North Carolina's Changing Climate: Extreme Heat and Rainfall

Jared H. Bowden

Carolina Science Cafe

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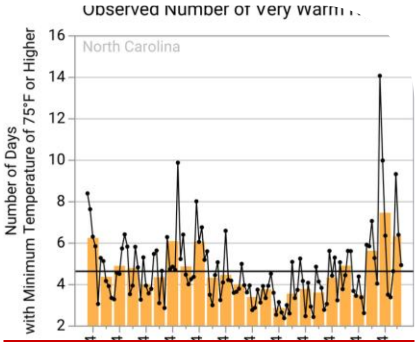
About the State Climate Office of North Carolina

Located on Centennial Campus at NCSU, the State Climate Office of North Carolina is dedicated to serving the needs of North Carolinians by translating climate information into useful and usable knowledge, and bridging the gap between scientists, decision-makers, and community members.

OUR THREE MISSION AREAS



Research

Original projects to address North Carolina's climate challenges

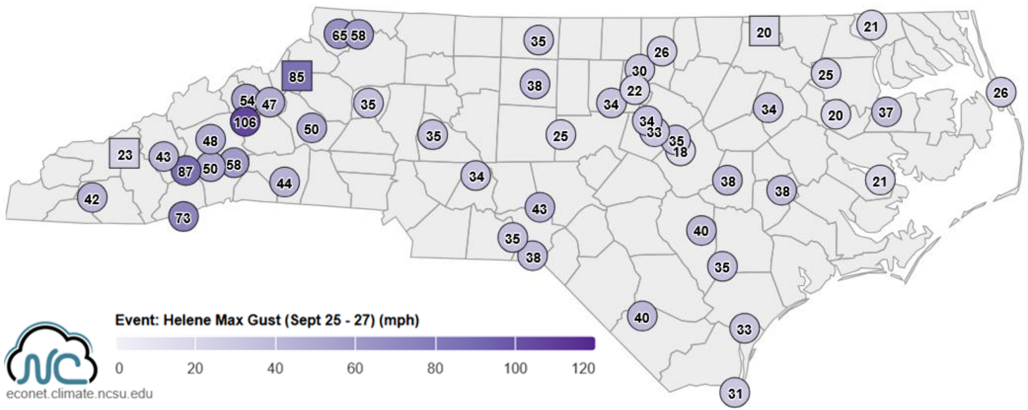
Extension & Education

Climate knowledge and support to all 100 counties

Monitoring

Understanding North Carolina's environment

NC ECONet - 46 Research Grade Weather Stations



Atmospheric and Soil Parameters Measured

- Air Temperature (2m & 9m)
- Relative Humidity (2m)
- Barometric Pressure (2m)
- Wind Speed & Direction (2m, 6m, 10m)
- Precipitation (1m & 2m)
- Total Solar Radiation (2m)
- Photosynthetically Active Radiation (2m)
- Leaf Wetness (0.6m)
- Soil Moisture (-20cm)
- Soil Temperature (-10cm)
- Black Globe Temperature (2m)

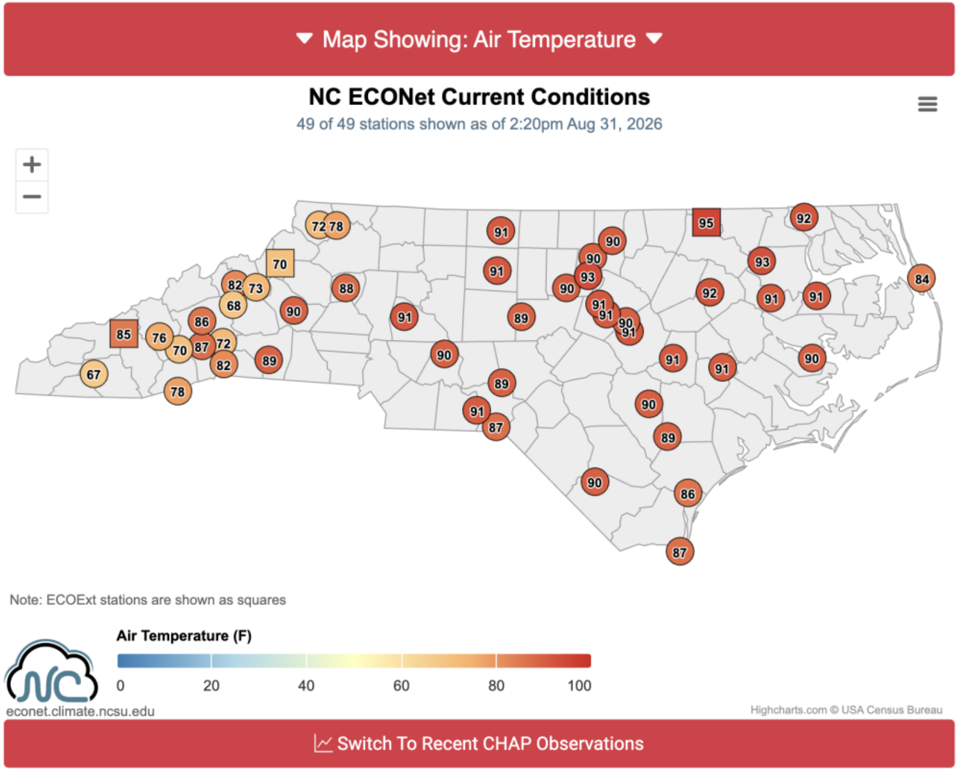
Real-time weather conditions (every 5 min.)

Change Station

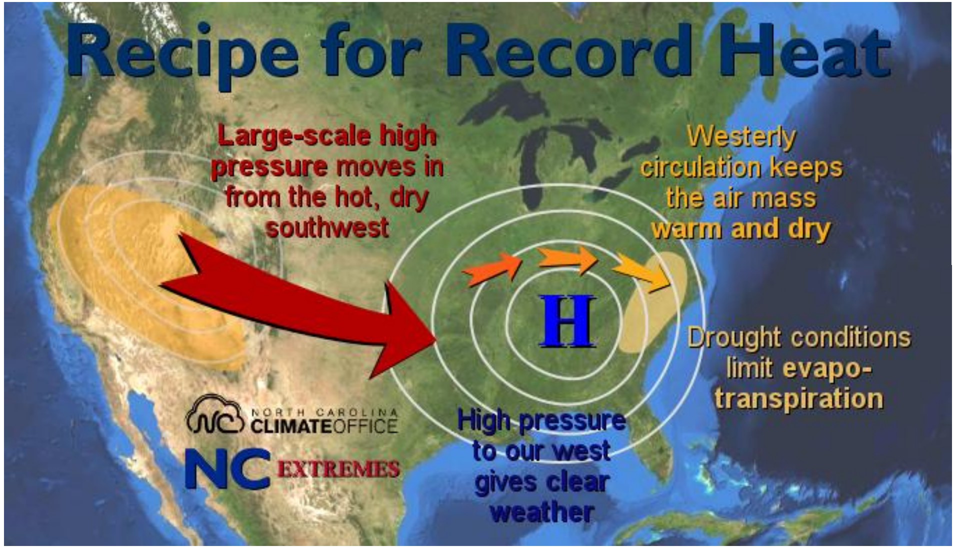
CHAP - Chapel Hill, NC
Horace Williams Airport
2:15pm Aug 31, 2026
(5 min ago)

Air Temperature 90 F	**Heat Index** 94.4 F
Wind Speed & Direction N 1 mph	
24-Hour Total Precipitation 0 in	**7-Day Total Precipitation** 0.11 in
Dew Point Temperature 69.2 F	**Soil Temperature** 81 F
24-Hour Maximum Air Temperature 90.3 F	**24-Hour Minimum Air Temperature** 67.6 F

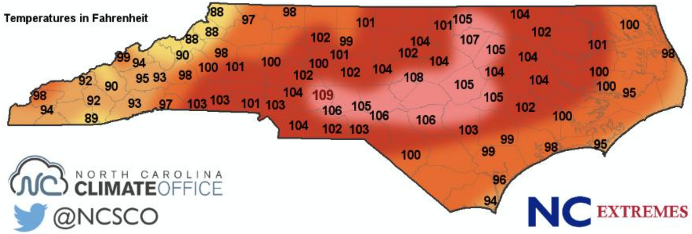
More CHAP Data



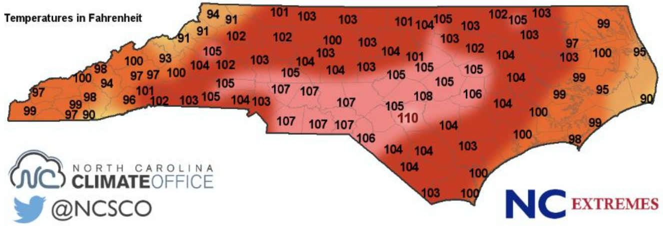
Recipe for Record Heat (Max. Temperatures)



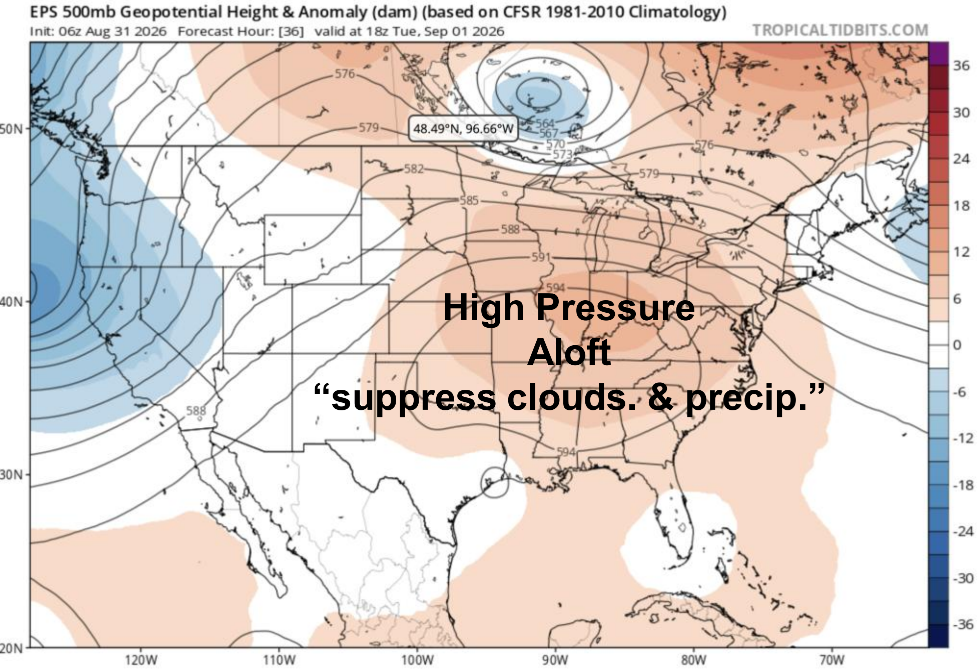
Maximum Temperatures from July 26-29, 1940

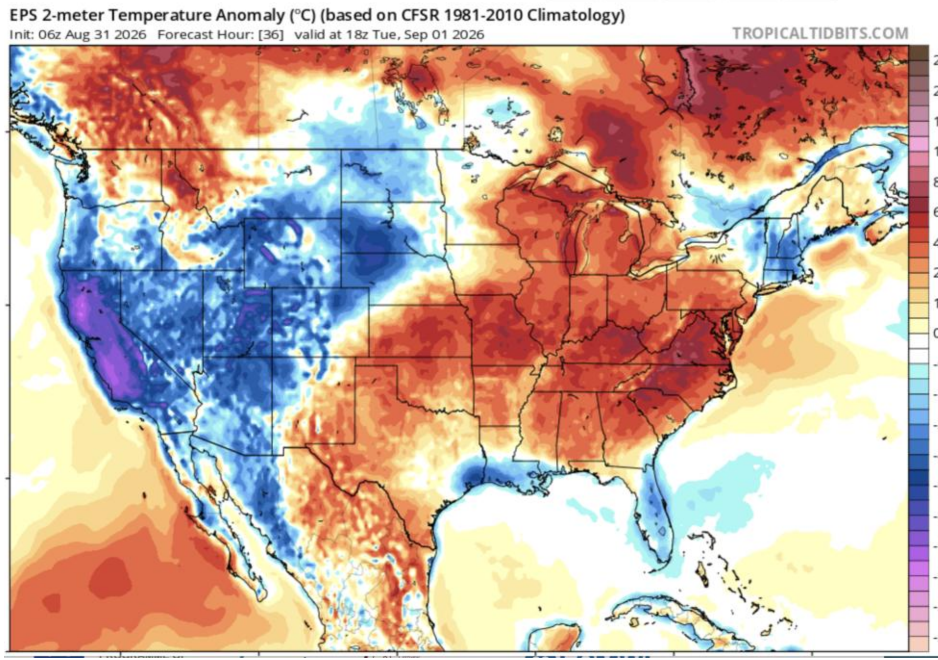


Maximum Temperatures from August 21-24, 1983

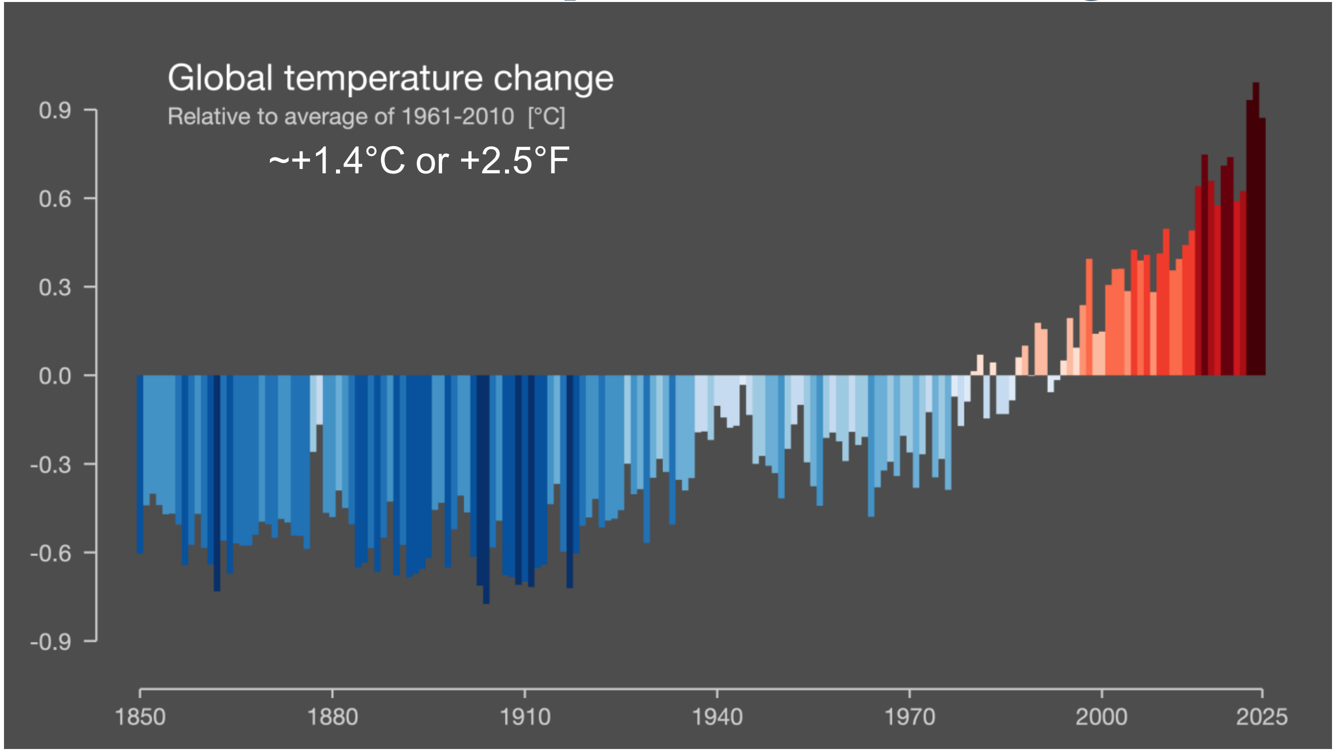


High Pressure Aloft (Heat Dome) Temperature Anomaly Forecast for Tue. September 1, 2026



