Extreme Ozone Distributions: Present and Future

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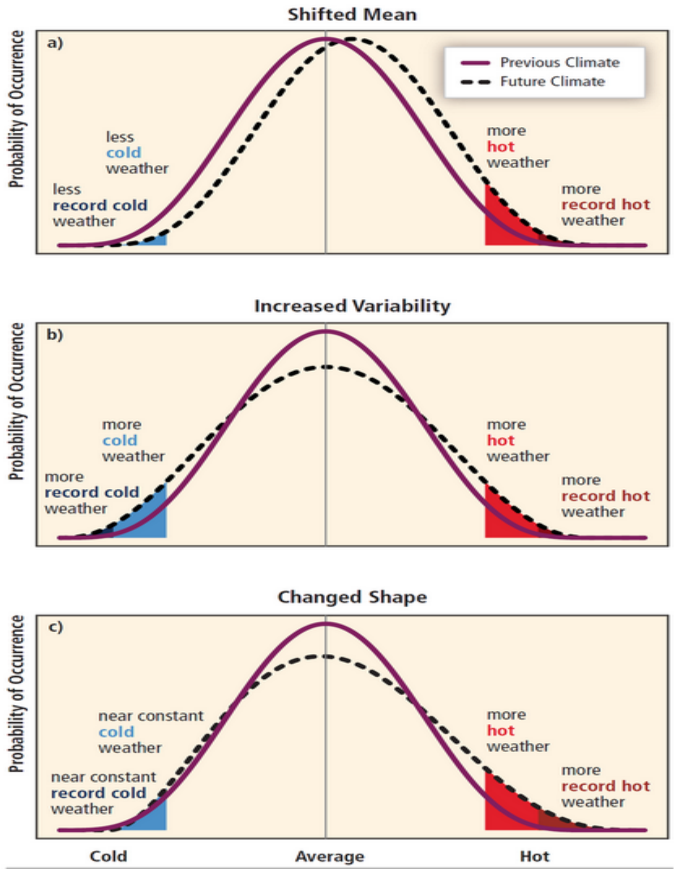
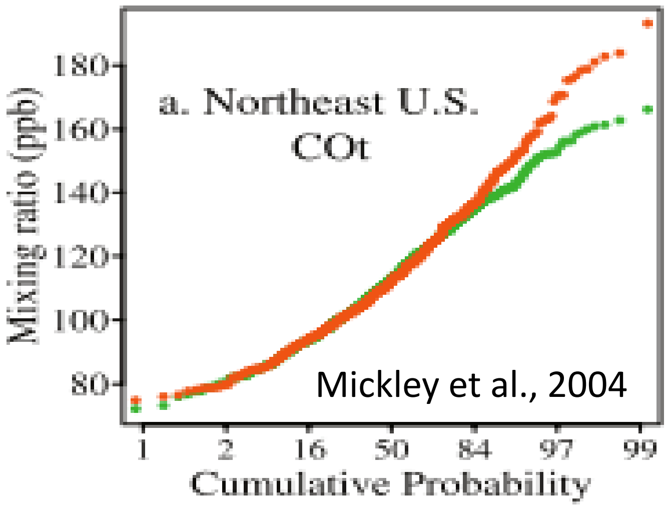
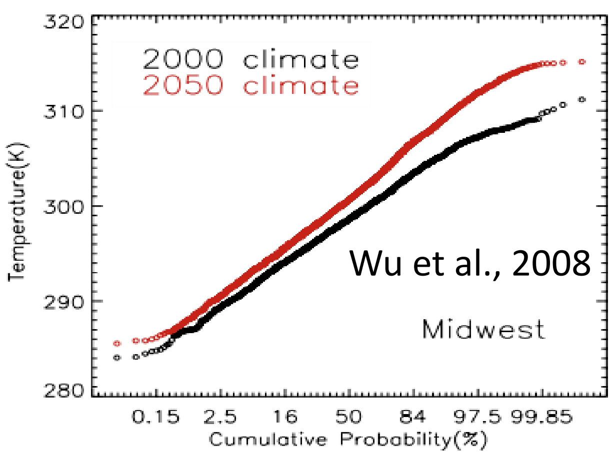
How does one characterize the tails of the ozone distribution and how do they change with changes in climate or emissions?



Does the ozone become more extreme in the future?



“A focused study by Mickley et al. (2004) for the eastern USA found an increase in the severity and persistence of regional pollution episodes due to the reduced frequency of ventilation by cyclones tracking across Canada. This effect more than offsets the dilution associated with the small rise in mixing depths. A decrease in cyclone frequency at northern mid-latitudes and a shift to higher latitudes has been noted in observations from the past few decades (McCabe et al., 2001).” (IPCC, 2007)



“Maximum change at the high end of the distribution representing heat waves. This likely reflects the increase in frequency of stagnation episodes”

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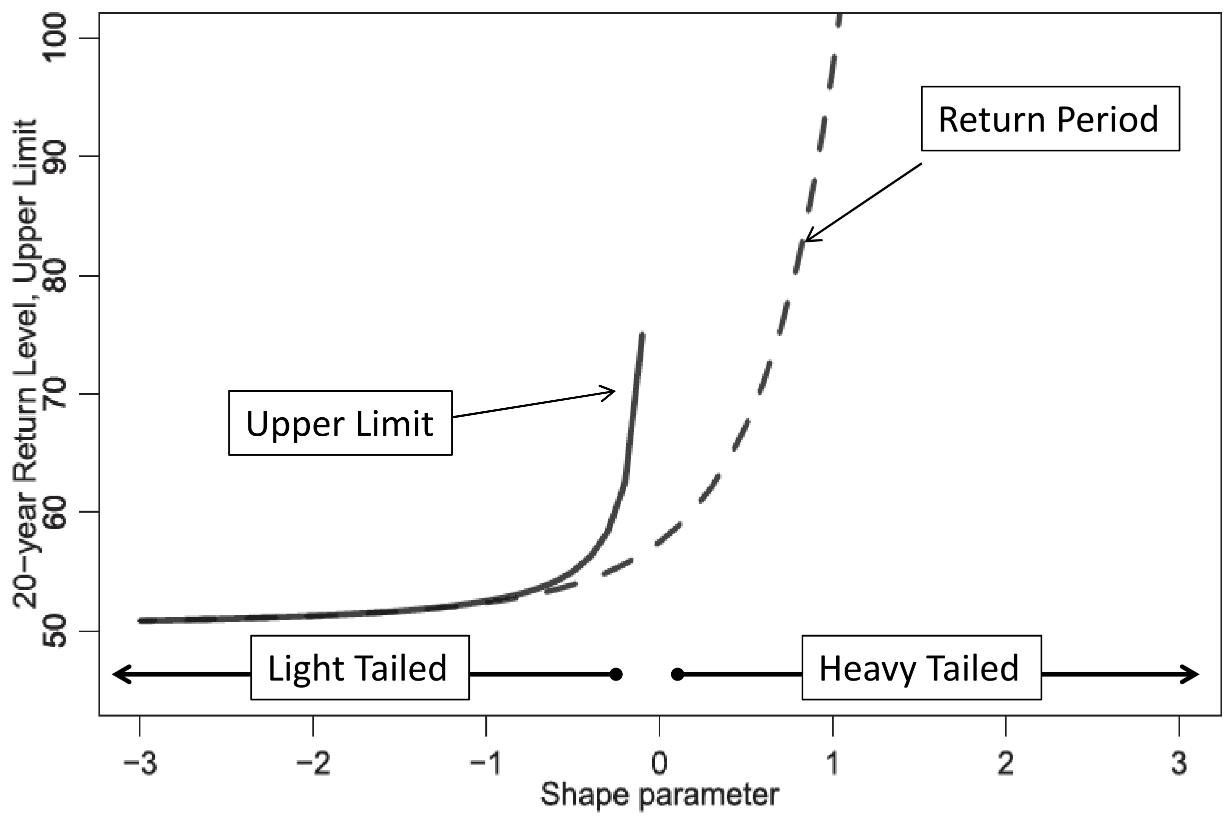
The Basics

