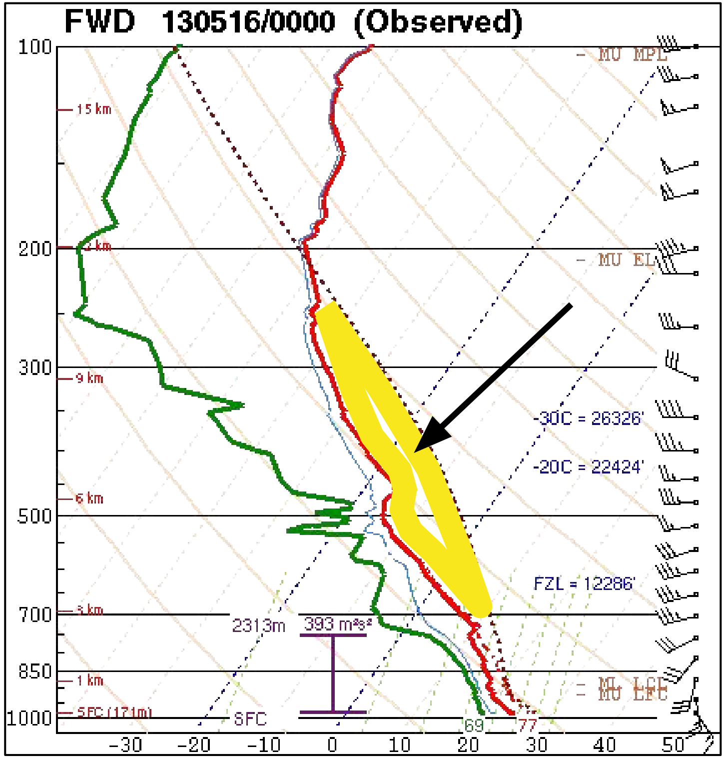
0-6 km Vertical Wind Shear

- Also referred to as *bulk shear*
- Increasing 0-6 km shear correlated to increasing tornado potential
    - 0-1 km shear better correlated to tornado development
- Deep layer shear ideal for sustaining convection
- There are severe convective storms that do not require intense vertical shear. However, they do exceed the 5 m/s 0-6 km shear requirement imposed by this study and others

Convective Available Potential Energy (CAPE)

- Measure of buoyant energy or convective instability
- Large instability = 1500-2500 J/kg
- Extreme instability = 2500+ J/kg
- Increased low level (LL) moisture can generate high CAPE due to buoyancy differences between LL moist air and higher, denser, dry air

$$\mathrm{CAPE} = \int_{z_f}^{z_n} g \left(\frac{T_{v,\mathrm{parcel}} - T_{v,\mathrm{env}}}{T_{v,\mathrm{env}}} \right) dz$$