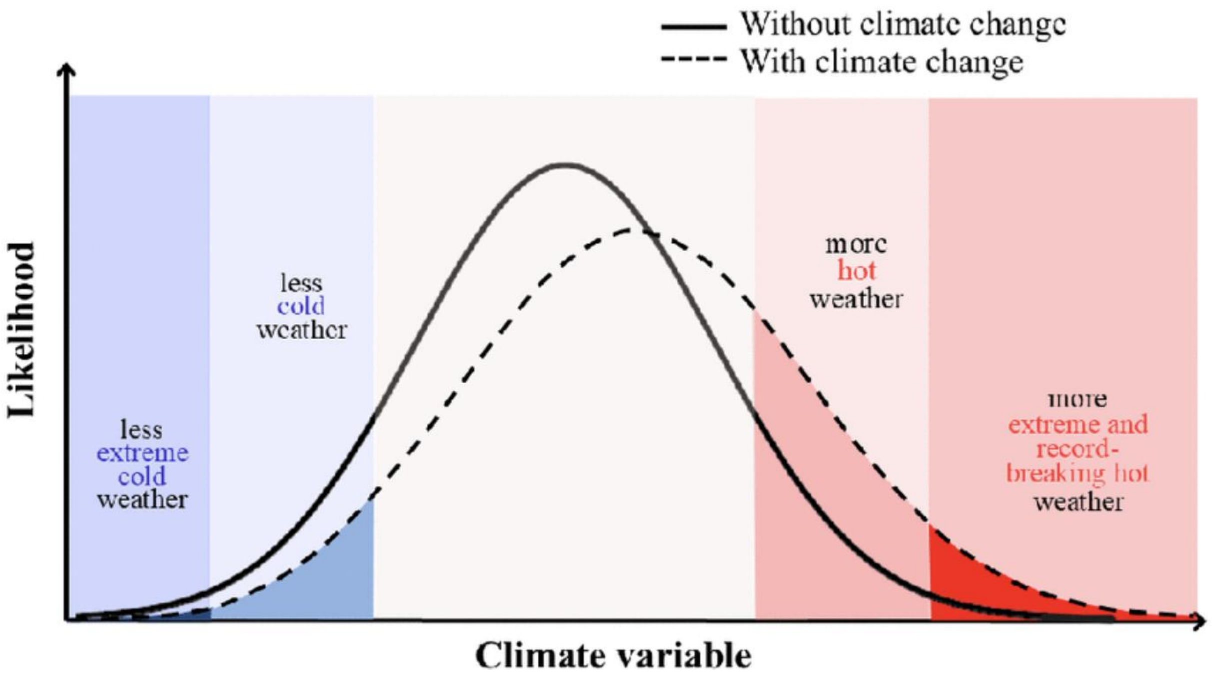


NC's Changing Climate Starts with Global Temperature Change



Climate stripes - Ed Hawkins - https://showyourstripes.info/

Extreme Heat Events in a Warmer World Become More Extreme



Source: IPCC 2012 Summary for Policy Makers

Current Economic and Societal Impact of Heat in the USA

Estimated annual US economic loss from heat affecting worker productivity

$100 billion

Estimated cost of the 2024 hurricane season was ~$129.5 billion (3rd most all-time)

Occupational injuries due to extreme heat

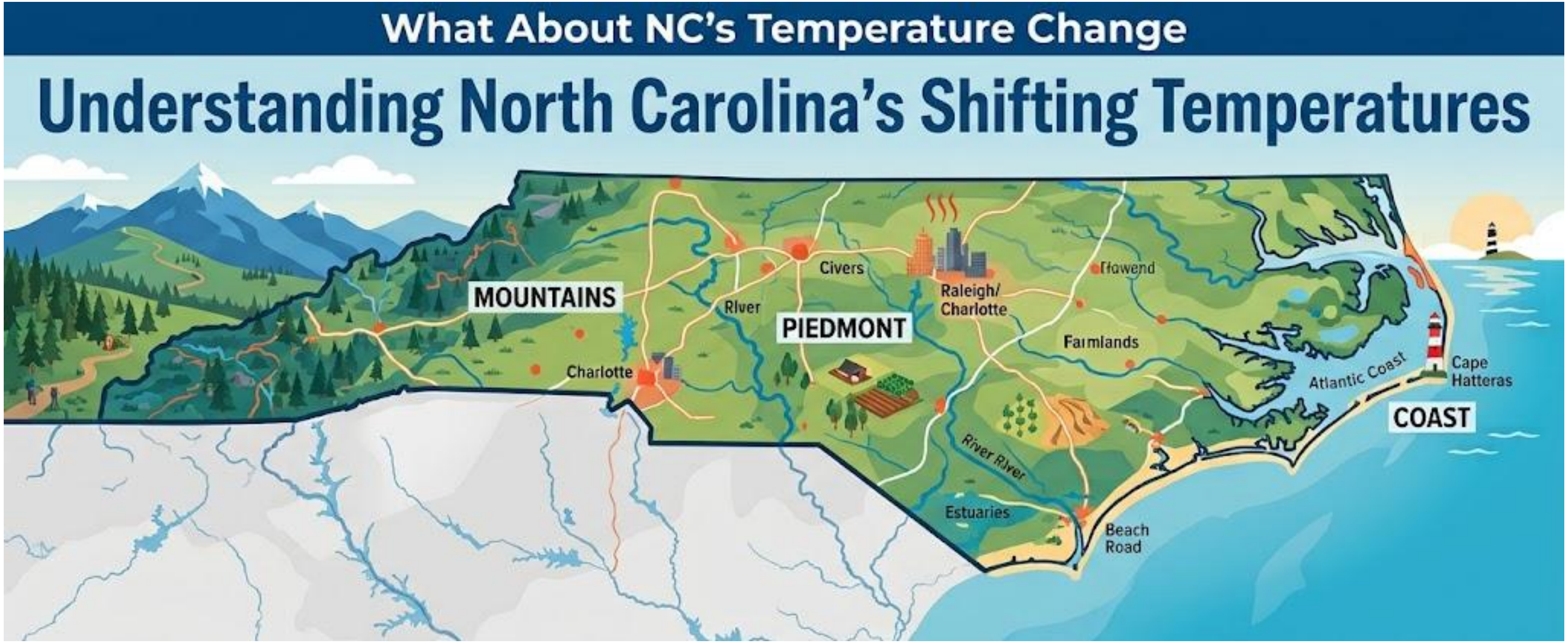
~120,000 / year

KESQ.com (6/18/21)

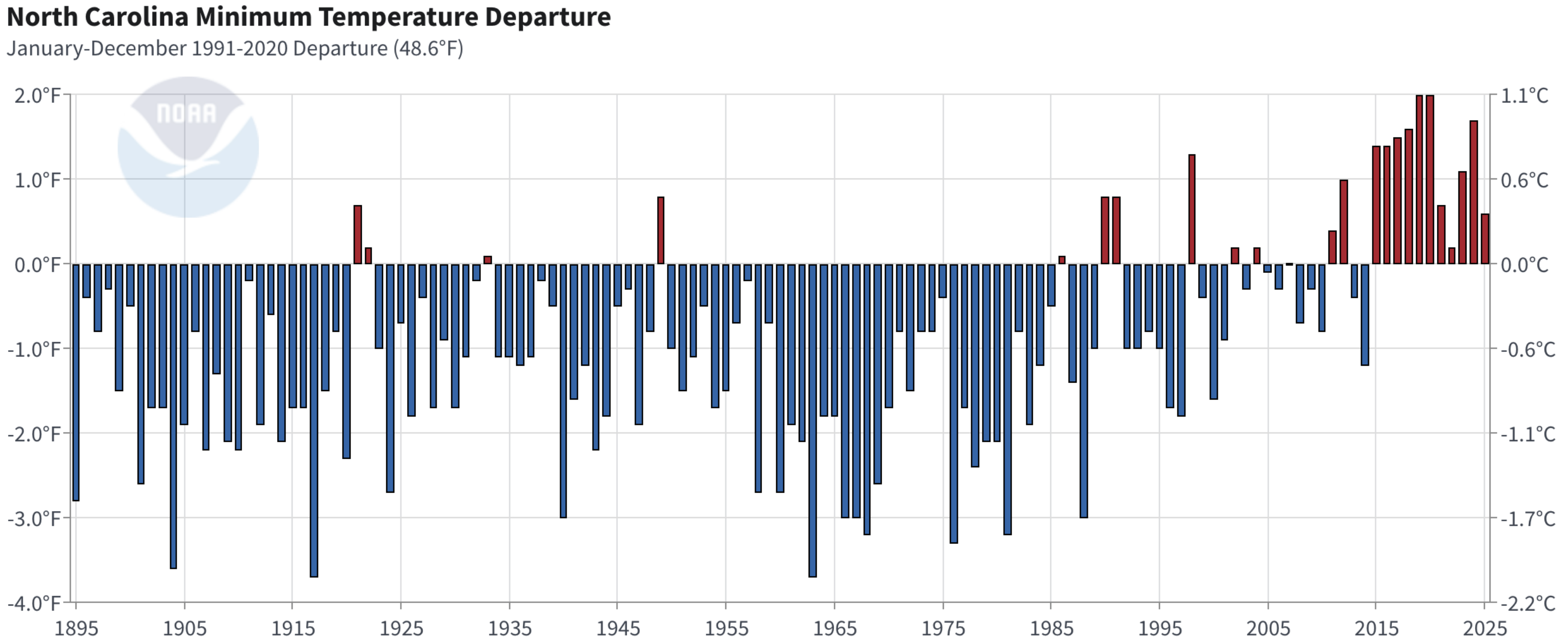
Deaths associated with average temperatures > 90°F

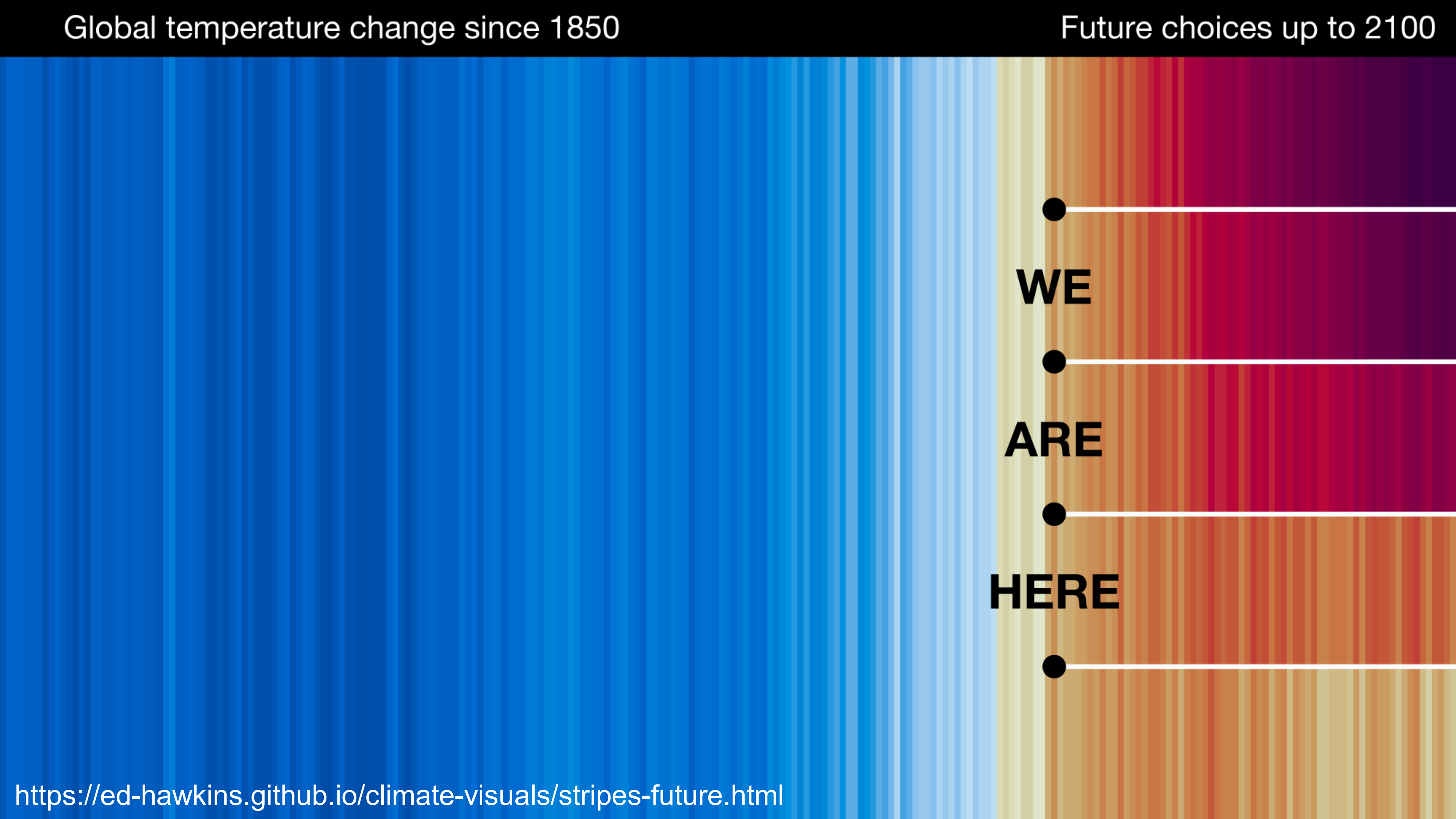
~8,500 / year

(Data from Sep. 2021 report of the Atlantic Council's Adrienne Arsht-Rockefeller Foundation Resilience Center)