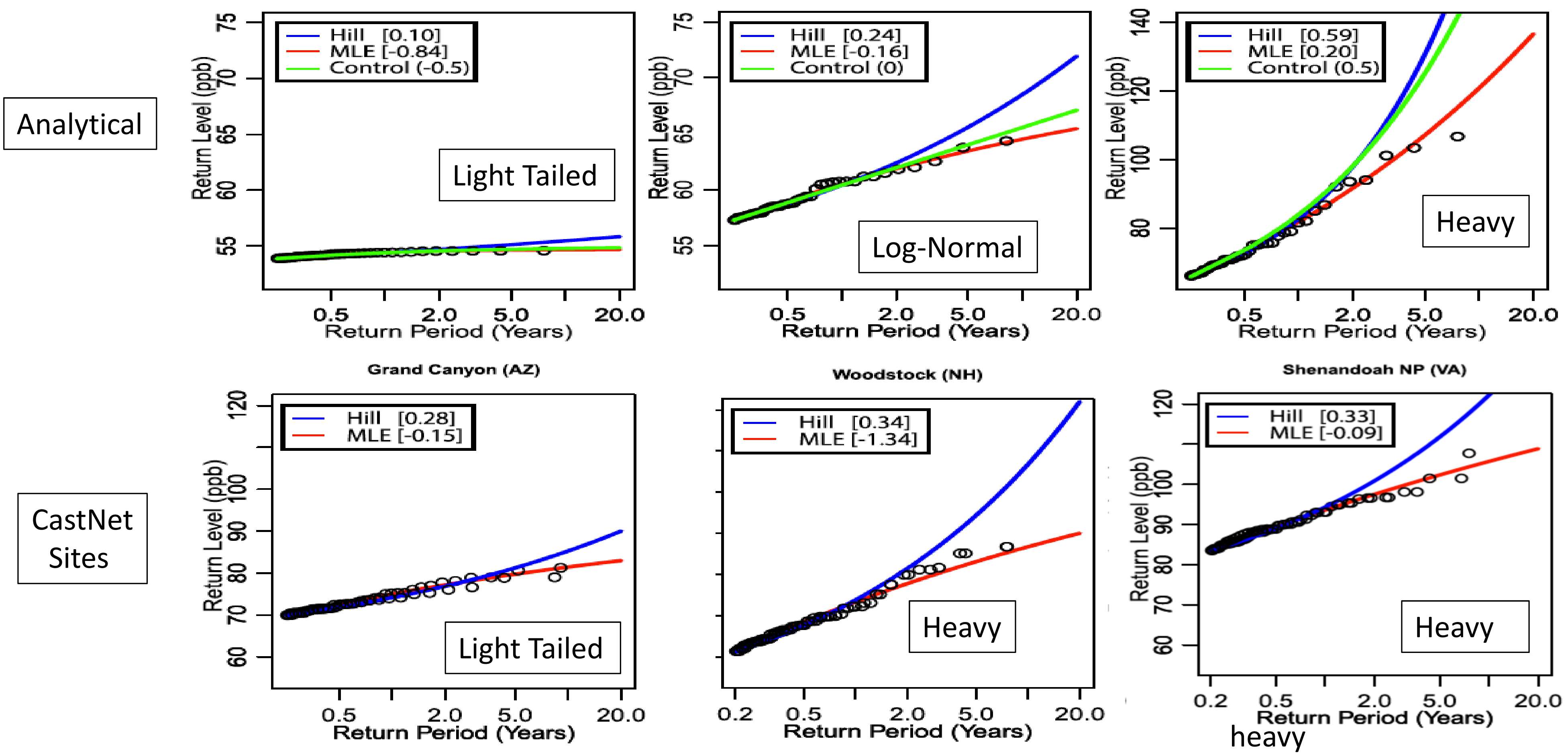
- Determining the tail parameters (location, scale and shape) of ozone distributions and thus the return interval is trickier than it may appear.
- An analysis of CASTNET ozone data shows that:
  - i) at some locations the ozone probability distribution is not exponentially bounded, and thus can be characterized as heavy tailed
  - ii) at other locations the distribution is not heavy tailed and is bounded to the right so that the ozone concentration is bounded for any return period.
- The tails of the ozone distribution become heavier following the NOx SIP call even as the mean ozone decreases.

Phalitnonkiat et al. (2016): Extreme ozone events: Tail behavior of the surface ozone distribution over the U.S. (Atmospheric Environment)

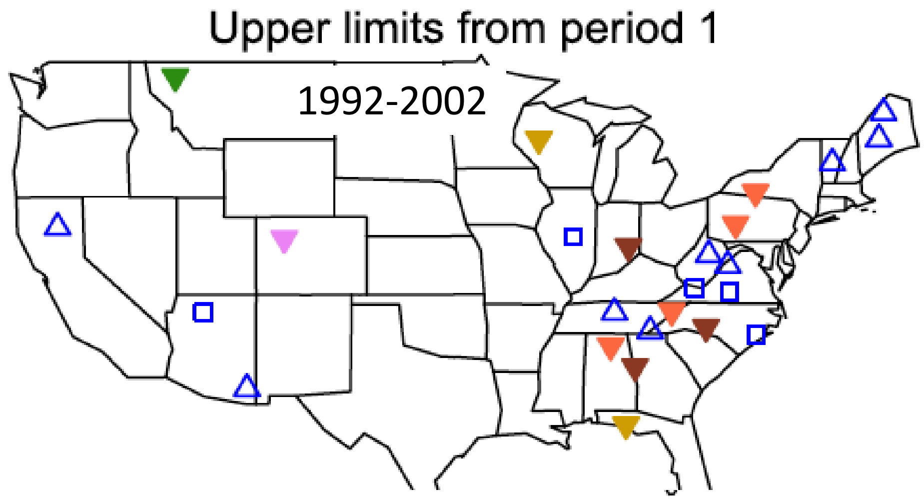
Dependence of Ozone on the Shape Parameter
(An Analytical Example)

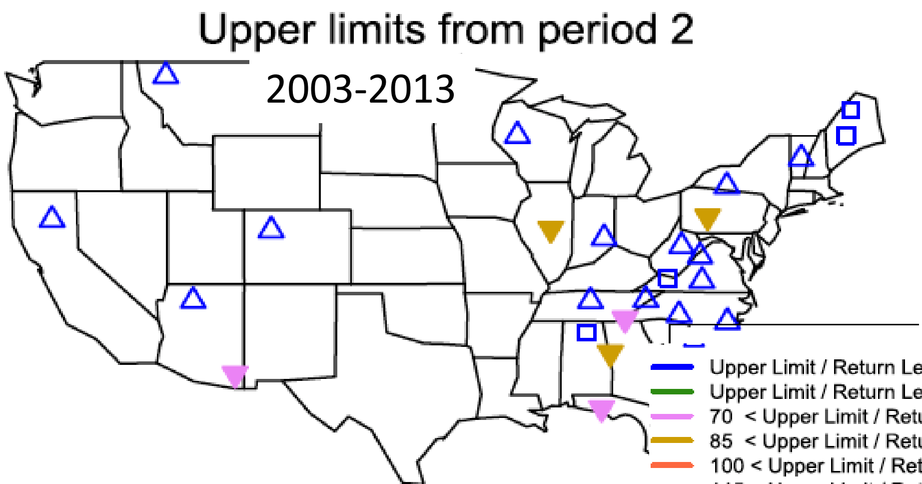


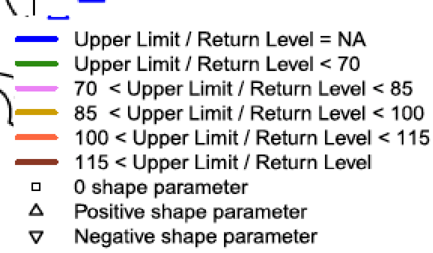
Heavy and Light Tails: Analytical and Castnet Stations



