Temperature extremes in the United States: Quantifying the response to aerosols and greenhouse gases with implications for the “warming hole”

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Observations show a “warming hole in southeast and central U.S.

Fig. 5b of Meehl et al, 2012

50 year trends in JJA daily maximum temperature

(d) warm days (TX90p)

50 and 100 year trends in annual TX90p

Fig. 3d of Donat et al, 2013
Possible natural causes of the warming hole

- This produces changes in local hydroclimate:
  - rainfall
  - soil moisture
  - cloud cover
  (Pan et al, 2004; Meehl et al, 2012; Weaver et al, 2012; Leibensperger et al, 2012; Yu et al., 2014)

Fig. 4 and 5 of Weaver et al, 2012
Potential anthropogenic contributors

- Anthropogenic forcing from aerosols (Leibensperger et al, 2012; Yu et al., 2014)
- Land use changes (Misra et al, 2013)
- Both factors potentially contribute to changes in hydroclimate

*Leibensperger et al., 2012*
Extreme Indices

- We focus on three indices defined by the Expert Team on Climate Change Detection and Indices (ETCCDI):
  - number of days above the 90th percentile daily maximum temperature (TX90p)
  - Total precipitation (PRCPTOT)
  - 99th percentile precipitation (R99p)
- 1961-1990 is used to define the climatological base period for TX90p and R99p (Sillman et al, 2013)

*IPCC AR5, 2014*
GFDL – CM3 Model

- Includes cloud-aerosol interactions (indirect effects) and interactive tropospheric chemistry
- Daily data are used from the:
  - “greenhouse gas only” simulations (1860-2005; 3 ensemble members)
  - “aerosol only” simulations (1860-2005; 3 ensemble members)
  - RCP8.5 and RCP8.5_2005Aer (2005-2100; 3 ensemble members)
  - Pre-Industrial control simulation (800 years)

Horowitz, 2014

Anti-correlation in summertime temperature extremes (TX90p)

Changes in days above the 90th percentile daily maximum temperature from 1860-1890 to 1976-2006

- ΔTX90p\textsubscript{AER} and ΔTX90p\textsubscript{GHG} are anti-correlated spatially
  - aerosols are masking GHG warming
- Strongest response to forcing in the Western U.S.
- Southeast U.S. warming/cooling hole collocated with observed warming hole (e.g. Meehl et al, 2012, Weaver et al, 2012, Leibensperger et al, 2012)

\[ r = -0.72 \]
Changes in hydroclimate in the Southeast US contributing to warming/cooling hole

Changes total summertime precipitation (mm) from 1860-1890 to 1976-2006

Aerosol Only

Greenhouse Gas Only

- Aerosols decrease summertime precipitation over the eastern U.S., with most significant decreases in the south east, collocated with the ‘cooling hole’
- Greenhouse gases significantly increase summer precipitation in the southeast, collocated with the ‘warming hole’
Aerosol effects on moisture and clouds

Changes from 1860-1890 to 1976-2006 for the aerosol only simulation

- Increasing aerosols reduces the summertime transport of moisture into the southeast U.S. and the total cloud fraction.
- As a result, the SW absorption increases, leading to warming relative to the rest of the U.S.A.
Low level circulation changes driven by changes in the Bermuda High

Changes from 1860-1890 to 1976-2006 for the aerosol only simulation. Contours on the left show the 1860-1890 asymmetric geopotential height.

Weakening of the Bermuda High reduces the winds from the Gulf into the southeast U.S., reducing moisture transport.
Southeast US temperature response is relatively small through mid-century

Changes in days above the 90th percentile daily maximum temperature from 1976-2006 to 2035-2065 for RCP8.5 (left) and RCP8.5_2005Aer (right)

- Rising greenhouse gases cause statistically significant warming across the US by mid-century (2035-2065)
- Aerosol reductions lead to increases of 10-15 days per summer over the U.S. by mid-century
- Warming in the southeast U.S. continues to be relatively weak
Conclusions

• Aerosol and greenhouse gas effects on extreme temperature are significantly anti-correlated, with the largest temperature changes occurring in the western U.S.

• Temperature response is weakest in the southeast U.S., corresponding to the observed warming hole. This feature persists through mid-century under RCP 8.5

• In the aerosol only simulation, weakening of the Bermuda High contributes to changes in the regional circulation.

• This results in a reduction in the transport of moisture into the southeast US and reduction in the total cloud fraction leading to warming.
Aerosol emissions from 1950-2100

Courtesy of Vaishali Naik, GFDL
Aerosol Radiative Forcing

Fiore et al, 2015 (in press)
1979-2005 Climatology

North American surface temperature. From Sheffield et al, 2013
Extreme Indices

- This work uses a set of extreme indices defined by the Expert Team on Climate Change Detection and Indices (ETCCDI):
  - % of days above the 90th percentile daily maximum temperature (TX90p)
  - Total annual precipitation (PRCPTOT)
  - 99th percentile precipitation (R99p)

Figure 10 (Sillman et al, 2013)
Climatological Precipitation

- Comparison between models and obs of 3mm/day contours in winter and summer.
- Models are generally better at simulating wintertime precipitation patterns
- GFDL has a wet bias, particularly in the Northwest U.S.

Sheffield et al, 2013
GHG impacts on moisture and clouds

Changes from 1860-1890 to 1976-2006 for the greenhouse gas only simulation

- Increasing GHGs increases the summertime transport of moisture into the southeast U.S.
- There is a local minimum in the change in total cloud fraction
- Surface SW absorption decreases in the southeast U.S., leading to cooling.
GHGs strengthen the Bermuda High

Changes from 1860-1890 to 1976-2006 for the GHG only simulation. Contours on the left show the 1860-1890 asymmetric geopotential height.

- Rising GHG concentrations strengthen the Bermuda High along its western edge.
- However, there is no clear impact on the low level circulation in the eastern U.S.
Wintertime changes in extreme rainfall

Changes in DJF extreme precipitation (mm) from 1860-1890 to 1976-2006.

- Aerosols significantly decrease extreme winter precipitation in the eastern U.S.
- Greenhouse gases significantly increase winter precipitation in the eastern U.S.
Significant increases in spring precipitation due to greenhouse gases

Changes in MAM extreme precipitation (mm) from 1860-1890 to 1976-2006 for

- Weak spatial correlation between greenhouse gases and aerosols
- Greenhouse gases cause increases in extreme precipitation over the central and midwest U.S.

$\text{r} = -0.24$
Decreasing aerosols increase R99p by 2100

Changes in seasonal extreme precipitation from 1976-2006 to 2070-2100 in the RCP8.5 (top) and RCP8.5_2005Aer scenario (bottom)