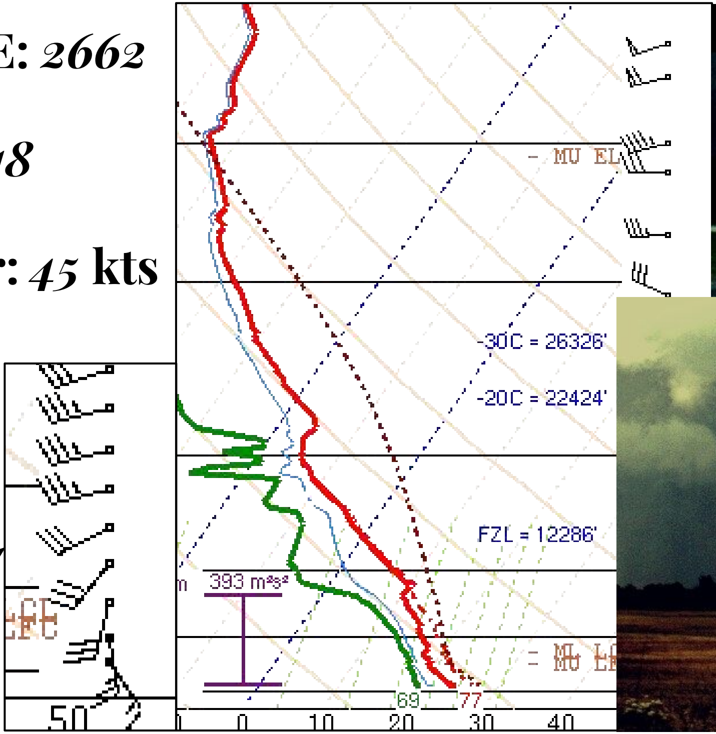


EXAMPLE: May 15, 2013, near DFW

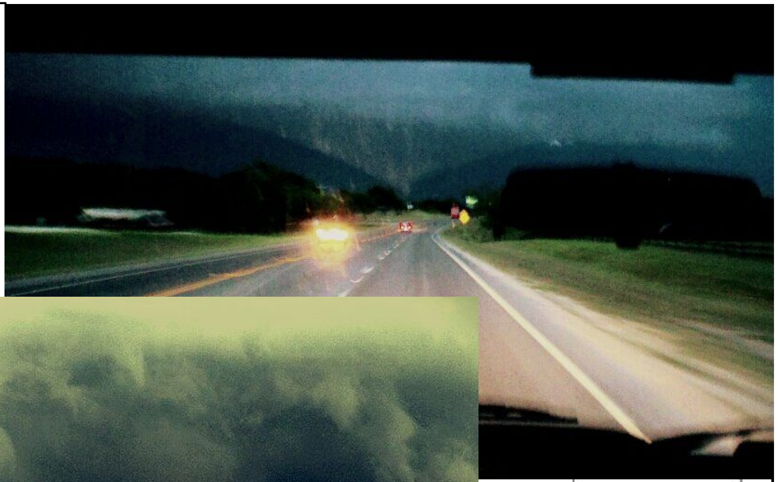
Surface CAPE: ***2662***

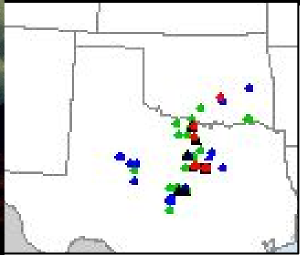
ML CAPE: ***1718***

0-6 km shear: ***45*** **kts (23.15 m/s)**



0 - ~4.5 km





Evaluating Potential Thunderstorm Days

NDSEV can be used to evaluate severe thunderstorm potential when:

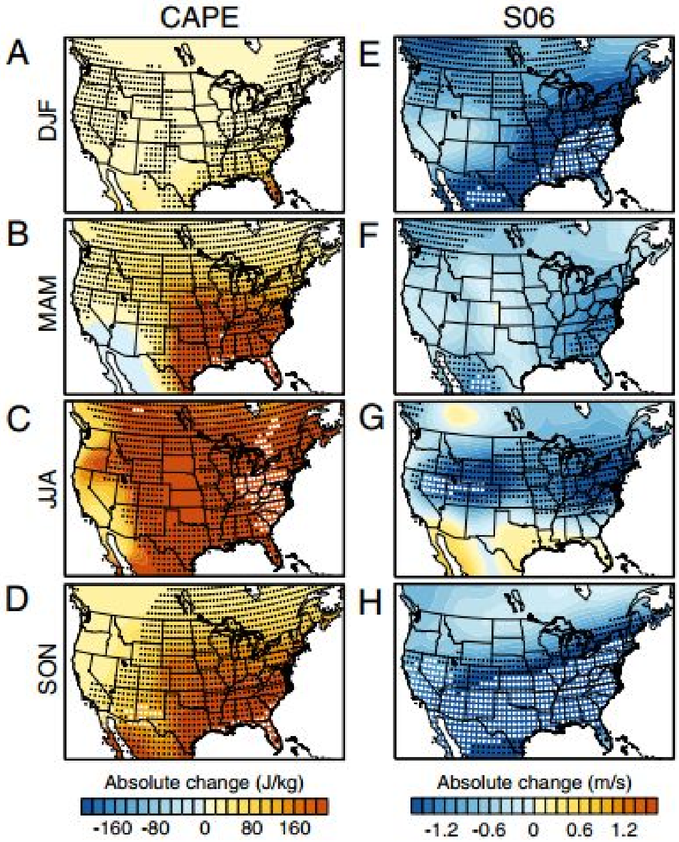
- **CAPE > 100 J/kg**
- **S06 (0-6 km shear) > 5 m/s**
- **6 km wind is greater than 0 km wind**
- **0 km wind > 5 m/s**