Blue: Hill's Estimator (accurate for heavy tails); Red: Maximum Likelihood Estimate (Accurate for light tails); Green: Anaytical Solution; **Circles**: station data or samples from analytical solution







Notes:

- Points Down: Negative Shape Parameter (Upper Limit)
- Points Up: Positive Shape Parameter (No Upper Limit)
- Box: ~Zero shape parameter
- 17/25 stations have increasing shape parameters From period 1 to period 2 (statistically significant)

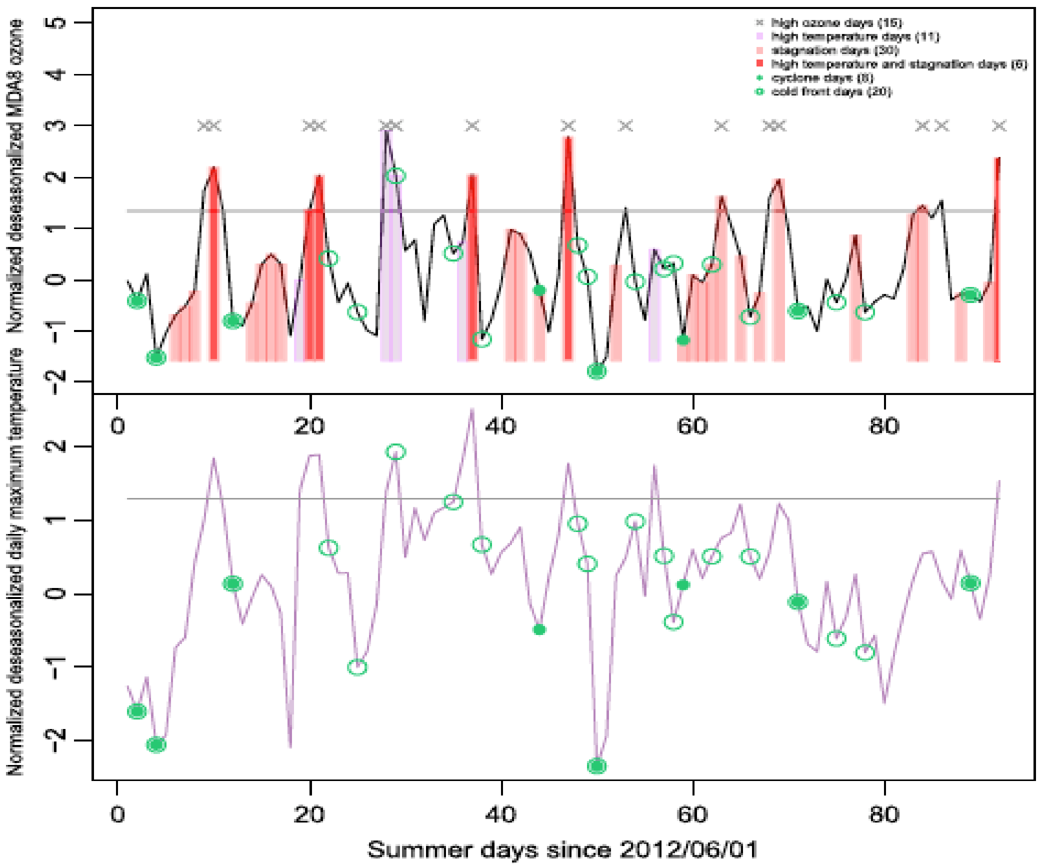
Examination of Meteorological Persistence on Extremes

- Ozone increases stagnation days in all regions of the U.S., with the highest increase in the Northeastern U.S. (0.4 standard deviation or ∼4.7 ppb per successive stagnation day).
- Ozone increases with days since cyclone passage only in the Northeastern and Mid-Atlantic regions of the U.S., but on average not enough to reach the 90th percentile concentration.
- Persistent high temperature does not result in further ozone increases in any region.
- On the interannual timescale there is little evidence that summers with large numbers of the above events increase ozone preferentially on the high end of the ozone distribution.

Sun et al. (2017, GRL): The impact of meteorological persistence on the distribution and extremes of ozone

Example Analysis at PSU CASTNET Station

(a) PSU106−Northeast

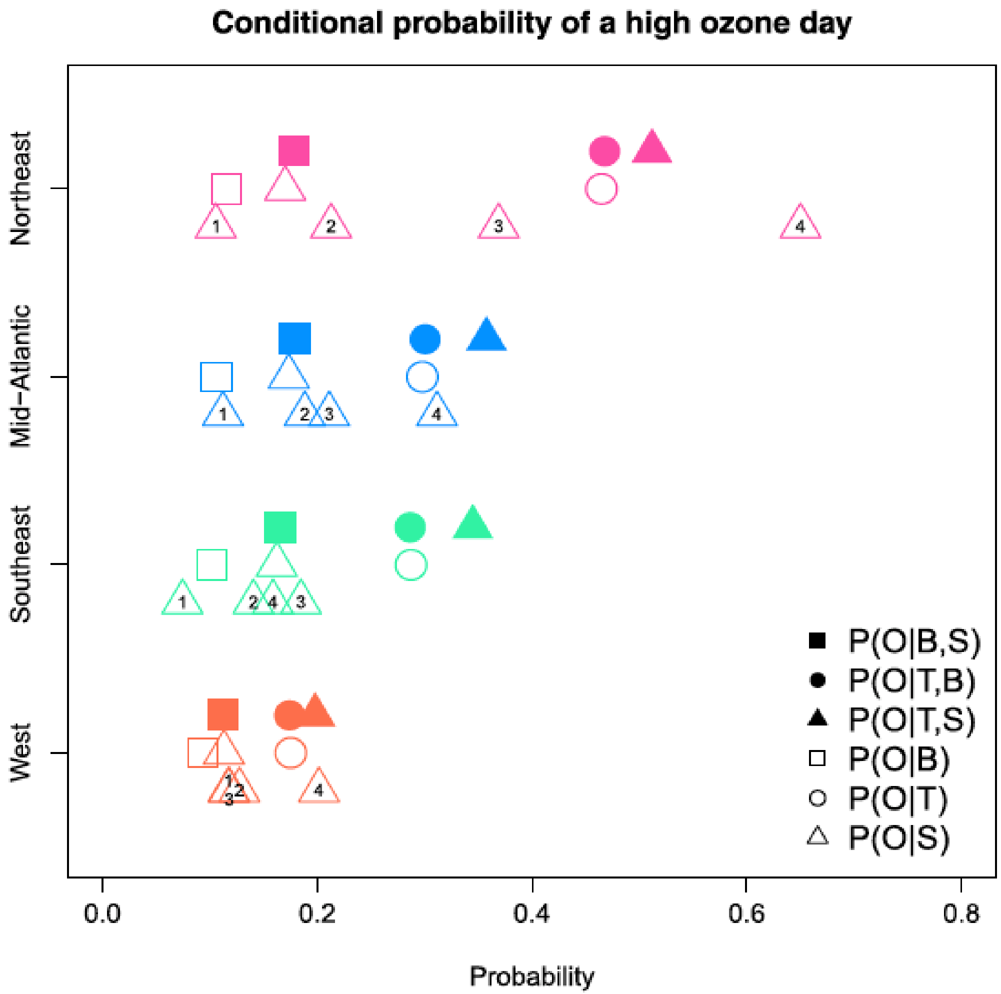


- high ozone days (15)
- high temperature days (11)
- stagnation days (30)
- high temperature and stagnation days (6)
- cyclone days (8)
- cold front days (20)