What About NC's Temperature Change
Understanding North Carolina's Shifting Temperatures
MOUNTAINS
Charlotte
River
Civers
PIEDMONT
Raleigh/
Charlotte
Farmlands
Atlantic Coast
Cape
Hatteras
COAST
River River
Estuaries
Beach
Road

NC Minimum Temperature
Strong warming observed overnight




Global temperature change since 1850
Future choices up to 2100
WE
ARE
HERE
https://ed-hawkins.github.io/climate-visuals/stripes-future.html

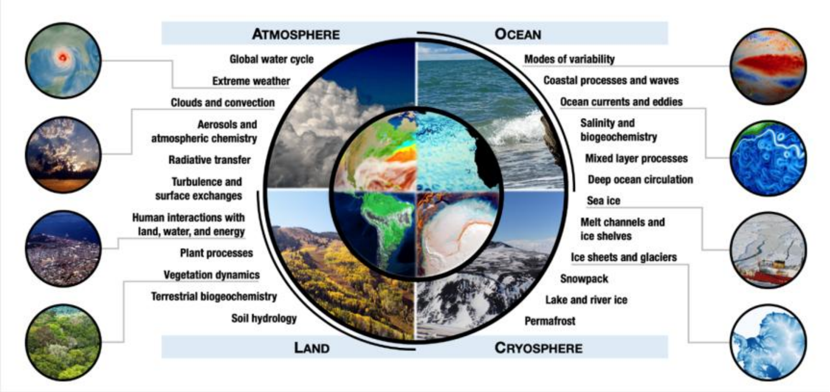
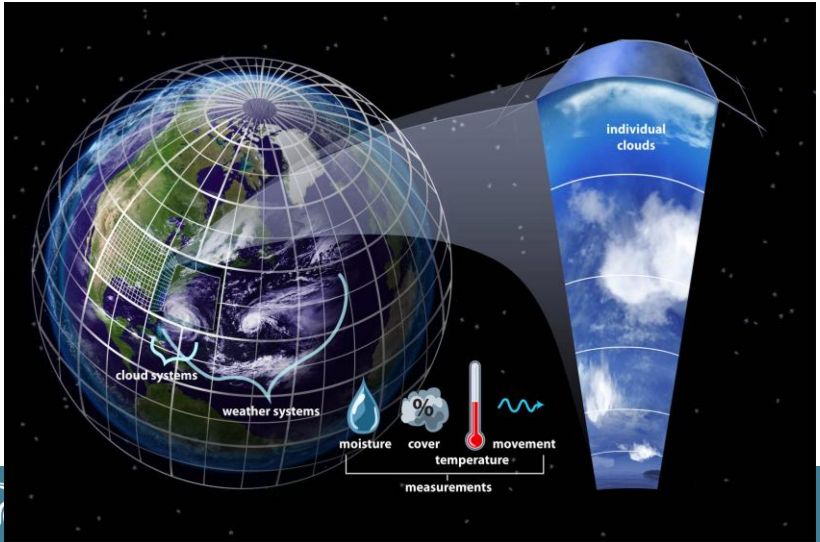


Image courtesy of Paul Ullrich, University of California, Davis



Global Climate Models GCMs

```
module cam_comp
!-----------------------------------------------------------------------
!
! Purpose:  The CAM Community Atmosphere Model component. Interfaces with
!           a merged surface field that is provided outside of this module.
!           This is the atmosphere only component. It can interface with a
!           host of surface components.
!
!-----------------------------------------------------------------------
   use shr_kind_mod,      only: r8 => SHR_KIND_R8, cl=>SHR_KIND_CL, cs=>SHR_KIND_CS
   use pmgrid,            only: plat, plev
   use spmd_utils,        only: masterproc
   use abortutils,        only: endrun
   use camsrfexch_types,  only: surface_state, srfflx_state
   use shr_sys_mod,       only: shr_sys_flush
   use infnan,            only: nan
   use physics_types,     only: physics_state, physics_tend
   use cam_control_mod,   only: nsrest, print_step_cost, obliqr, lambm0, mvelpp, eccen
   use dyn_comp,          only: dyn_import_t, dyn_export_t
   use ppgrid,            only: begchunk, endchunk
   use perf_mod
   use cam_logfile,       only: iulog

   implicit none
   private
   save
   !
   ! Public access methods
   !
   public cam_init      ! First phase of CAM initialization
   public cam_run1      ! CAM run method phase 1
   public cam_run2      ! CAM run method phase 2
   public cam_run3      ! CAM run method phase 3
   public cam_run4      ! CAM run method phase 4
   public cam_final     ! CAM Finalization
   !
   ! Private module data
   !
#if ( defined SPMD )
   real(r8) :: cam_time_beg              ! Cam init begin timestamp
   real(r8) :: cam_time_end              ! Cam finalize end timestamp
   real(r8) :: stepon_time_beg = -1.0_r8 ! Stepon (run1) begin timestamp
   real(r8) :: stepon_time_end = -1.0_r8 ! Stepon (run4) end timestamp
   integer  :: nstep_beg = -1            ! nstep at beginning of run
#else
   integer  :: mpicom = 0
#endif
```

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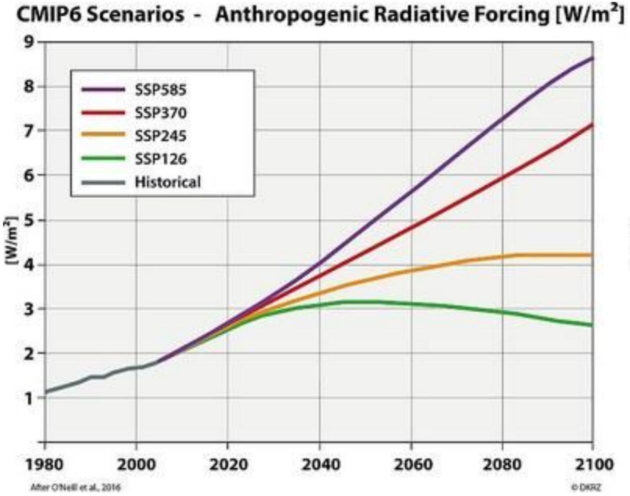
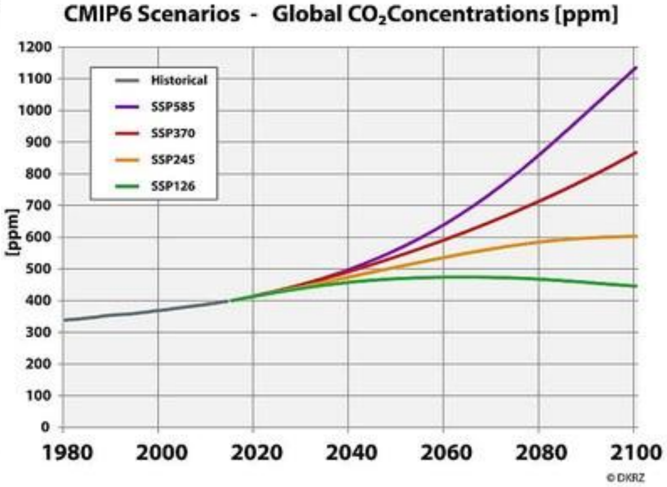
Line: 63:73 Plain Text Tab Size: 4

GCMs - Lab Experiments
Climate sensitivity to future greenhouse gas concentrations

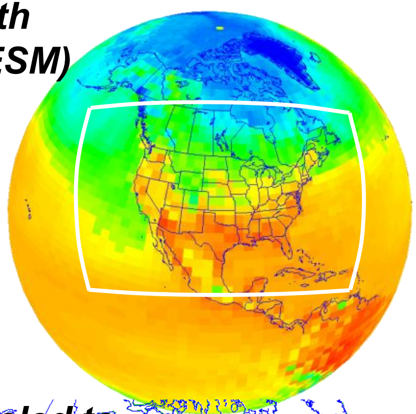
Earth's Energy Imbalance
GHG Emission Scenarios



GCM forcing
increase GHG concentrations



Community Earth System Model (CESM)



Downscaled to higher-resolution

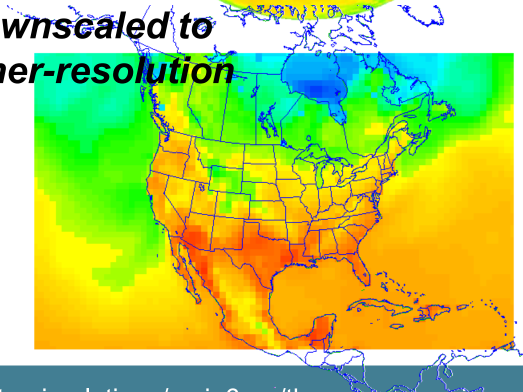
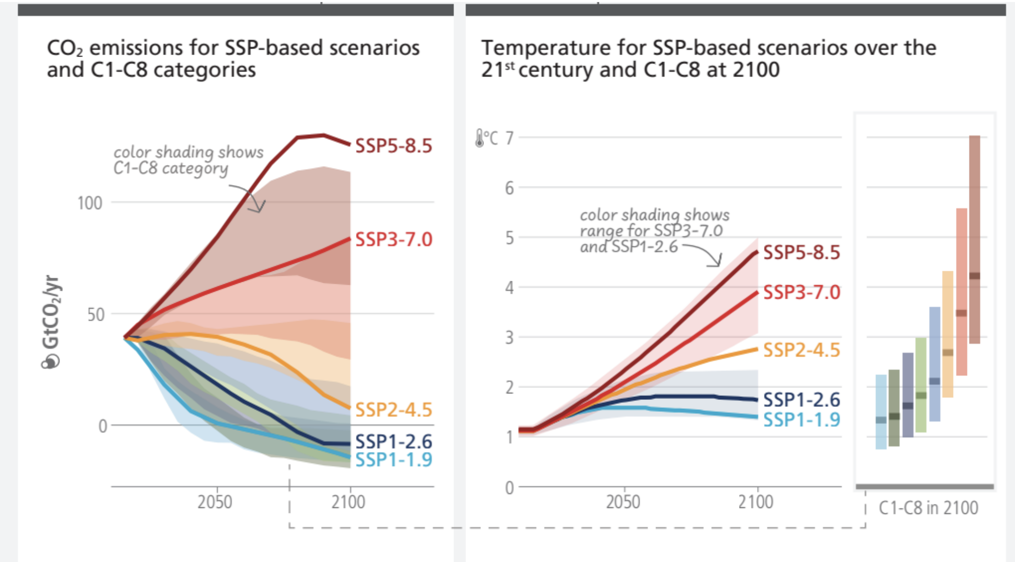


Figure Credits: https://www.dkrz.de/en/communication/climate-simulations/cmip6-en/the-ssp-scenarios

Future Emission Scenarios



<u>RCP4.5 / SSP2-4.5</u> **(intermediate emissions)**

Limit global warming to 3ºC by 2100

<u>SSP3-7.0 (high emissions)</u>

Limit global warming to 4ºC by 2100

<u>RCP8.5/SSP5-8.5</u> **(very higher emissions)**

Exceed warming of 4ºC by 2100

Figure source: IPCC AR6 Synthesis Report

Climate Change Projections @ Mid-Century NC Resilience Exchange Tool

Extreme Heat for Chapel Hill (Orange County)

Days with Heat Index Over 95 F

Historical	Best Case Scenario	Worst Case Scenario
Between 1983 and 2014, on average, Orange County experienced heat indices of 95 F or greater	By the 2060s, on average, Orange County will experience heat indices of 95 F or greater	By the 2060s, on average, Orange County will experience heat indices of 95 F or greater
25 days per year	60 days per year	75 days per year
Source: LOCA v2 Historical (1983-2014)	Source: LOCA v2 SSP 245 (2045-2074)	Source: LOCA v2 SSP 585 (2045-2074)

Days with Max Temps Over 95 F

Historical	Best Case Scenario	Worst Case Scenario
Between 1983 and 2014, on average, Orange County experienced high temperatures of 95 F or greater	By the 2060s, on average, Orange County will experience high temperatures of 95 F or greater	By the 2060s, on average, Orange County will experience high temperatures of 95 F or greater
8 days per year	28 days per year	41 days per year

Nights with Min Temps Over 70 F

Historical	Best Case Scenario	Worst Case Scenario
Between 1983 and 2014, on average, Orange County experienced low temperatures of 70 F or greater	By the 2060s, on average, Orange County will experience low temperatures of 70 F or greater	By the 2060s, on average, Orange County will experience low temperatures of 70 F or greater
17 nights per year	47 nights per year	64 nights per year
Source: LOCA v2 Historical (1983-2014)	Source: LOCA v2 SSP 245 (2045-2074)	Source: LOCA v2 SSP 585 (2045-2074)

Cooling Degree Days (CDD)