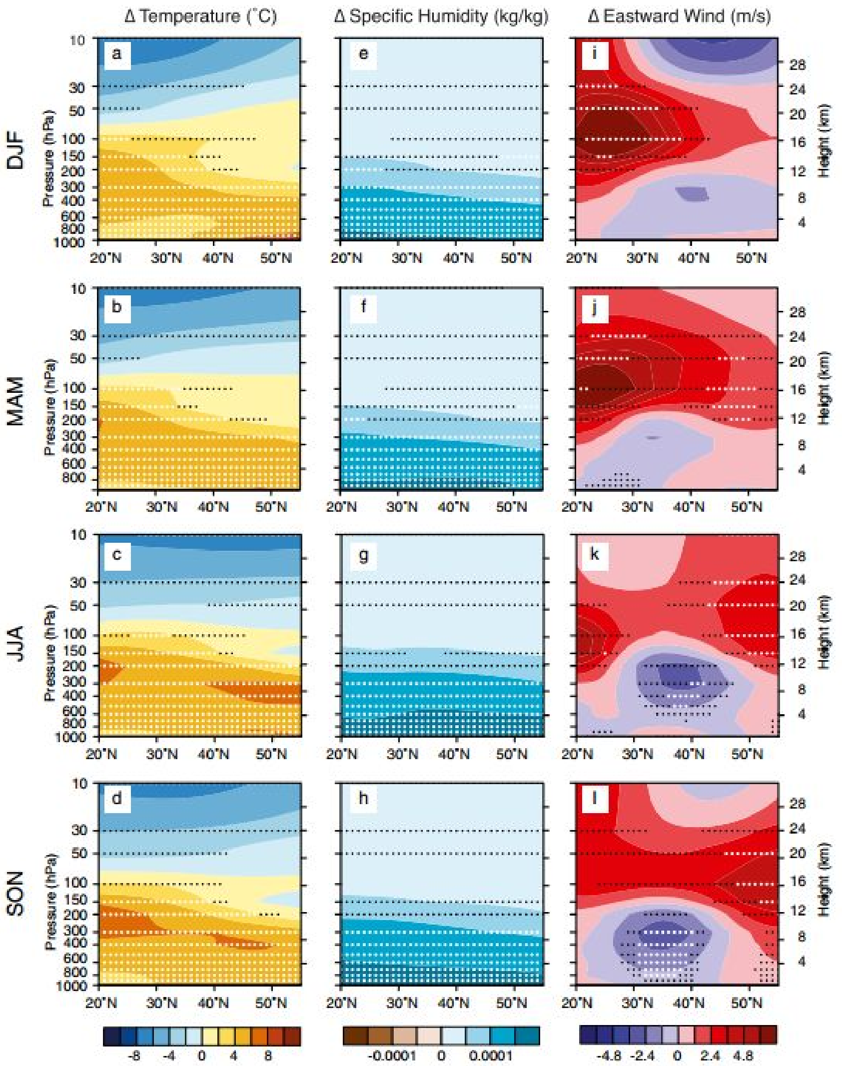
NDSEV = 1 when [CAPE]*[S06] ≥ 10000

NDSEV = 0 when [CAPE]*[S06] < 10000

***other studies use $[CAPE]*[S06]^{gamma}$ = beta (Seeley and Romps 2015)**

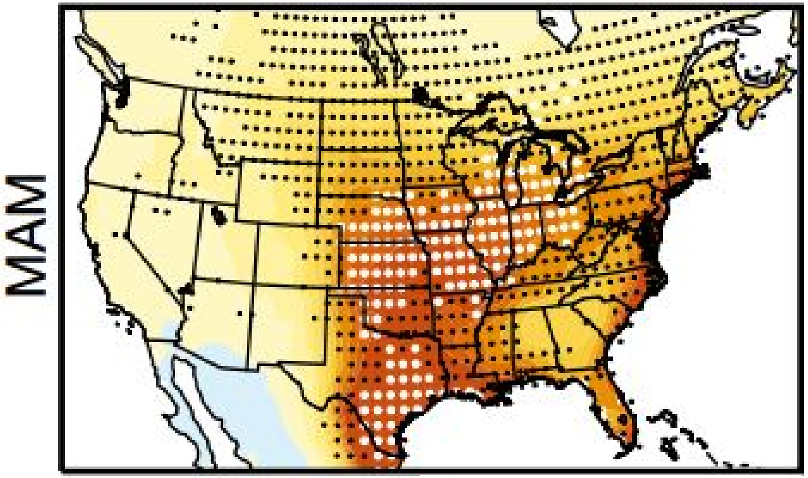
_CMIP5 Forecast___________

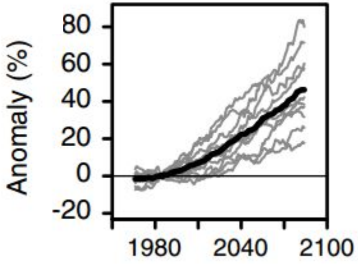




Spring Results

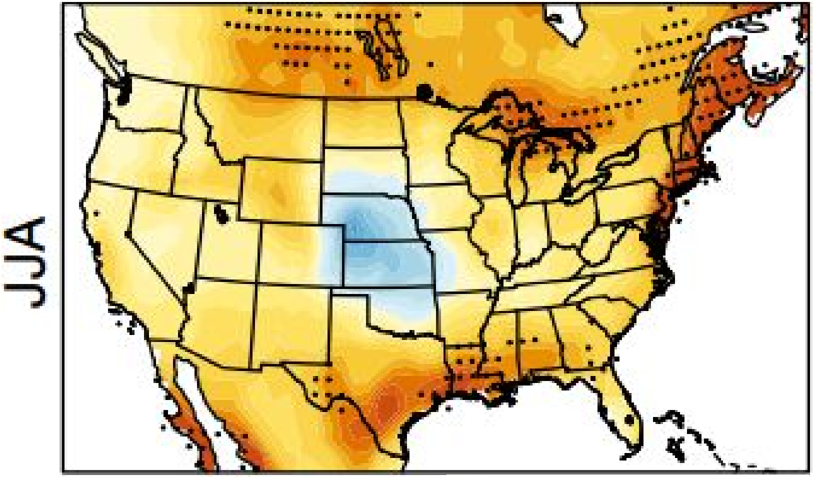
- Largest absolute increase in NDSEV
- Most consistent results across all models