Notes:

-High temperature days and high ozone days frequently concurrent

-Stagnation days and high ozone days frequently concurrent



Notes:

- The best single indicator of a high ozone day is a high temperature day
- High temperature and stagnation is a better predictor than high temperature alone
- Ozone builds up with successive stagnation days in all regions (but Southeast)

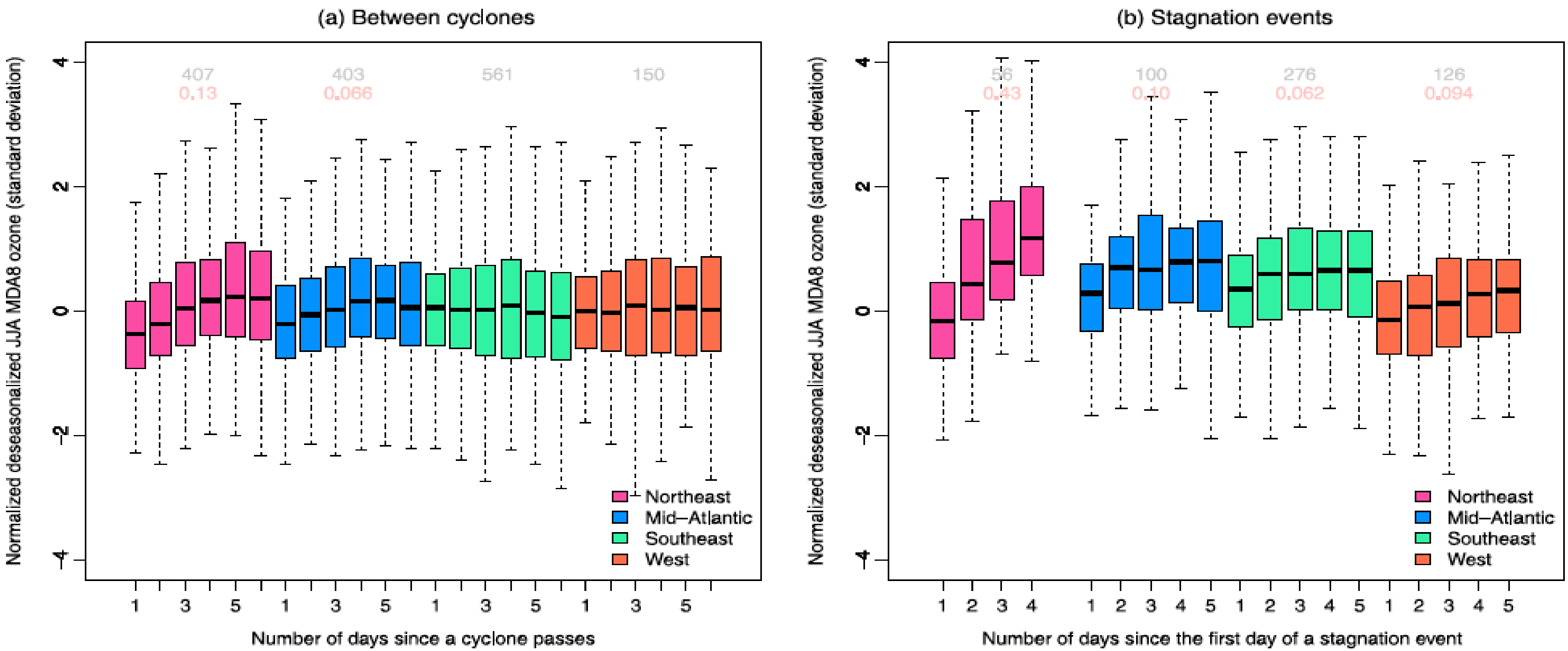
Key:

B: Between cyclone day

T: High temperature day

S: Stagnation day

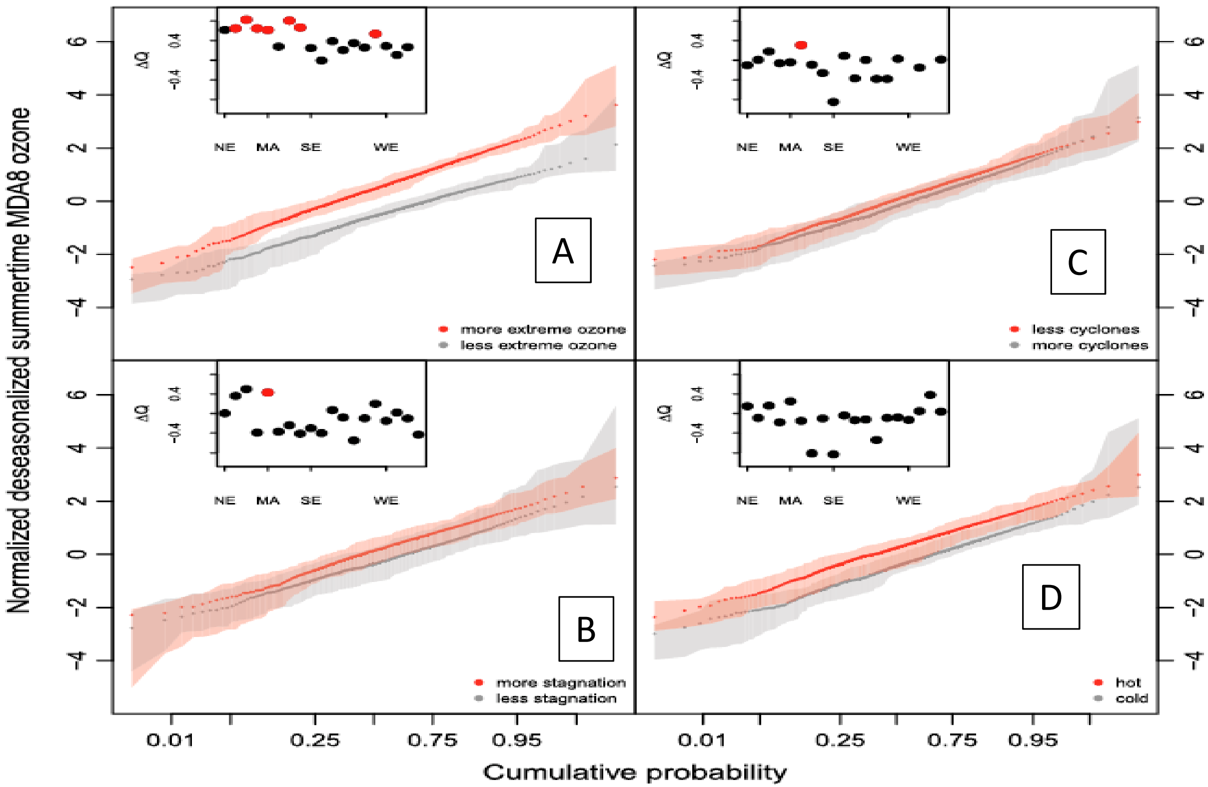
Ozone Build-Up with Successive Events*



*There is no buildup with high temperature

Normalized Cumulative Probability Plots Contrasting Ozone Distributions In Contrasting Summers