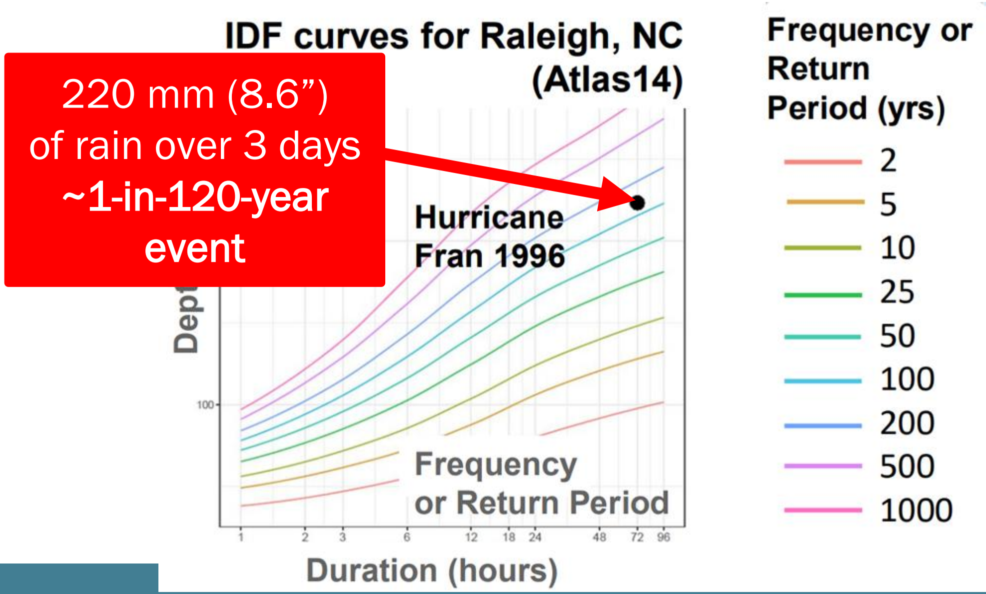
Historical	Best Case Scenario	Worst Case Scenario
Between 1983 and 2014, on average, Orange County experienced	By the 2060s, on average, Orange County will experience	By the 2060s, on average, Orange County will experience
1458 CDD per year	2030 CDD per year	2319 CDD per year
Source: LOCA v2 Historical (1983-2014)	Source: LOCA v2 SSP 245 (2045-2074)	Source: LOCA v2 SSP 585 (2045-2074)

https://www.resilienceexchange.nc.gov

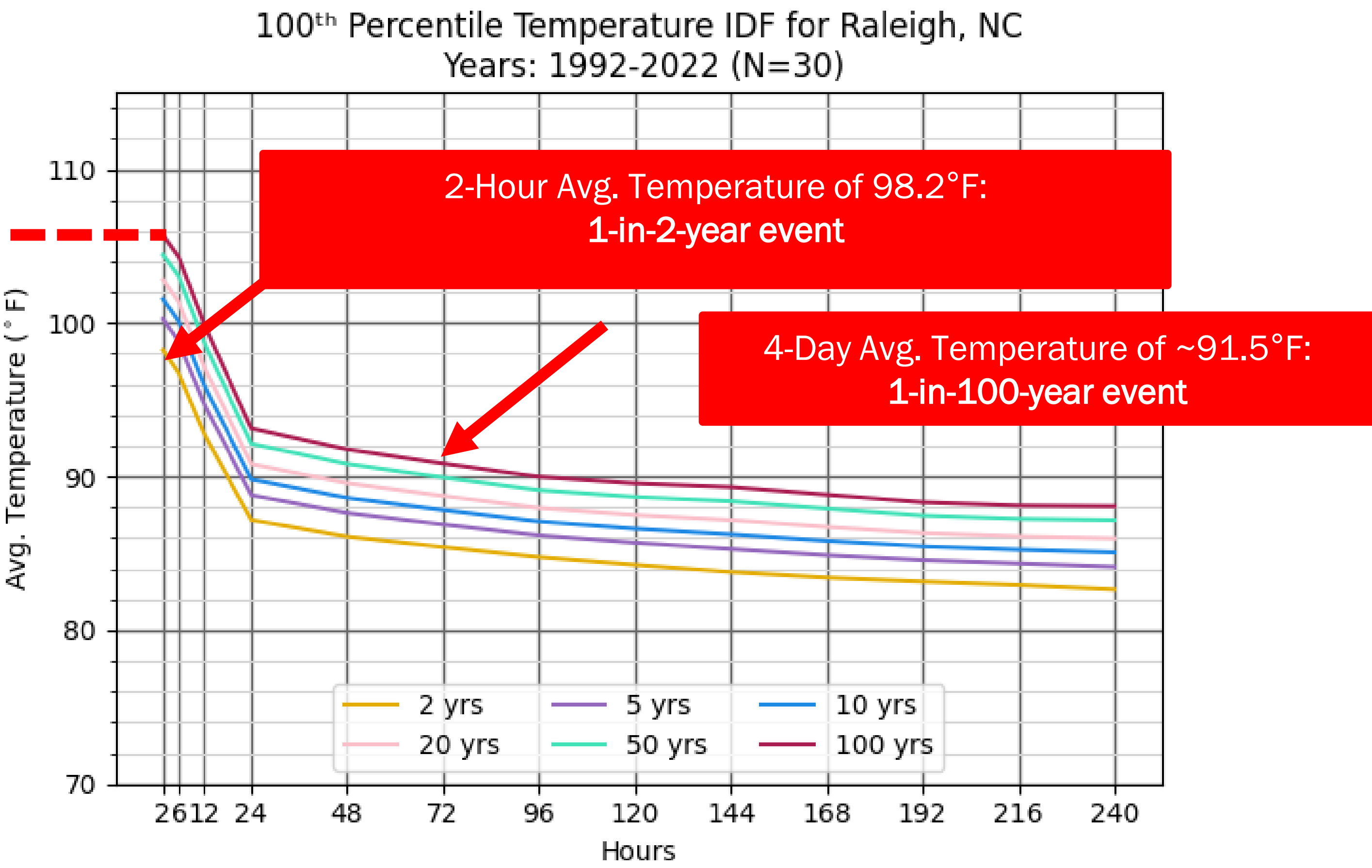
Given the *Intensity* and *Duration* of an event, IDF curves provide an estimate of the return period (or *Frequency*) of such an event (IDF Curves)

- IDF curves were originally developed for precipitation extremes and used for infrastructure design (e.g., stormwater drainage)

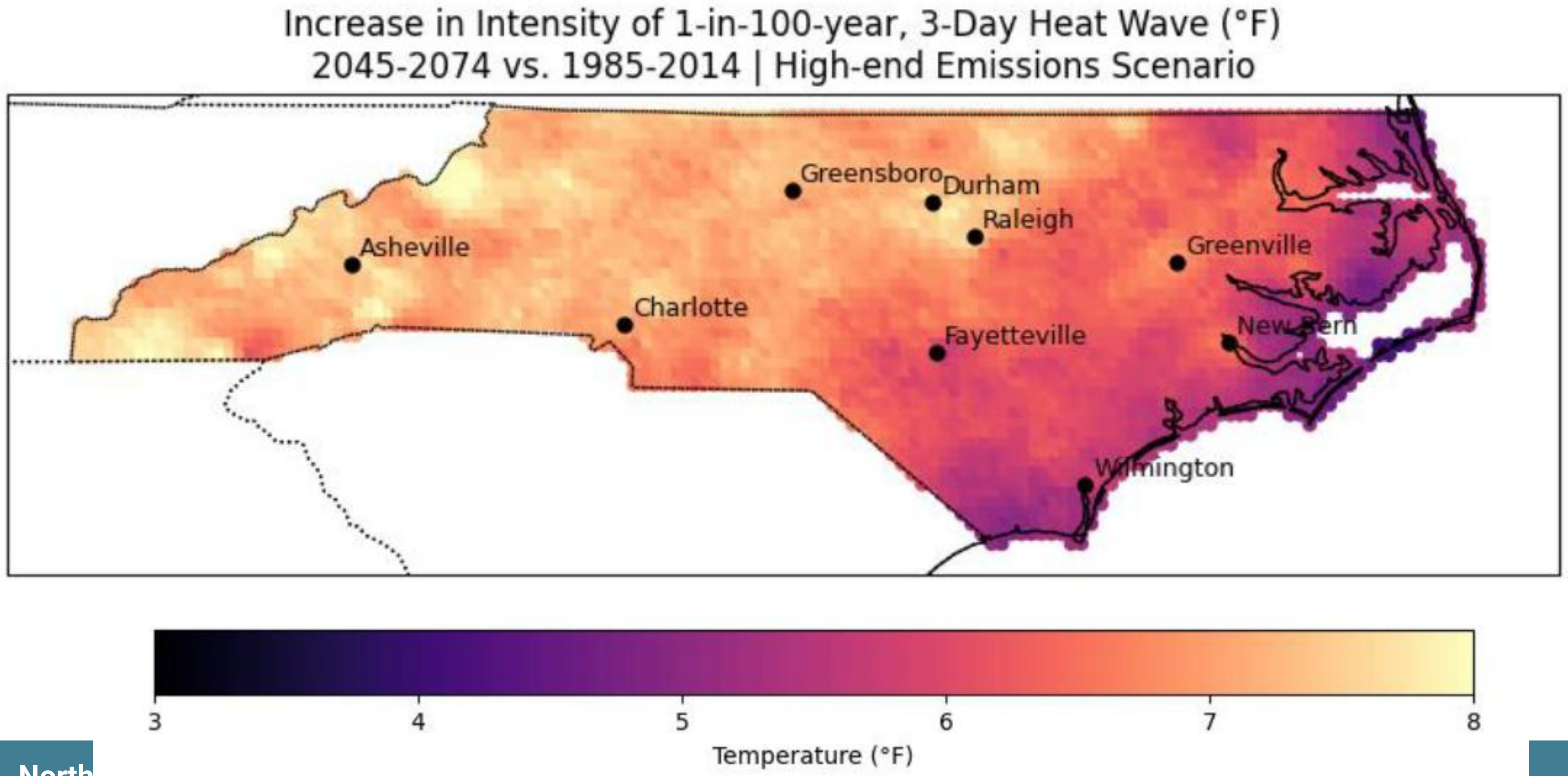
- IDF curves were first used for modeling the return rate of extreme precipitation and flooding events (i.e. 100-year or 500-year floods)



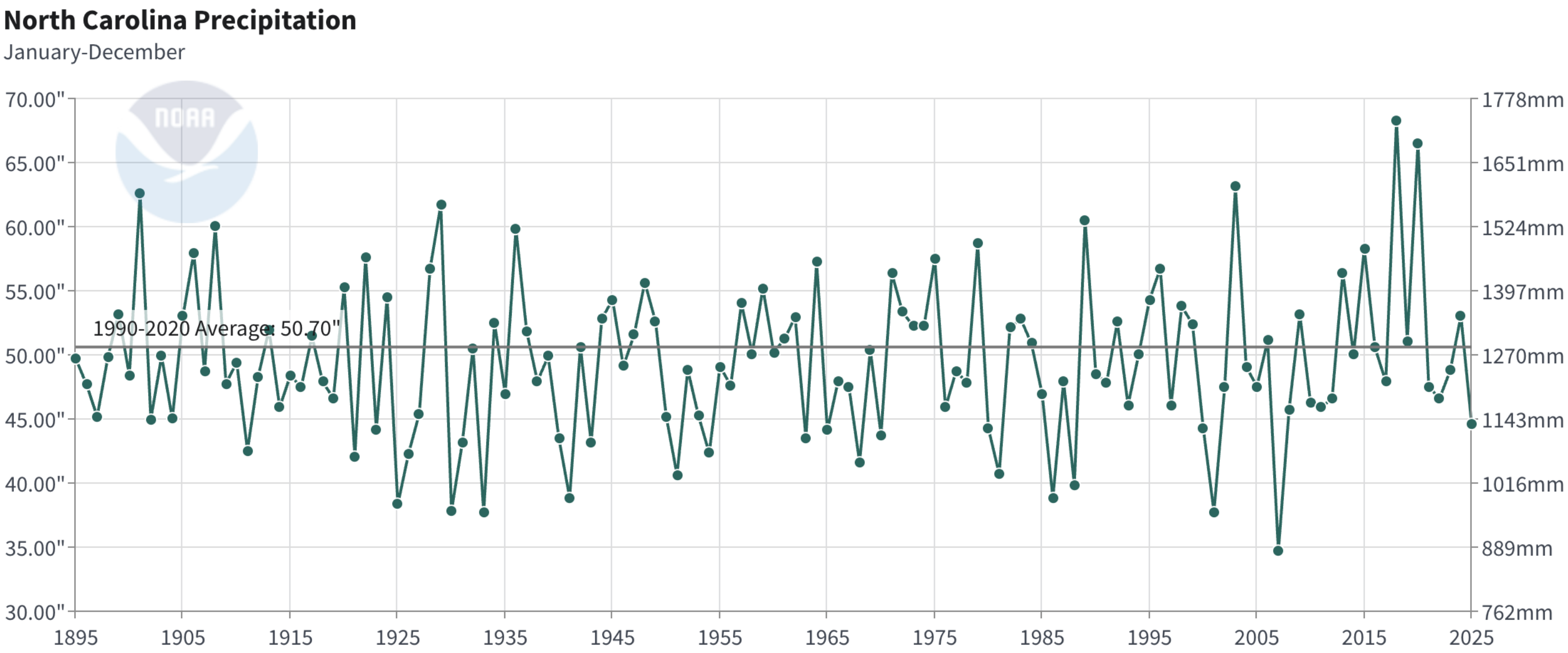
Raleigh, NC
All-time Record High:
106°F

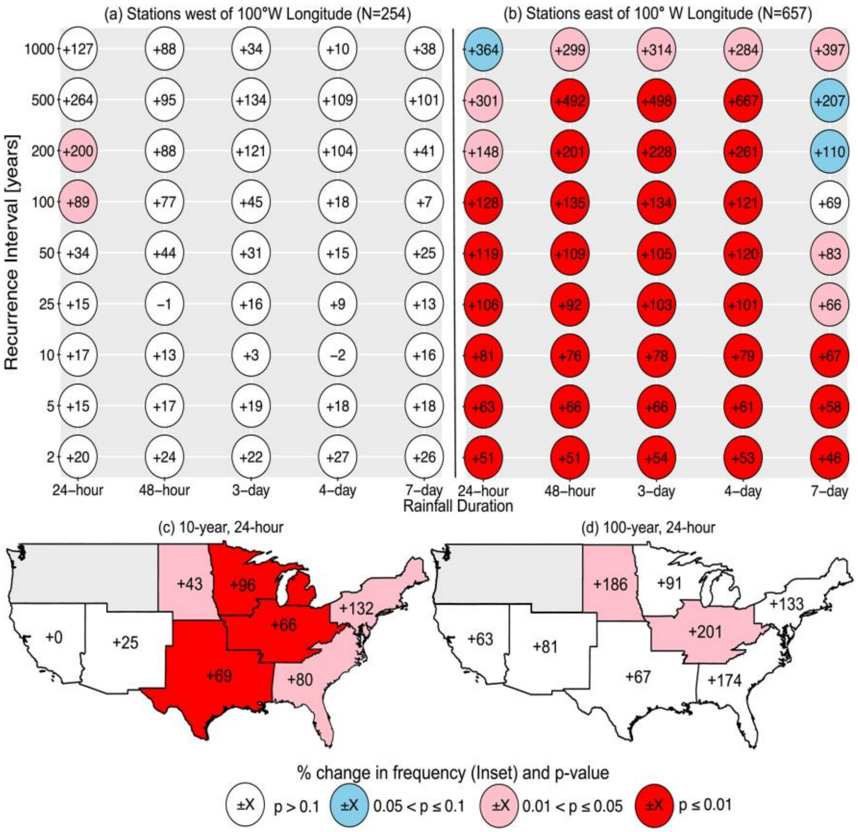


Creating a Future IDF Heat Atlas for NC (HANC)



NC Annual rainfall totals





Large increases in the <u>frequency</u> of extreme rainfall events for the eastern half of the CONUS.