  - All showing positive multidecadal changes in NDSEV, CAPE, and surface specific humidity after 2030
- Highly robust increases in NDSEV
- Smallest decrease in S06

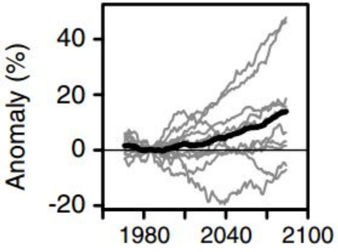




Summer Results

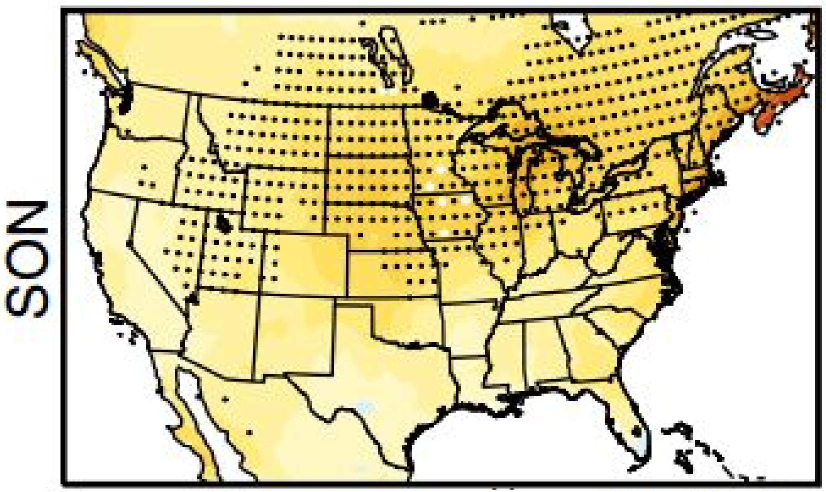
- Smallest relative change in NDSEV (<20%)
- Largest variability across models
- Robust increases over Northeast and Gulf Coast
- Robust decreases in S06 due to decreases in the summer zonal wind below 6 km