A) Summers with many high ozone events versus few high ozone events
B) Summers with many stagnation events versus few stagnation events
C) Summers with more cyclones versus fewer cyclones
D) Summers that are hot versus summers that are cold



Notes:

- As measured by:

$\Delta Q = \Delta\{ (O3|O3>90^{th}) - (O3|O3=50^{th}) \}$

these type of events do not amplify the top end of the probability distribution

- Difference in temperature between hot and cold summers ~difference expected due to climate change

- Number of cyclones show relatively little impact on distribution

Characterization of Temperature and Ozone Extremes in CCMI Constant Emission Simulations

- Ozone increases almost everywhere across the US due to changing climate
- Relative temperature extremes (with respect to the mean) generally decrease except across the Northern US, the Northeast and along the East Coast to the Southeast
- Relative ozone extremes generally follow the pattern of the temperature extremes

Phalitnonkiat et al. (2017, in preparation): Extremal Dependence between Temperature and Ozone over the Continental U.S.

CCMI Simulations

Table 1: Details and descriptions for each model.

Simulation (Years)	GHG[1] forcing	Emissions	SST[2] and sea ice	Meteorology
SDM[3] (1992-2010)	CMIP5[4] (updated until 2010)	Anthropogenic and biomass burning emission: MACCity[5] Biogenic emissions: MEGAN2[6]	HadISST2[7]	MERRA[8]
GCM2000 (2006-2025)	$CO_2 = 369$ ppm. Other GHG from SDM.	Anthropogenic and biomass burning from AR5[9]. Biogenic emissions: Monthly values from MEGAN2 for 2000	Online[10]	Online[10]
GCM2100 (2106-2125)	$CO_2 = 669$ ppm. Other GHG as in GCM2000.	GCM2000	Online[10]	Online[10]

[1] Greenhouse gas. [2] Sea surface temperature. [3] Specified Dynamics Model. [4] Coupled Model Intercomparison Project. [5] Granier et al. (2011). [6] Guenther et al. (2012). [7] Hadley Center Sea Ice and Sea Surface Temperature data set (Titchner and Rayner (2014)). [8] Modern Era Retrospective-analysis for Research and Applications (Rienecker et al. (2011)). [9] Assessment Report 5 (Eyring et al. (2013)). [10] Tilmes et al. (2016).

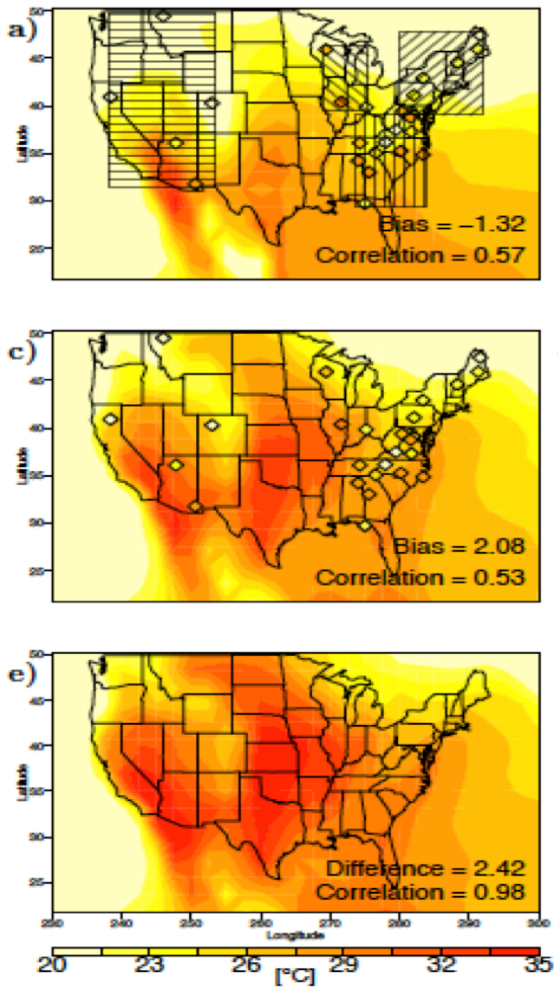
Phalitnonkiat et al. (2017, in preparation): Extremal Dependence between Temperature and Ozone over the Continental U.S.

Temperature

REFC1SD
(1992-2010)

REFC2
GCM2000
(2006-2025)

REFC2
GCM2100
(2106-2125)

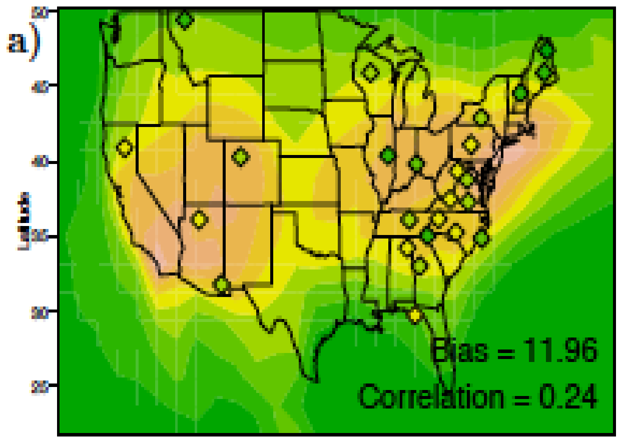


Notes:

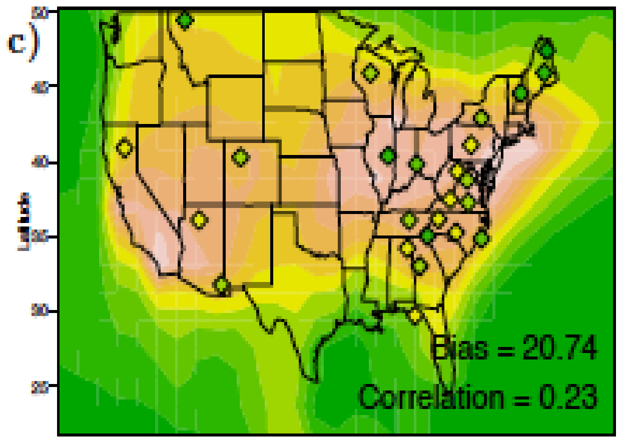
- Present Day Temperature Biases -1-2° C
- GCM2100 Temperature increase 2.4° C
- CCMI REFC2 Increases 2.8° C

Results: Comparison to Measurements

REFC1SD
(1992-2010)



REFC2
GCM2000
(2006-2025)