Research Letters

U.S. Hydrologic Design Standards Insufficient Due to Large Increases in Frequency of Rainfall Extremes

Daniel B. Wright[1], Christopher D. Bosma[1], and Tania Lopez-Cantu[2]

Wright et al. (2019); Geophysical Research Letters; https://doi.org/10/1029/2019GL083235

Geophysical Research Letters

RESEARCH LETTER
10.1029/2019GL083235

U.S. Hydrologic Design Standards Insufficient Due to Large Increases in Frequency of Rainfall Extremes

Daniel B. Wright[1], Christopher D. Bosma[1], and Tania Lopez-Cantu[2]

[1]Department of Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, WI, USA,
[2]Department of Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, PA, USA

Key Points:
- Conventional analyses neglect trends in extreme rainfall events such as the 100-year storm, which are critical for engineering design
- A regional aggregation approach reveals significant trends in very extreme rainfall in the United States, mainly due to climate warming
- Existing hydrologic infrastructure and analyses in much of the United States may be underperforming due to increases in storm activity

Supporting Information:
- Supporting Information S1

Correspondence to:
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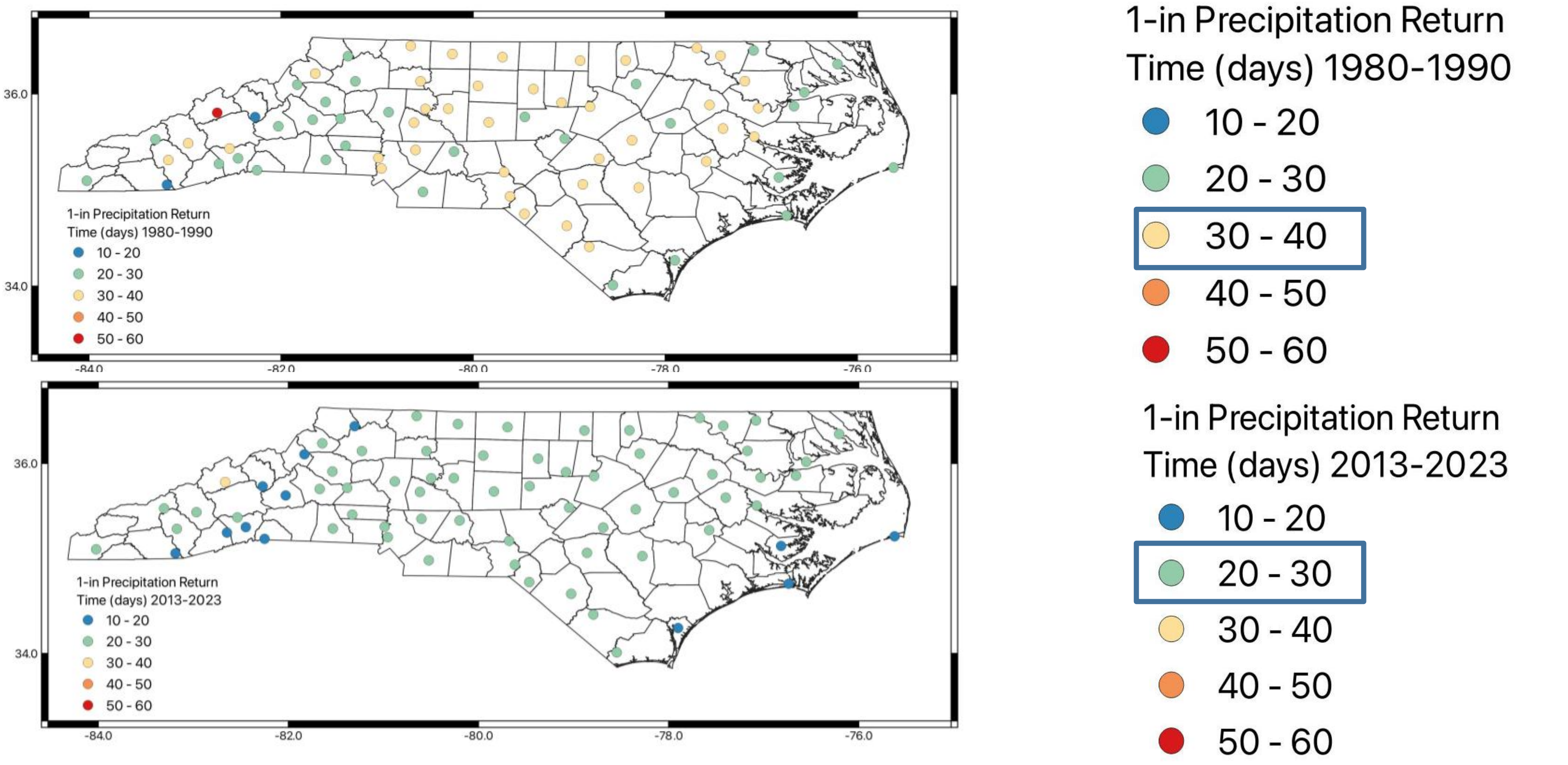
danielb.wright@wisc.edu

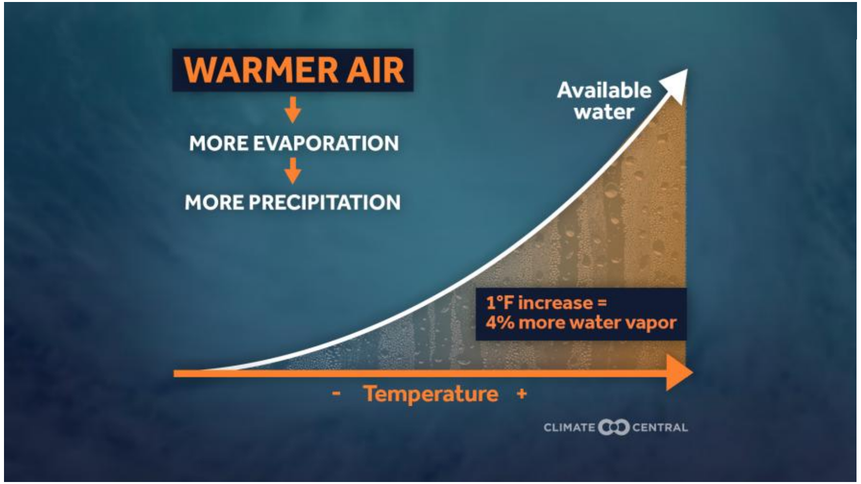
Abstract Evidence for intensifying rainfall extremes has not translated into “actionable” information needed by engineers and risk analysts, who are often concerned with very rare events such as “100-year storms.” Low signal-to-noise associated with such events makes trend detection nearly impossible using conventional methods. We use a regional aggregation approach to boost this signal-to-noise, showing that such storms have increased in frequency over much of the conterminous United States since 1950, a period characterized by widespread hydrologic infrastructure development. Most of these increases can be attributed to secular climate change rather than climate variability, and we demonstrate potentially serious implications for the reliability of existing and planned hydrologic infrastructure and analyses. Though trends in rainfall extremes have not yet translated into observable increases in flood risks, these results nonetheless point to the need for prompt updating of hydrologic design standards, taking into consideration recent changes in extreme rainfall properties.

Smaller storms: Frequency change for 1” storms



The role of warming temperatures
A warmer atmosphere = a thirstier atmosphere

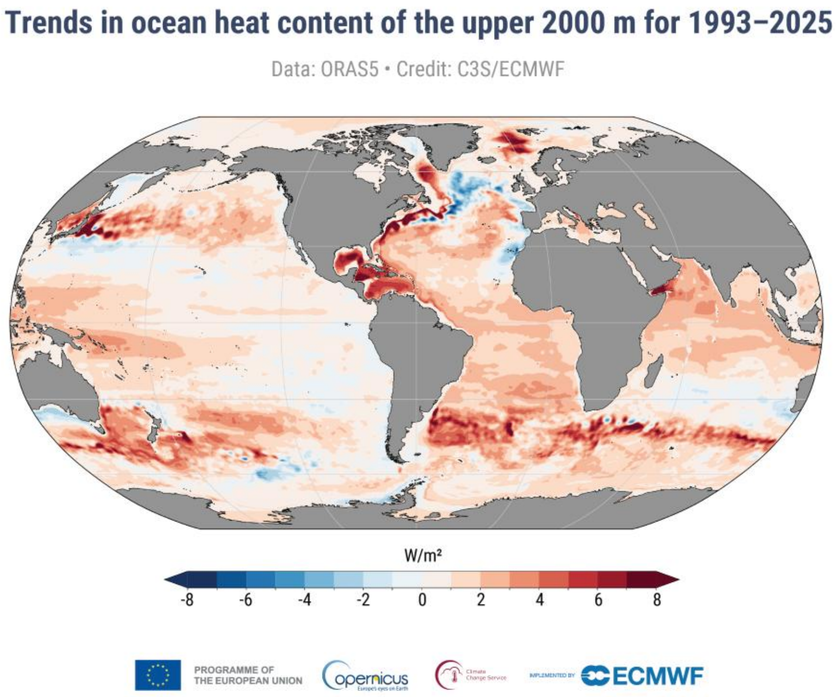
Cooler Atmosphere



Warmer Atmosphere

Clausius-Clapeyron Equation:
~ +4% increase is moisture capacity per ºF

Ocean Heat Content
Warming nearby oceans



Future Precipitation IDF Curves RaInDROP Tool for NC

- A resource to assist with flood resilience
- Allows users to compare two maps or create tables with different precipitation frequency estimates to help plan and design for future environmental uncertainties.

https://products.climate.ncsu.edu/climate/raindrop-tool/

Contact:
Jared Bowden
jhbowden@ncsu.edu

Large frequency changes in the future

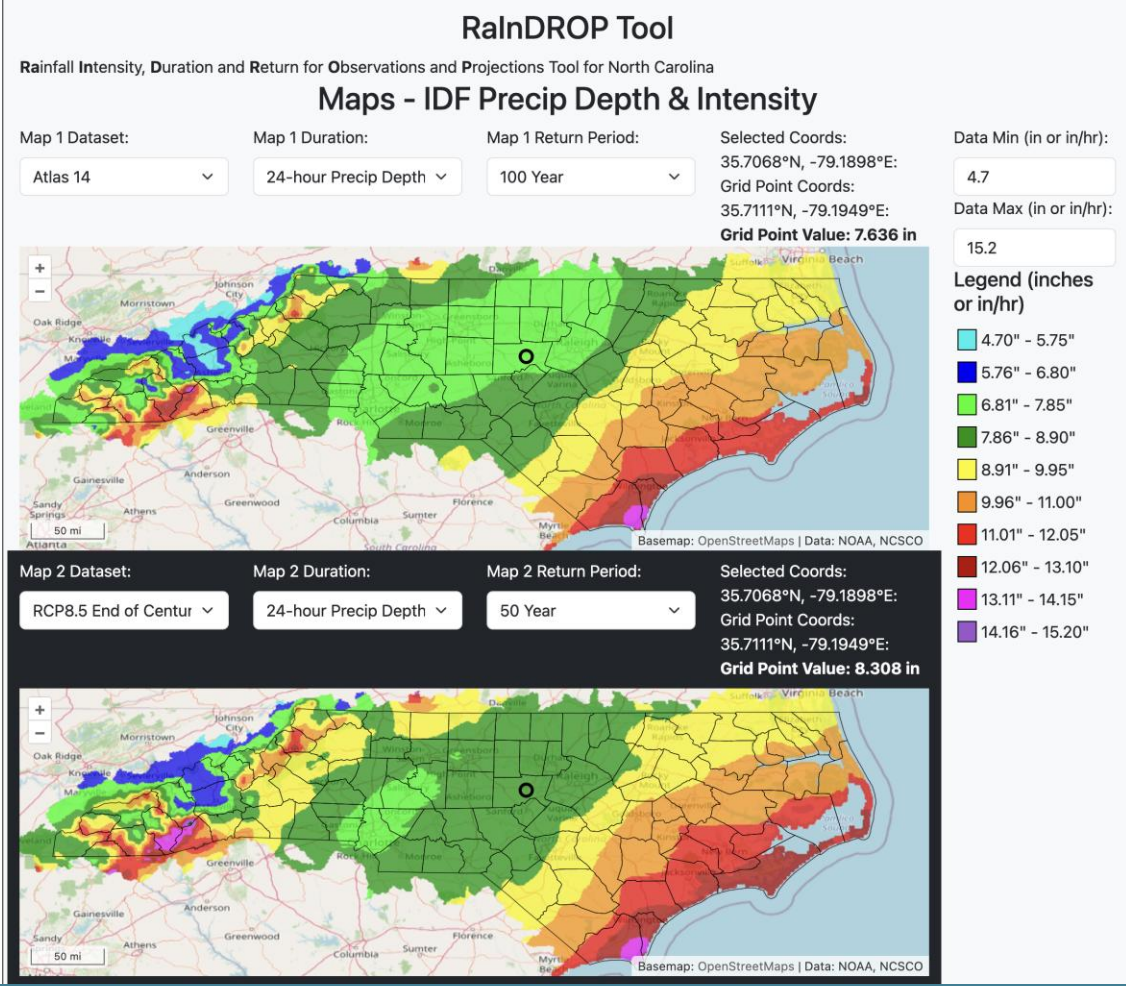
Pick a point and get estimate for high emission scenario at end-century

Example for
24-hour rainfall depth:

Atlas 14 – 100 year (top = 7.64”)