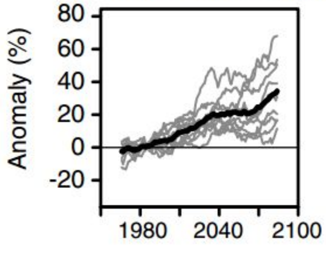




Fall Results

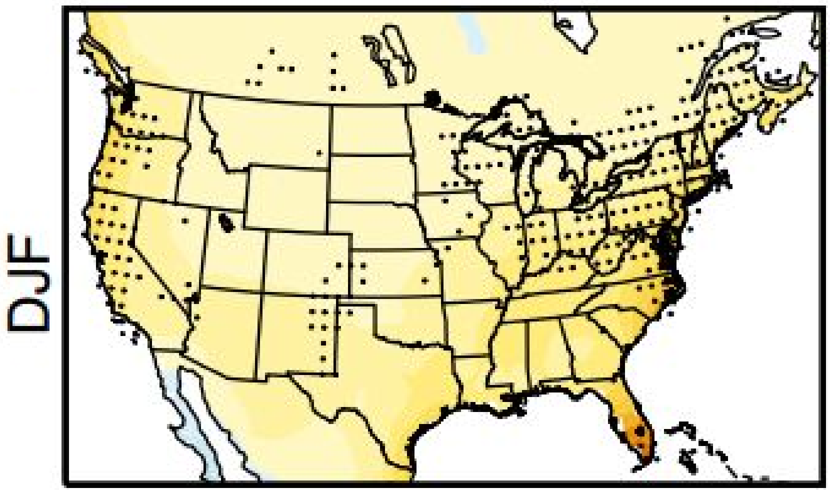
- Greatest increases in NDSEV:
  - Great Plains
  - Midwest
  - Northeast
- Highly robust decreases in S06
- Robust increases in NDSEV due to increases in CAPE
- General increase in CAPE days