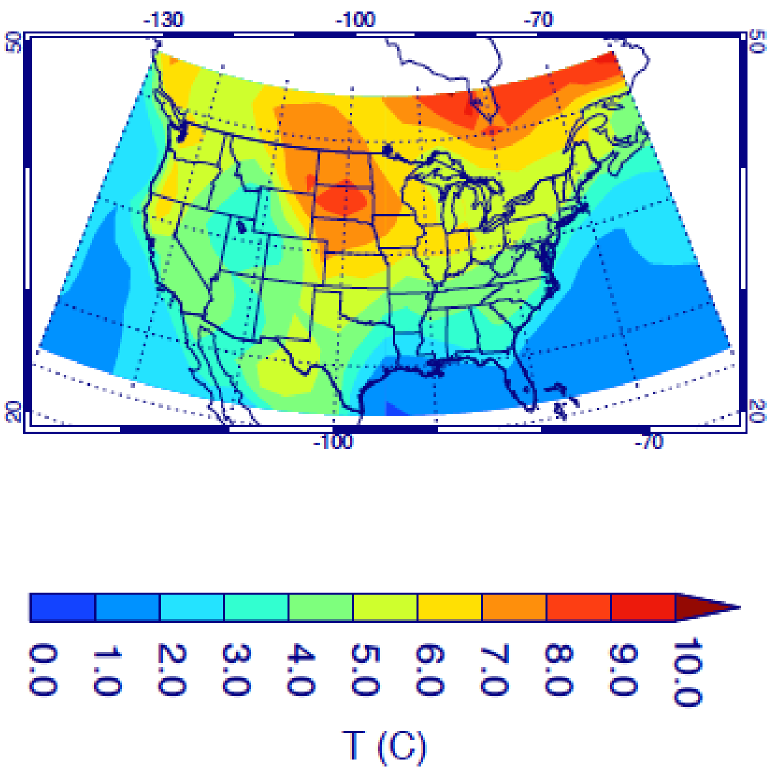


Ozone Biases are Profound (as measured at CASTNET Sites):

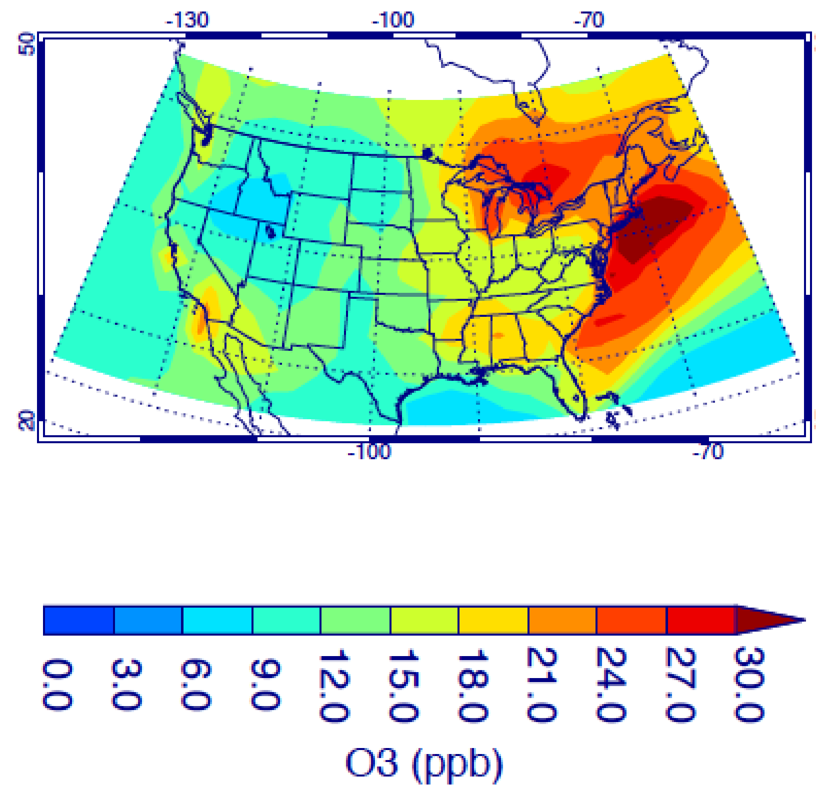
- REC1SD: ~12 ppb
- CGM2000: ~21 ppb

Where is Temperature and Ozone Most Extreme (GCM2000) ?

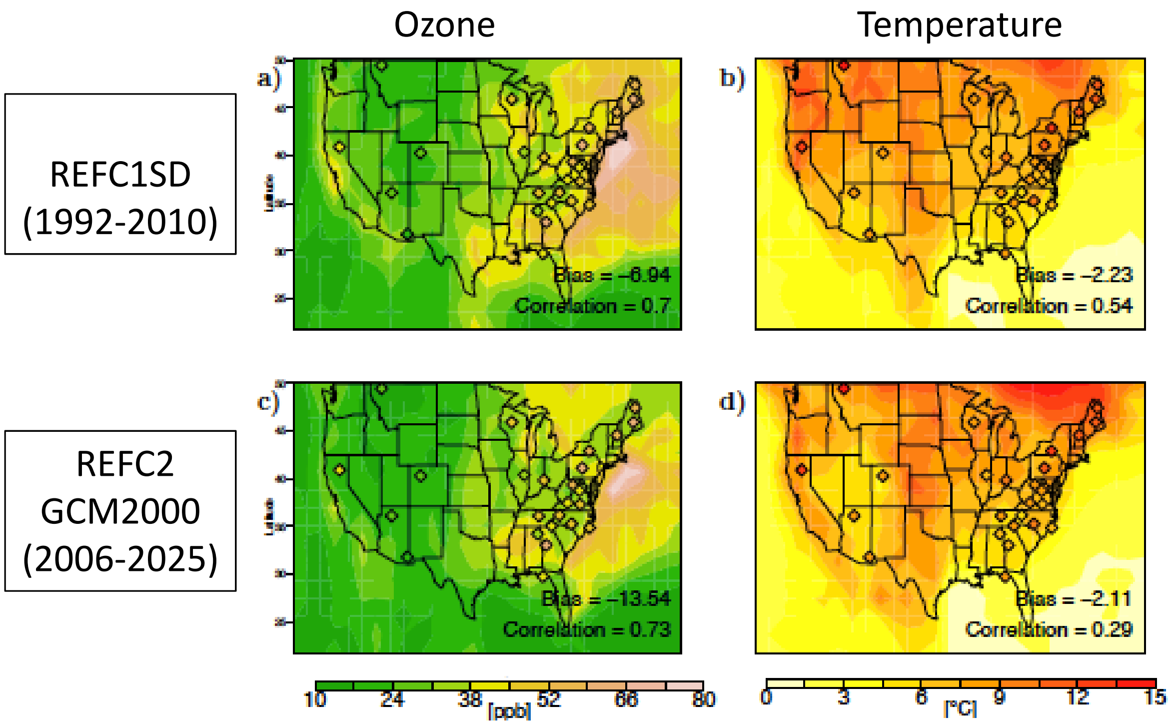
Temperature: [T|T>90%] – [T]



Ozone: [O3|O3>90%] – [O3]