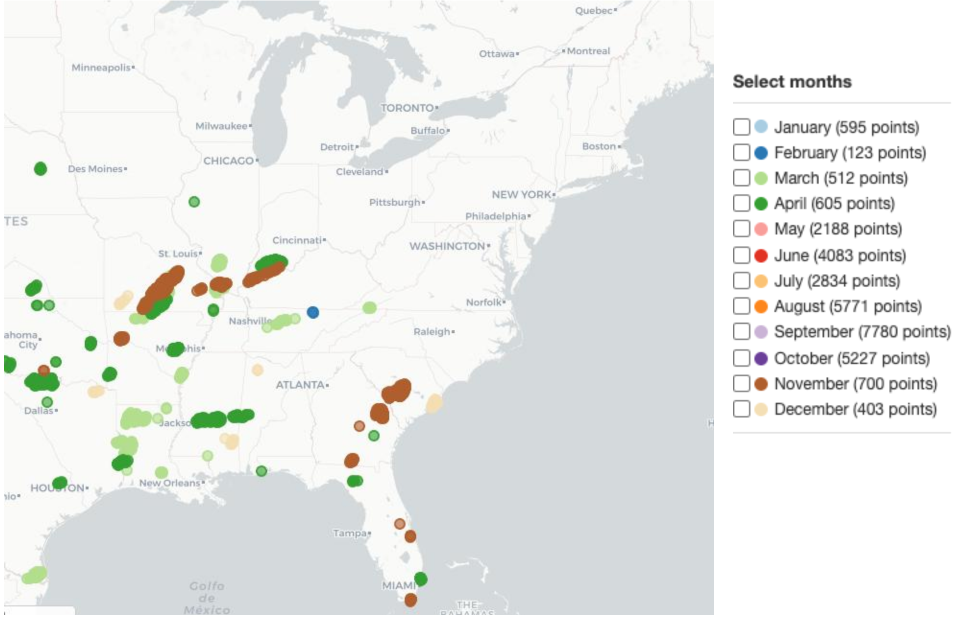
RCP8.5 – 50 year (bottom = 8.31 in)
Ensemble average

<u>Future 50yr exceeds current 100yr</u>

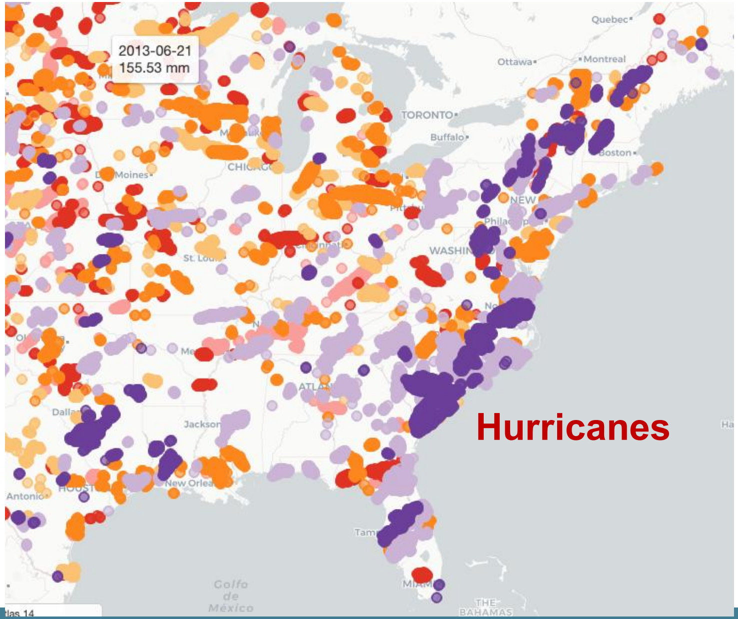


Rainfall extremes during the summer and fall *rainfall from future hurricanes

100-year (24hr) storms; (Nov.-Apr.)
2002-2025

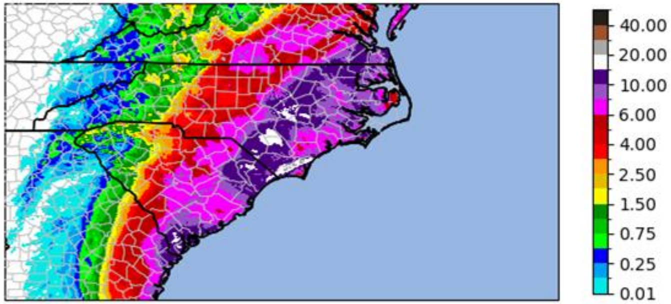


100-year (24hr) storms; (May-Oct.)
2002-2025



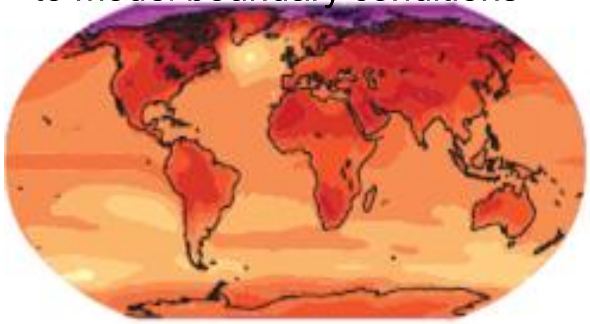
Simulating a historical storm but in a warmer environment Future Hurricane Matthew (2100 high-emission)

Historical High-Resolution Atmospheric Model Storm Simulations



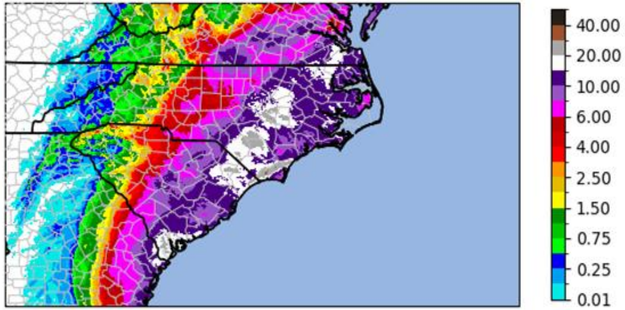
Simulated Matthew (2016)
Total Rainfall
Physics Ensemble

Climate model projection
Δ applied
to model boundary conditions



Δ example high emission scneario:
Warmer
Sea Surface Temps.
and Atmospheric Temps.

Future High-Resolution Atmospheric Model Storm Simulations

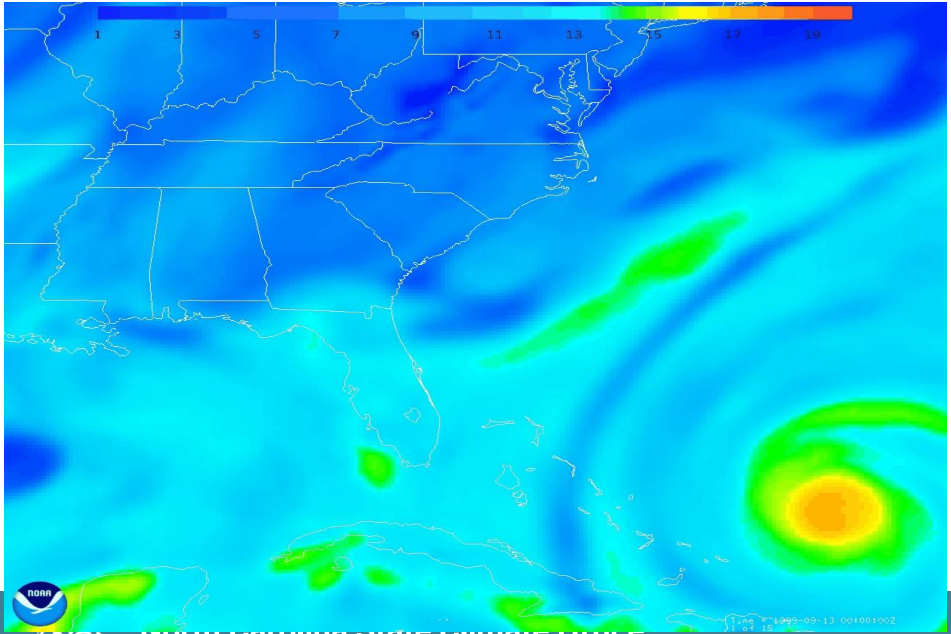


Simulated Matthew (2100)
Total Rainfall
Physics Ensemble

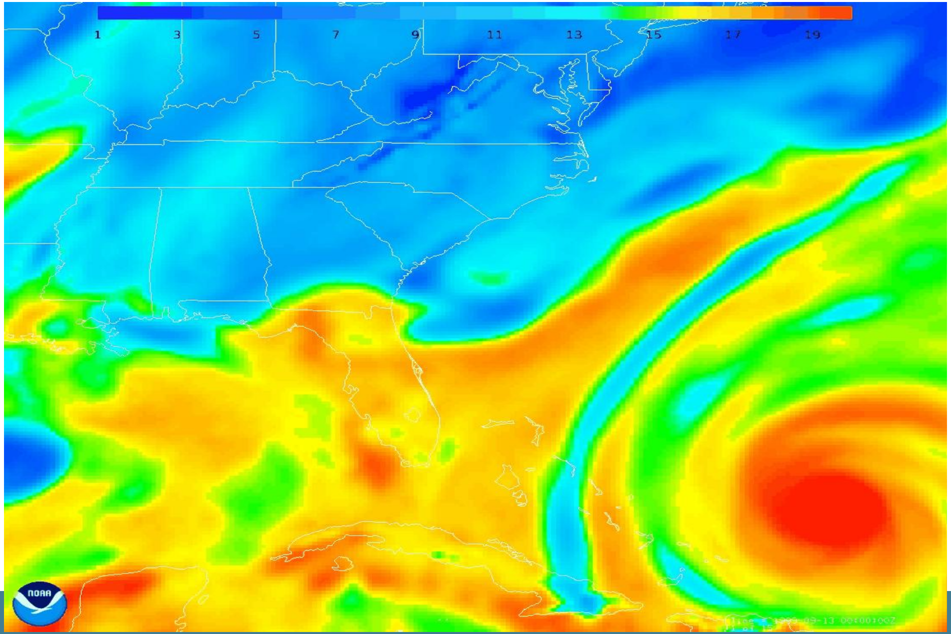
One of my major concerns future flooding and hurricanes

Water Vapor Comparison

Historical Simulation



Future Simulation



Thank you!

Making sense of a rapidly changing NC

North Carolina Climate Blog

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CLIMATE BLOG

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August 27, 2026

Fifteen Years Later, Irene Remains a Bridge to Roadway Resilience

August 17, 2026

For Haywood County, Five Years of Heartache Started With Fred

August 03, 2026

Holiday Heat Gave Way to Wet Weather in July

EXTRA SLIDES

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John McGuire

Applied Meteorologist and Data

Myleigh Neill

Instrumentation Technician

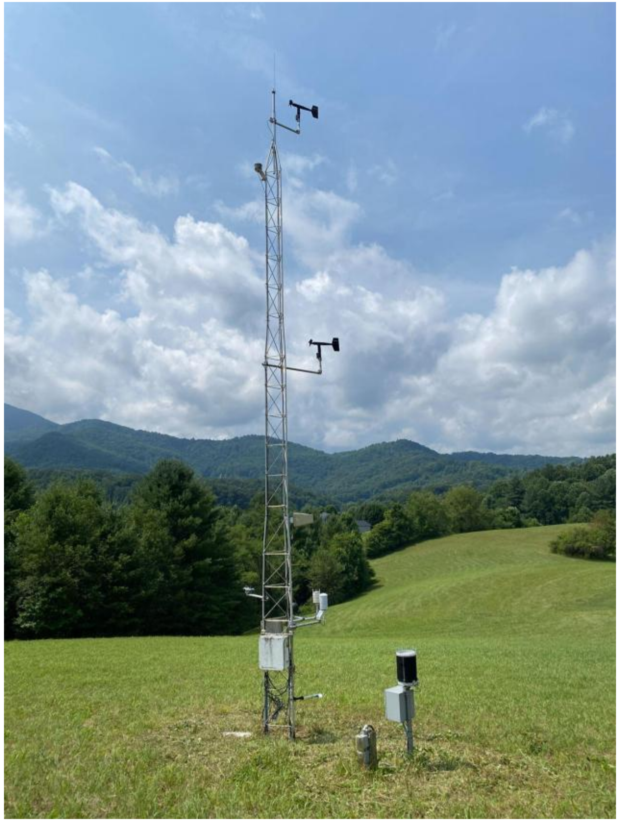
McKenzie Peters

Dr. Greg Tierney

Allison Whitaker

NC ECONet - North Carolina's Mesonet

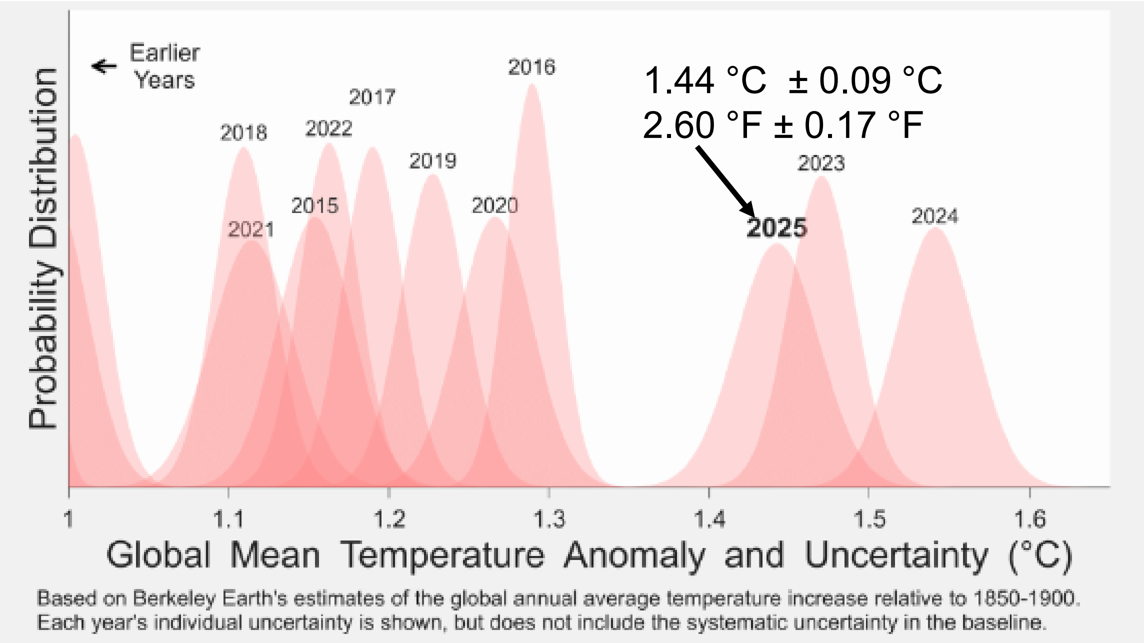
- **Network of research grade weather stations.**
- Measure number of weather variables on 1 minute intervals
- Data retrieval in near real time.
- Data used for a number of applications across different sectors
  - Agriculture
  - Forestry
  - Human Health