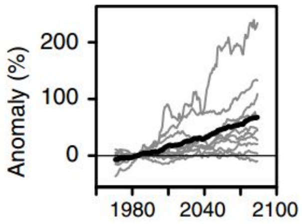




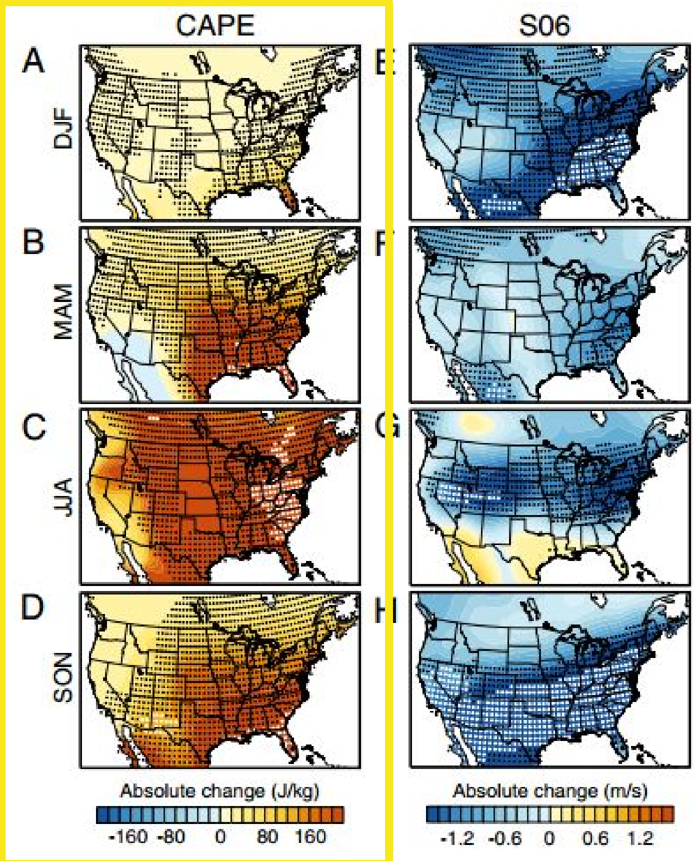
Winter Results

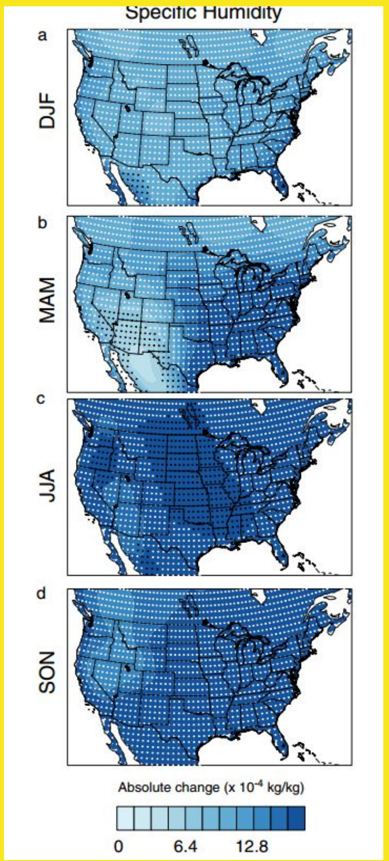
- 50%+ increase in NDSEV by end of 21st century
- Robust increases simulated across parts of the Midwest and Northeastern U.S.
- Southeast gets stormier, but not robust signal across all models
- General increase in CAPE days





Specific Humidity and CAPE





0-1 km Vertical Wind Shear

0-1 km wind shear was also considered given its importance in supercell/tornado

- Concentrated low level shear = conducive to tornado development

NOTE: tornadogenesis still largely understood, so gauging future tornadic activity implicitly only works so well