20-year Return Periods minus mean for Ozone and Temperature

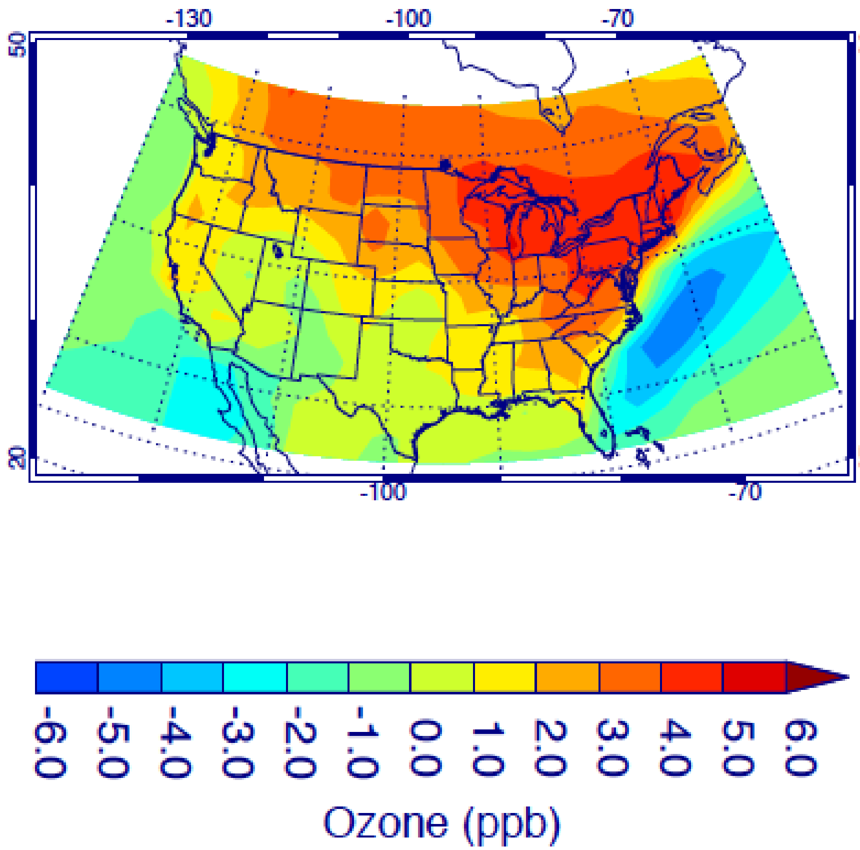


Notes:

- ❑ Return Difference for Ozone Significantly Underestimated
  - 7 ppb in REFC1SD
  - 13.5 ppb in REFC2
  - Modeled tail is weaker than observed
- ❑ Return difference for Temperature Slightly Underestimated
  - ~2^{o} in each simulation

Ozone Increase GCM2100-GCM2000 (Constant Emissions)

Ozone Difference GCM2100-GCM2000 Climate Signal (Constant Emissions)

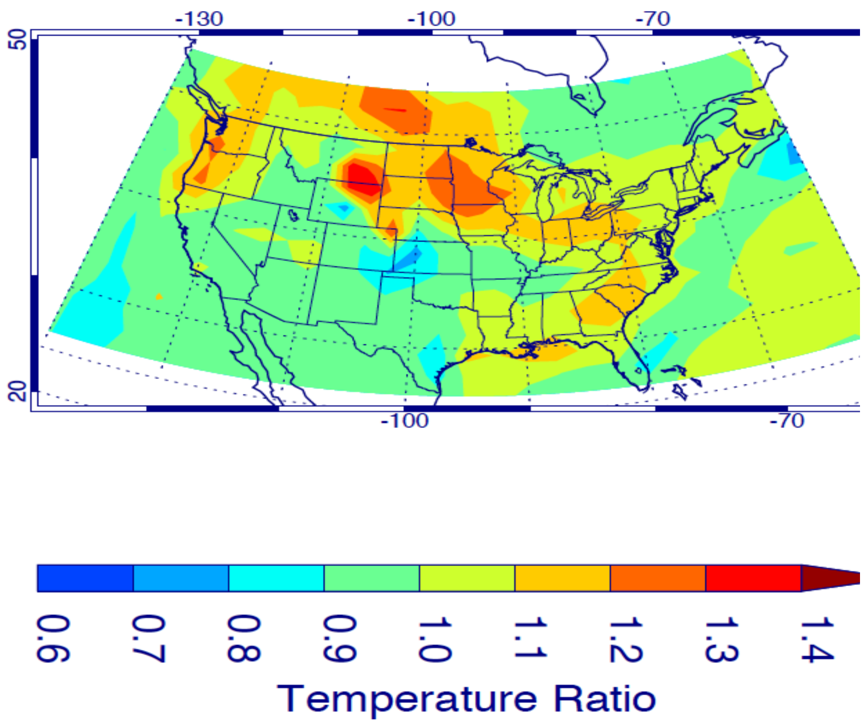


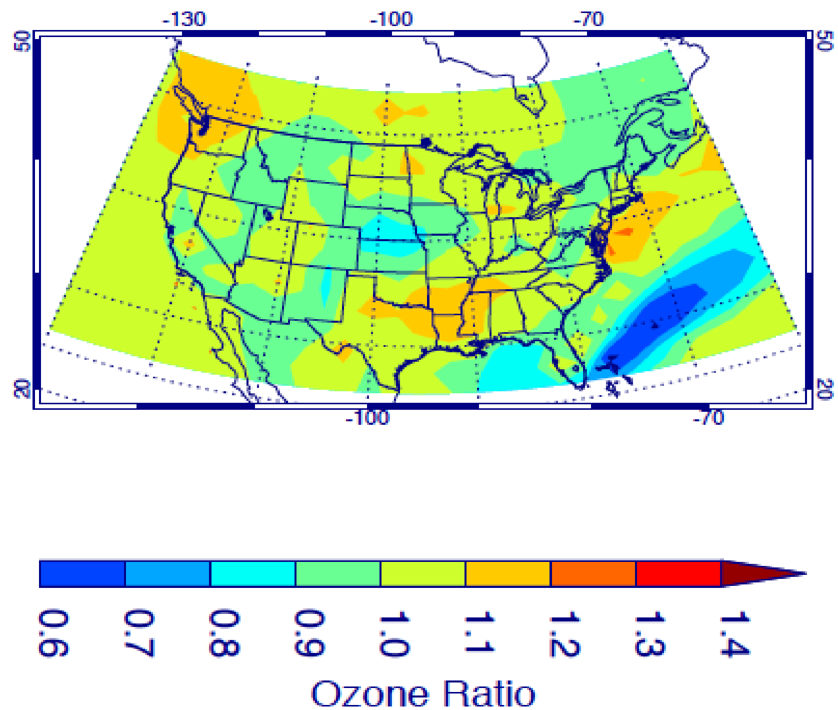
Notes:

- Average O3 Increase ~2.1 ppb
- Ozone increases almost everywhere
- Decreases over the ocean

Where Do Future Temperatures/Ozone Become More Extreme
With Respect to the Mean (where do the tails increase)?

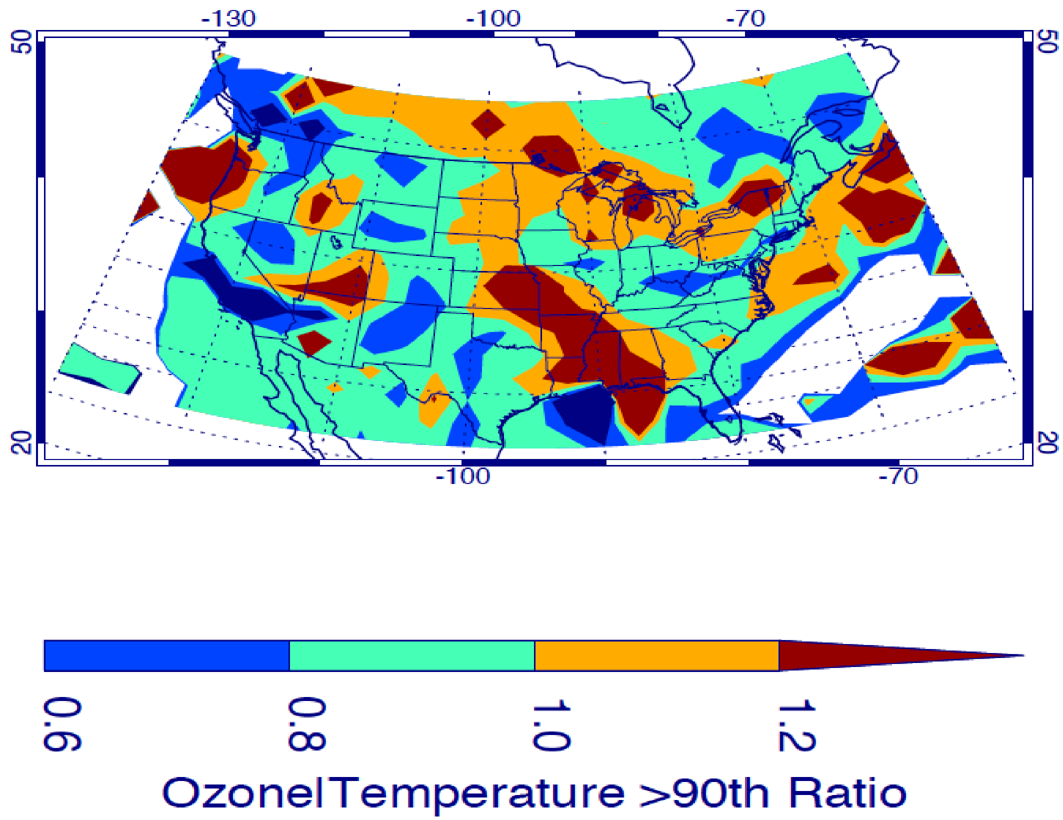
Define R = [GCM2100(X|X>90%)-GCM2100(X|45%<X<55%)]/[GCM2000(X|X>90%)-GCM2000(X|45%<X<55%)]