Last 3 Years – Warmest on Record

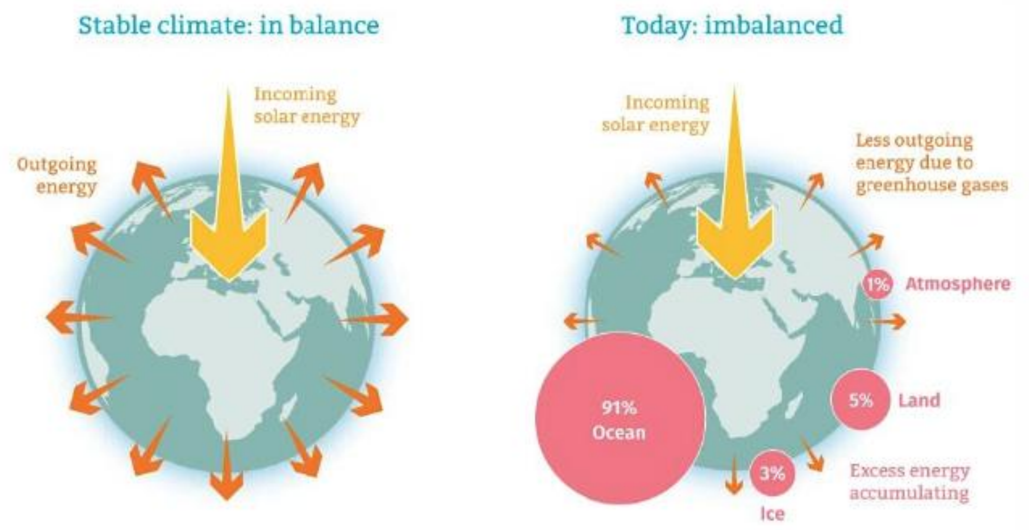
Per NOAA:

- 3rd-warmest year on record globally since 1850 (very close to 2023)
- Record warmth past 11 years

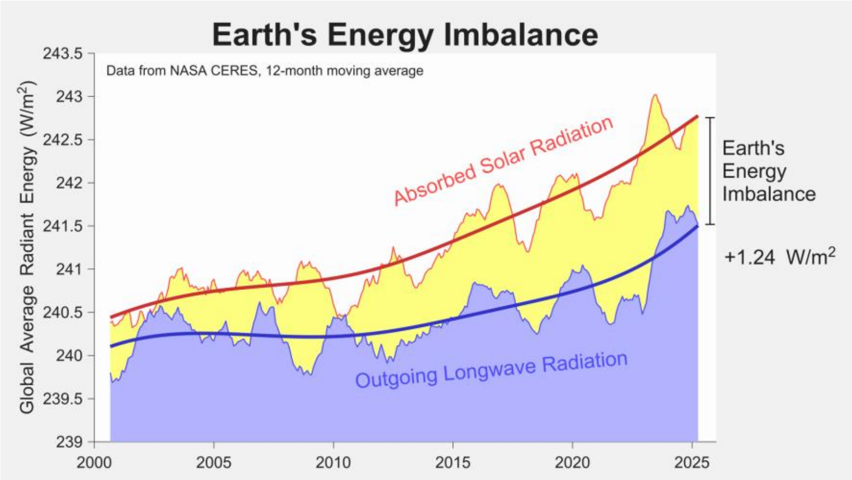


Source: Berkeley Earth's Analysis

Earth's Energy Imbalance
Greenhouse Gases



https://wmo.int/publication-series/state-of-global-climate/state-of-global-climate-2025



https://berkeleyearth.org/global-temperature-report-for-2025/

Greenhouse Gases

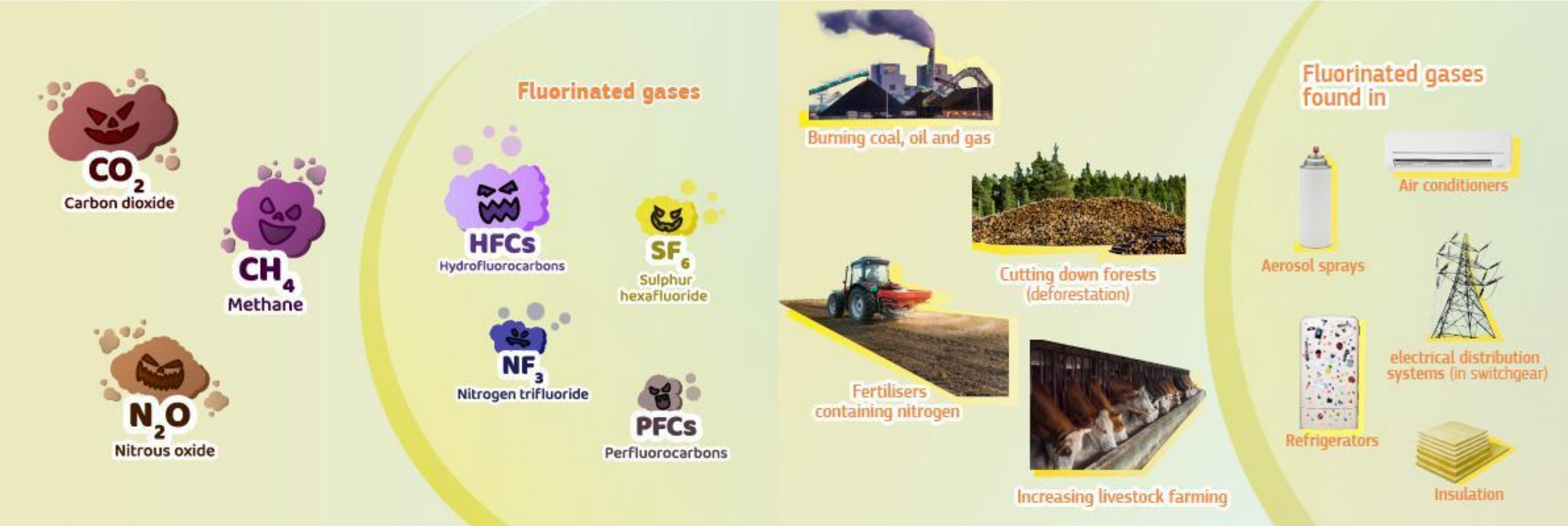
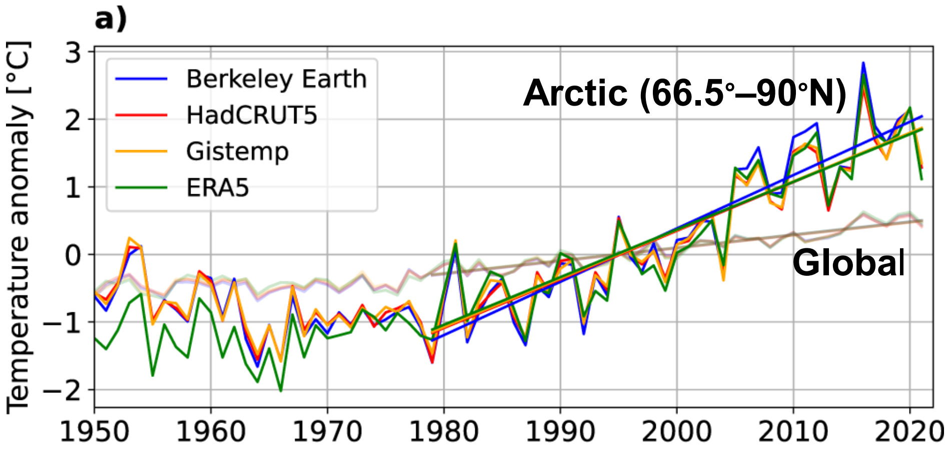
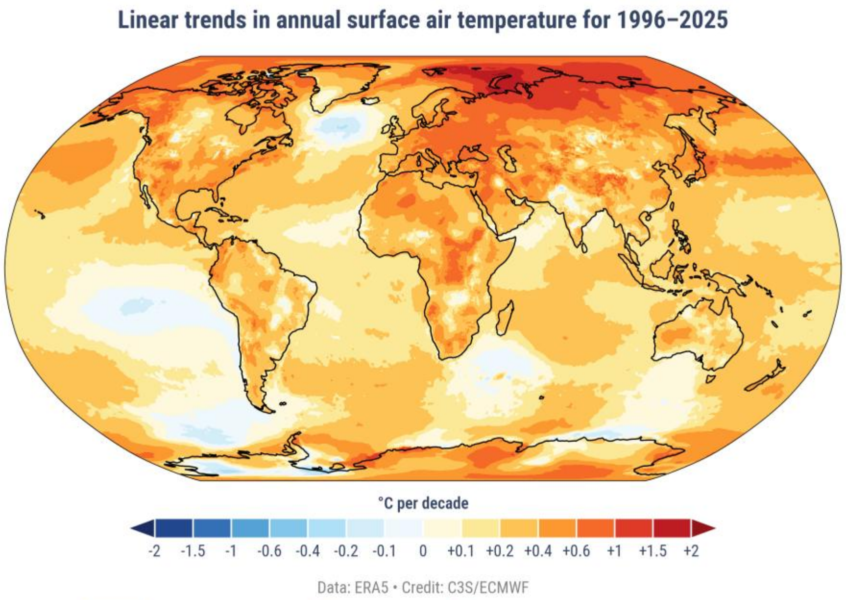


Figure credit: https://climate.ec.europa.eu/climate-change-explained/causes-climate-change_en#greenhouse-gases

Notable Feature - Arctic Amplification up to 4 times faster warming in the Arctic compared to the global average