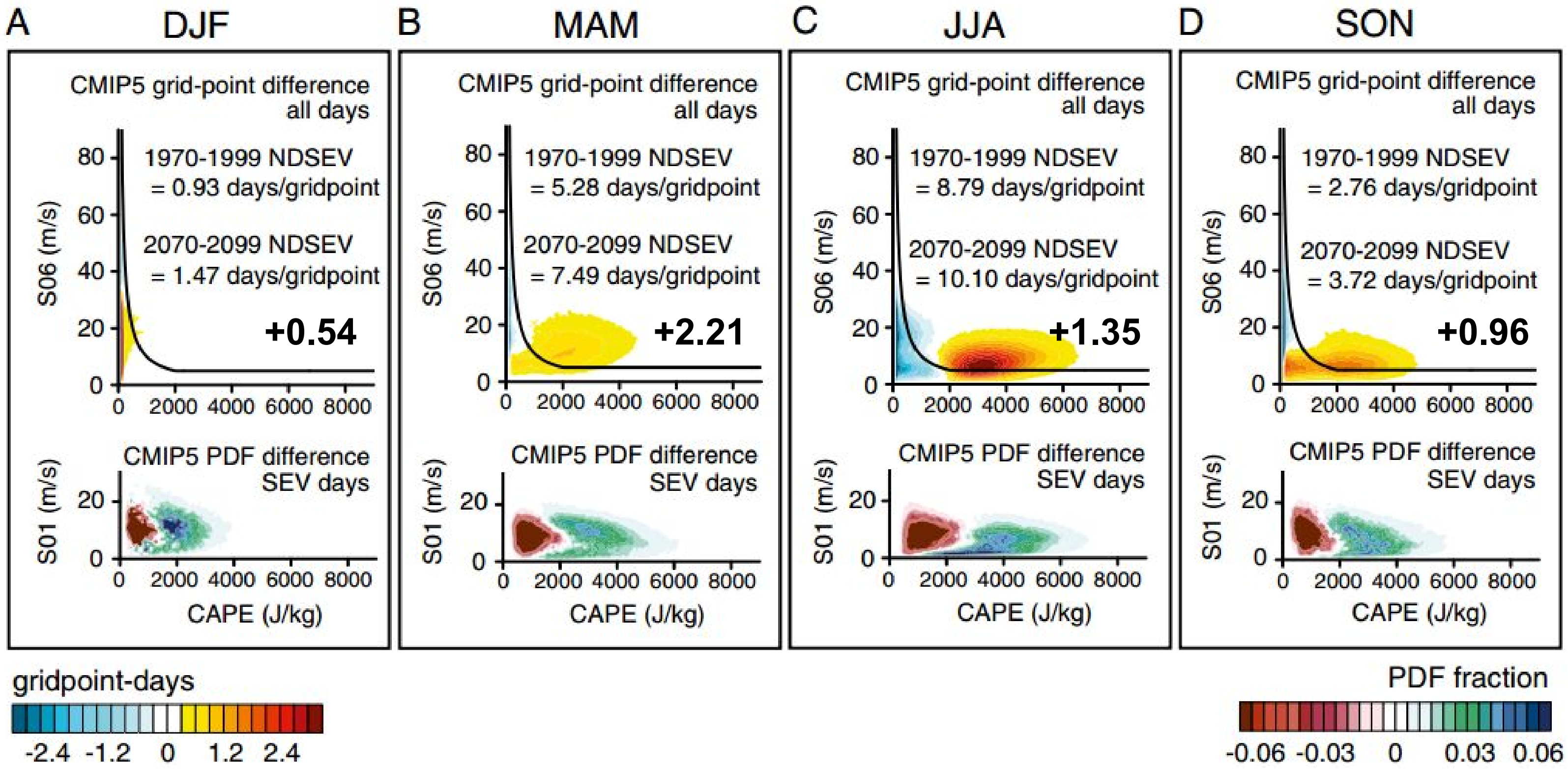
CAPE + 0-1 km Wind Shear

Increase in days with high 0-1 km wind shear and high CAPE; although HIGHER increase in days with high CAPE and low 0-1 km wind shear

- **CAPE (high) > 2000 J/kg**
- **S01 (high) = 10-20 m/s**

Little mention of amounts of CIN on NDSEV days: tornadoes/very severe storms require some amount of CIN to suppress convection in surrounding regions

Summary of Results



*PDF = probability density function

Summary of NDSEV Results

- Changes in CAPE and shear across seasons partly explained by changes in the vertical structure of the atmosphere
- Changes in CAPE generally tied to changes in surface specific humidity
- Increasing occurrence of high CAPE in the spring, summer, and fall
- Loss of high shear days does not decrease overall number of NDSEV because both high CAPE and high shear are needed for the typical severe weather environment
- Atmospheric vertical structure sensitive to model vertical structure; varying numbers of vertical levels across models
- High summertime CAPE bias across subsection of models

Issues

- **Not all storms develop in the classic high CAPE/high shear environment**
- **Storms don't always develop on days where the environment is favorable for convection (*"initiation problem"*)**
  - **CIN (convective inhibition; opposite of CAPE) could be too high**
- **Convective initiation not explicitly captured by these models given coarse resolution**
  - **Convective initiation processes resolved at 3-4 km or less**

Issues

- **S01 and S06 do not indicate direction of shear, only magnitude**
  - **Veering winds vs. backing winds, etc.**
- **Storm-scale dynamics of severe weather phenomena are still not understood, which introduces a high degree of uncertainty in forecasting future convection**
- **Some people have questioned the scientific utility of the CMIP5 models given some of their inabilities to accurately simulate the past (Pielke, 2012)**

Other Factors to Consider

- Changes in SST (sea surface temperature) rather than global circulations like NAO, MJO, ENSO, etc. (Jung and Kirtman, 2016; Tippett, et. al. 2015)
- Changes in EML intensity with aridification of Great Plains
- Increased evapotranspiration even in drying areas due to irrigation (Mutiibwa and Irmak 2013)
- Strongly forced vs. weakly forced convection: strongly forced convection may decrease as jet/front systems become weaker
  - Unable to study due to inability for models to explicitly resolve convection/convective initiation processes

Conclusions

1. **Global warming leads to a shift in daily CAPE/S06 distribution**
   a. Higher frequency of high CAPE/high shear days
   b. Additional high CAPE days coincide with lower CIN days, indicating convection likely to occur
2. **Increases in CAPE robust across CMIP5 ensemble, while decreases in shear concentrated in lower CAPE days**
   a. Previous work suggests overall increased CAPE, decreased shear, but daily distributions have not been explored until now
3. **Increases in spring/fall CAPE/NDSEV apparent before mid-21st century**
4. **Increases in tropospheric moisture concentrated at low levels**

Questions?

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