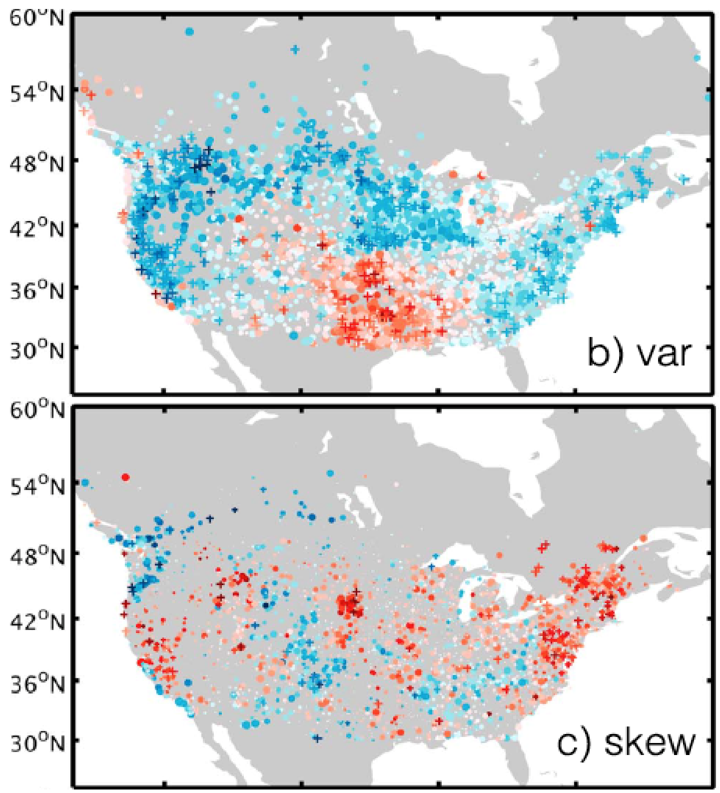
How Does Ozone Sensitivity to Temperature Change?

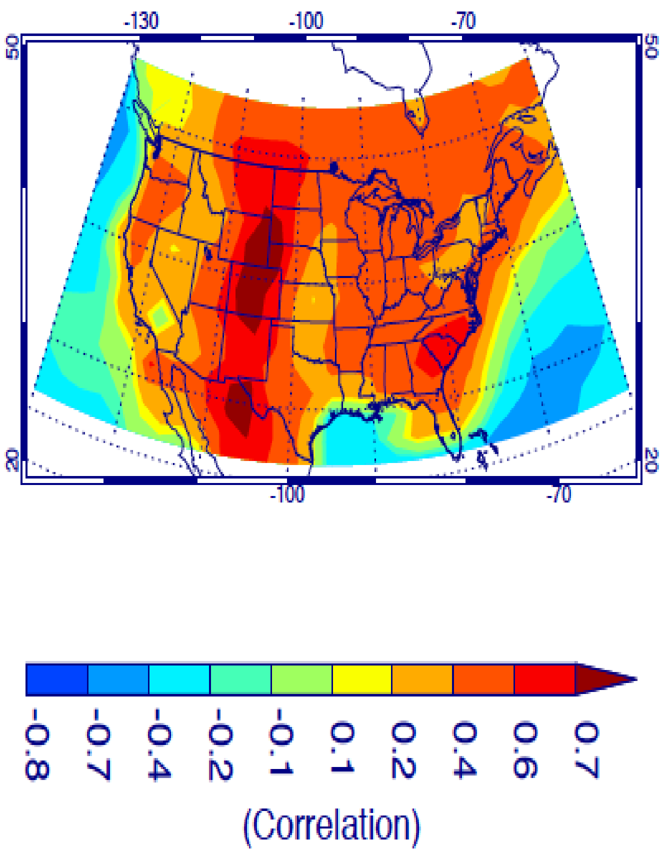
Define R = [GCM2100(O3|T>90%)-GCM2100(O3|45%<T<55%)]/[GCM2000(O3|T>90%)-GCM2000(O3|45%<T<55%)]

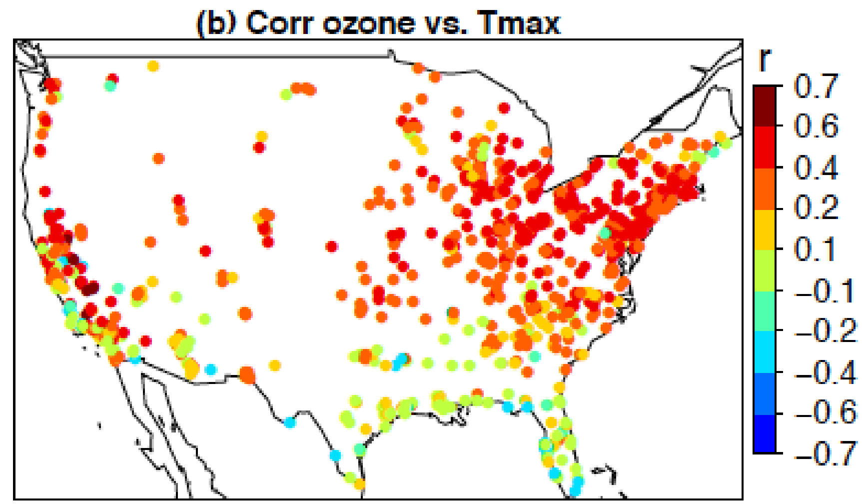


Conclusions

- In many locations over the US ozone has light tails and thus has an upper bound
- Analysis suggests following NOx SIP reductions the tails get more extreme while the mean decreases
- Persistence of high temperature (e.g., heat waves) events does not act to increase ozone, but persistence of stagnant conditions does.
- Little evidence from current climate that summers with more frequent stagnation events, hot summers or summers with less cyclone passages increases the tail of the ozone distribution
- In most locations in the US the tail of the future temperature distribution becomes lighter
- In most locations the tail of the future ozone distribution becomes lighter


60°N
54°N
48°N
42°N
36°N
30°N
b) var
60°N
54°N
48°N
42°N
36°N
30°N
c) skew





Shen et al. (2016)

Correlation: O3-T