From Rantanen et al. 2022
https://doi.org/10.1038/s43247-022-00498-3

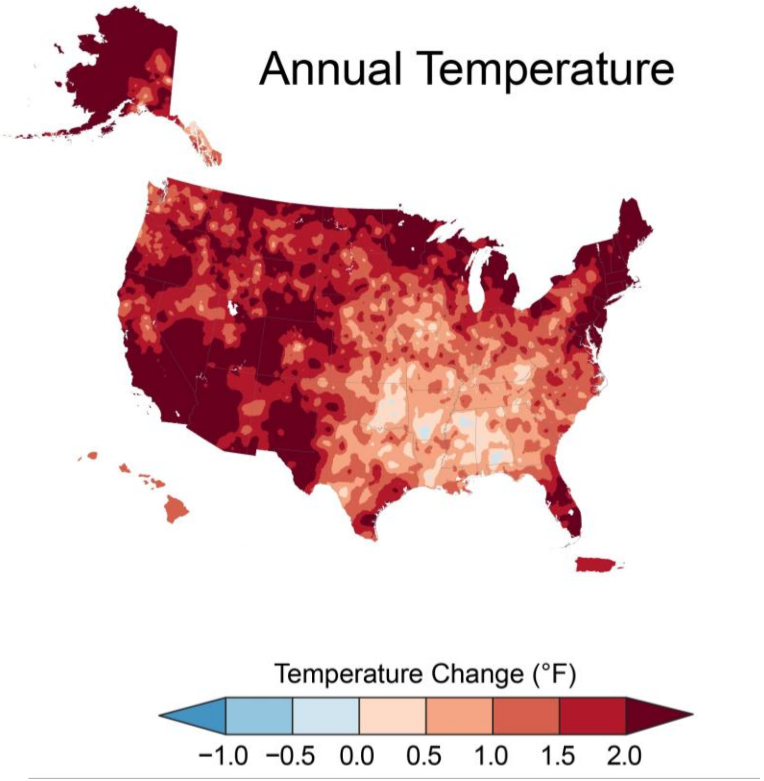


PROGRAMME OF THE EUROPEAN UNION
Copernicus
ECMWF

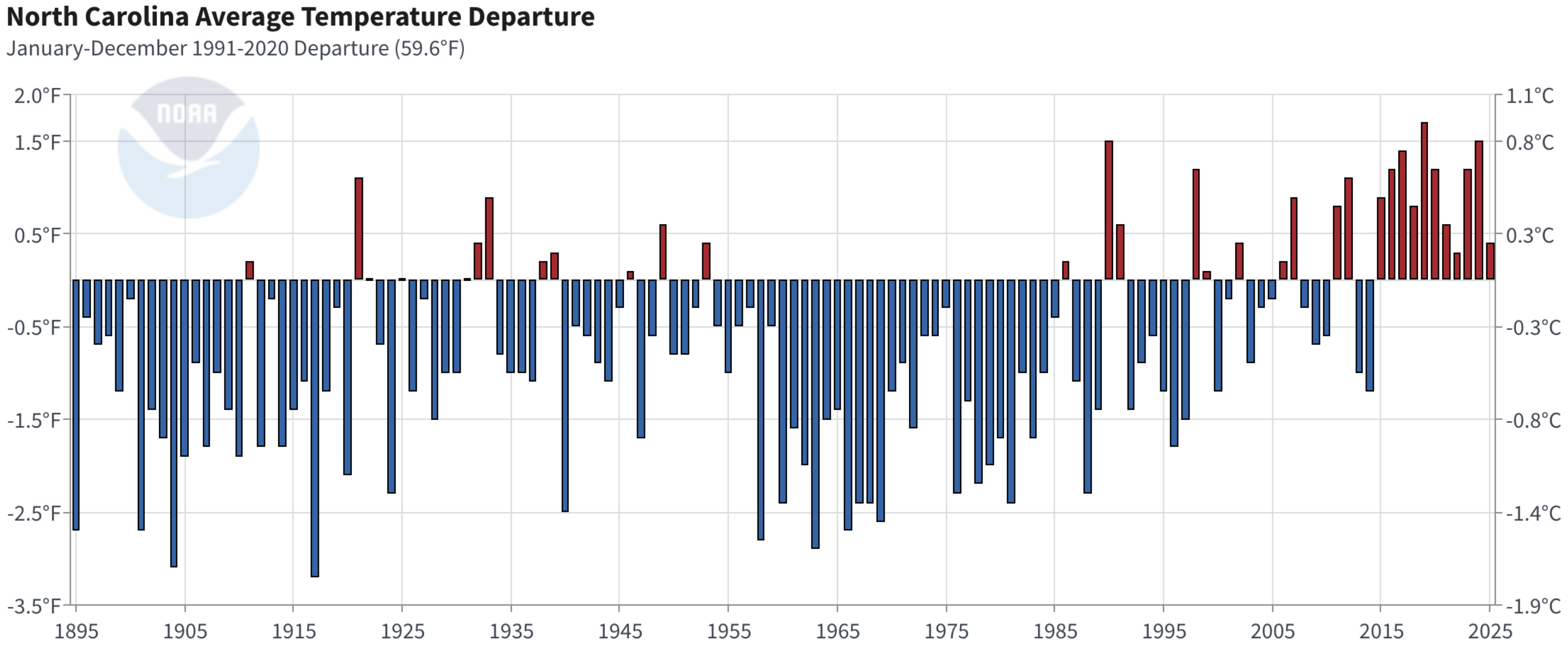
Annual Temperature Change

Contiguous US = + 2.5°F

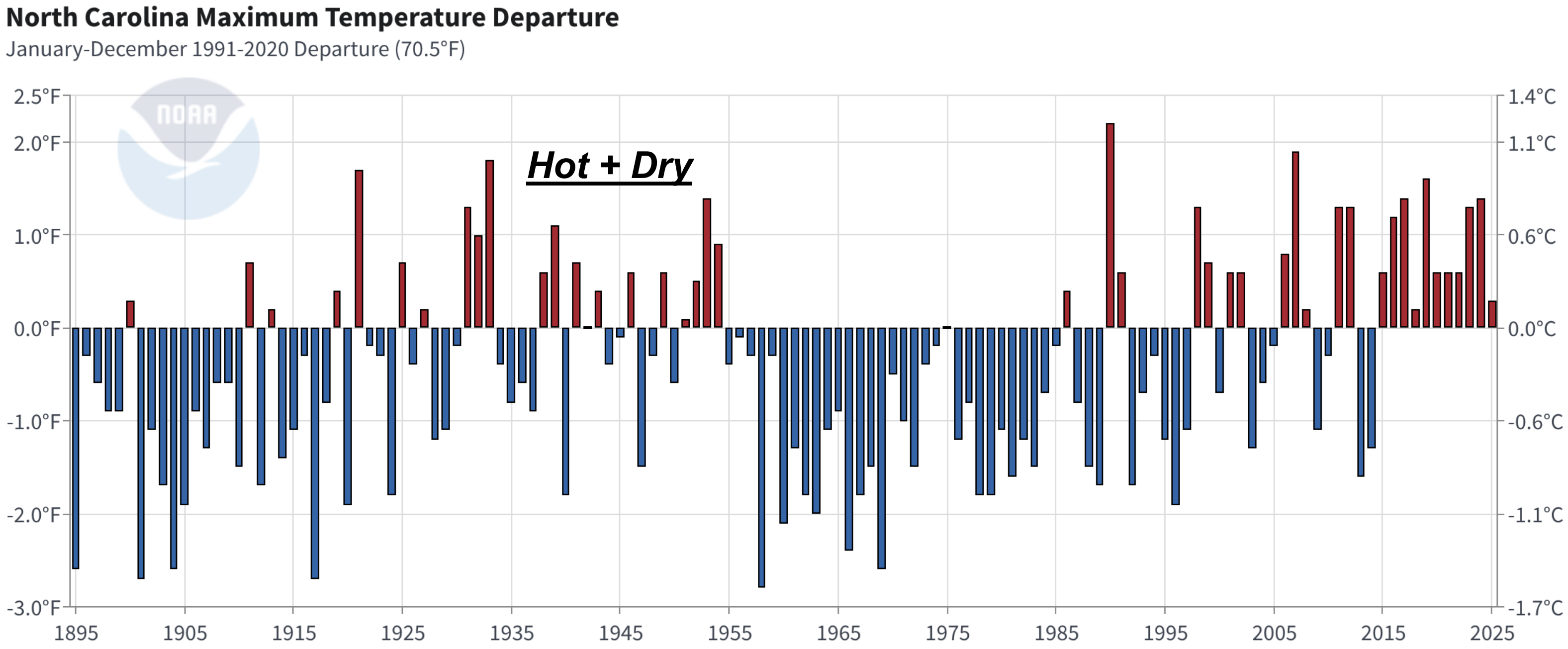
Alaska = + 4.2°F



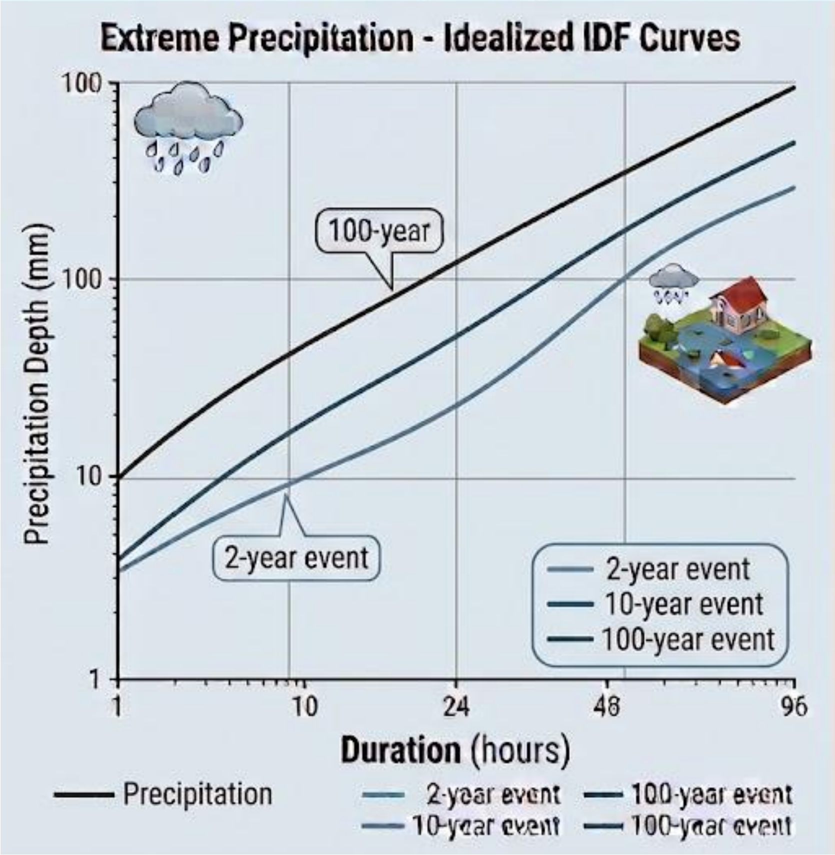
NC Annual Average Temperature
Last 11 years warmer than 1991-2020 average

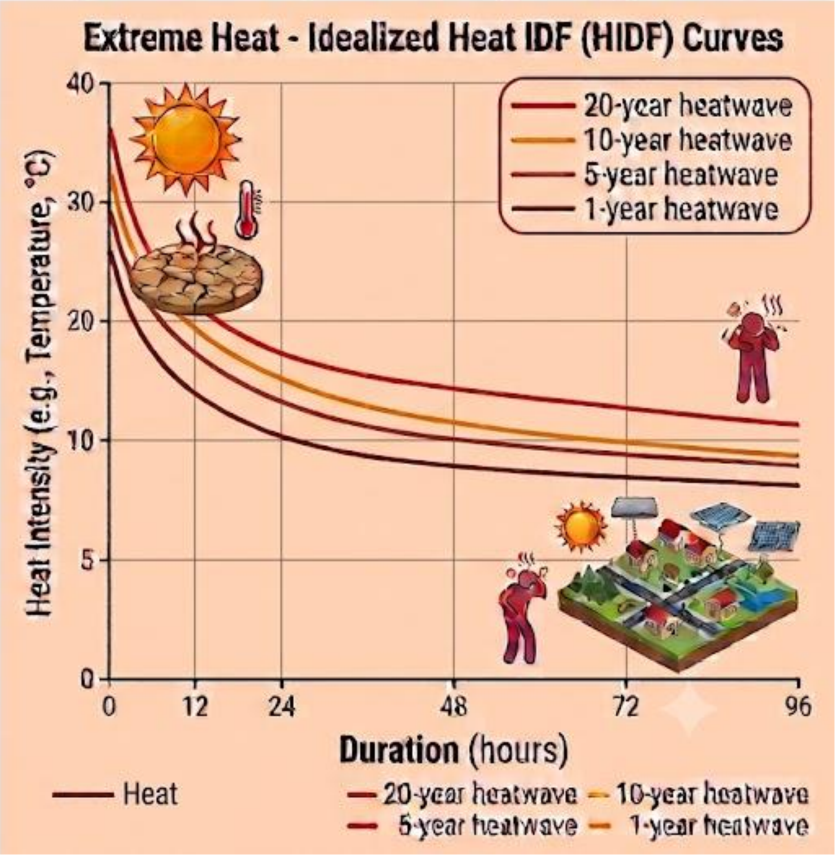


NC Maximum Temperature
Not as strong of a signal (warm period 1930s to 1950s)



Extreme heat and precipitation - Intensity, Duration, and Frequency Curves





Many Definitions for Extreme Heat - Heat Waves

Xu et al (2016)

- Examined how different heatwave definitions affect the calculation of relative risk and mortality.

- 39 different definitions of a heat wave (event-specific omitted):
- 15 using maximum temperature
- 13 using mean temperature
- 11 using other/combined metrics

Table 1
Heatwave definitions used in the existing literature (maximum temperature, mean temperature and specific heatwave events).

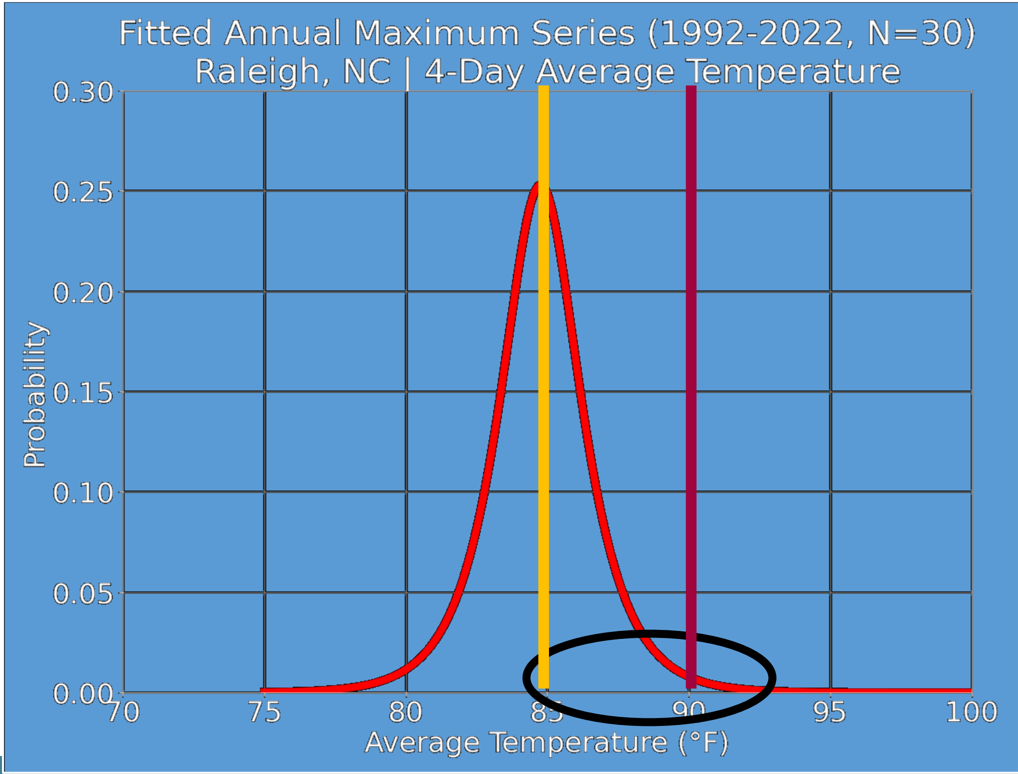
Heatwave definitions used in the existing literature (maximum temperature)

Duration	Intensity	Heatwave criteria	Studies
2	35 °C	Maximum temperatures ≥35 °C for ≥2 days	Tong et al. (2010b) Wang et al. (2012)
2	37 °C	Maximum temperatures ≥37 °C for ≥2 days	Tong et al. (2010b)
2	97.5th	Maximum temperatures ≥97.5th percentile of the warm season for ≥2 days	Tong et al. (2010b)
3	95th	Maximum temperatures ≥95th percentile for ≥3 days	Xu et al. (2013) Tong et al. (2010b)
3	95th (warm season)	Maximum temperatures ≥95th percentile of the warm season for ≥3 days	Basagaña et al. (2011)
3	97.5th	Maximum temperatures ≥97.5th percentile for ≥3 days	Tong et al. (2010b)
3	98th	Maximum temperatures ≥98th percentile for ≥3 days	Lan et al. (2012)
3	30 °C	Maximum temperatures ≥30 °C for ≥3 days	Hutter et al. (2007)
3	32 °C	Maximum temperatures ≥32 °C for ≥3 days	Hertel et al. (2009)
3	35 °C	Maximum temperatures ≥35 °C for ≥3 days	Huang et al. (2010), Nitschke et al. (2011), Sun et al. (2014), Tong et al. (2010b), Williams et al. (2012)[a]
4	95th	Maximum temperatures ≥95th percentile for ≥4 days	Tong et al. (2010b)
5	95th	Maximum temperatures ≥95th percentile for ≥5 days	Tong et al. (2010b)
5	25 °C	Maximum temperatures ≥25 °C for ≥5 days, or maximum temperature ≥ 30 °C for ≥3 days	Huynen et al. (2001)
5	Exceeding the average maximum temperature by 5 °C	Maximum temperature exceeds the average maximum temperature by 5 °C for 5 consecutive days	Tong et al. (2010b)
6	30 °C	Maximum temperature > 30 °C for 6 days	Kovats et al. (2004)

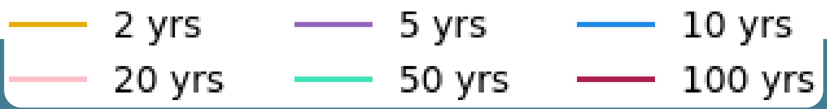
Xu, Z., FitzGerald, G., Guo, Y., Jalaludin, B., & Tong, S. (2016). Impact of heatwave on mortality under different heatwave definitions: a systematic review and meta-analysis. *Environment international*, *89*, 193-203.

Creating IDF Curves, Briefly

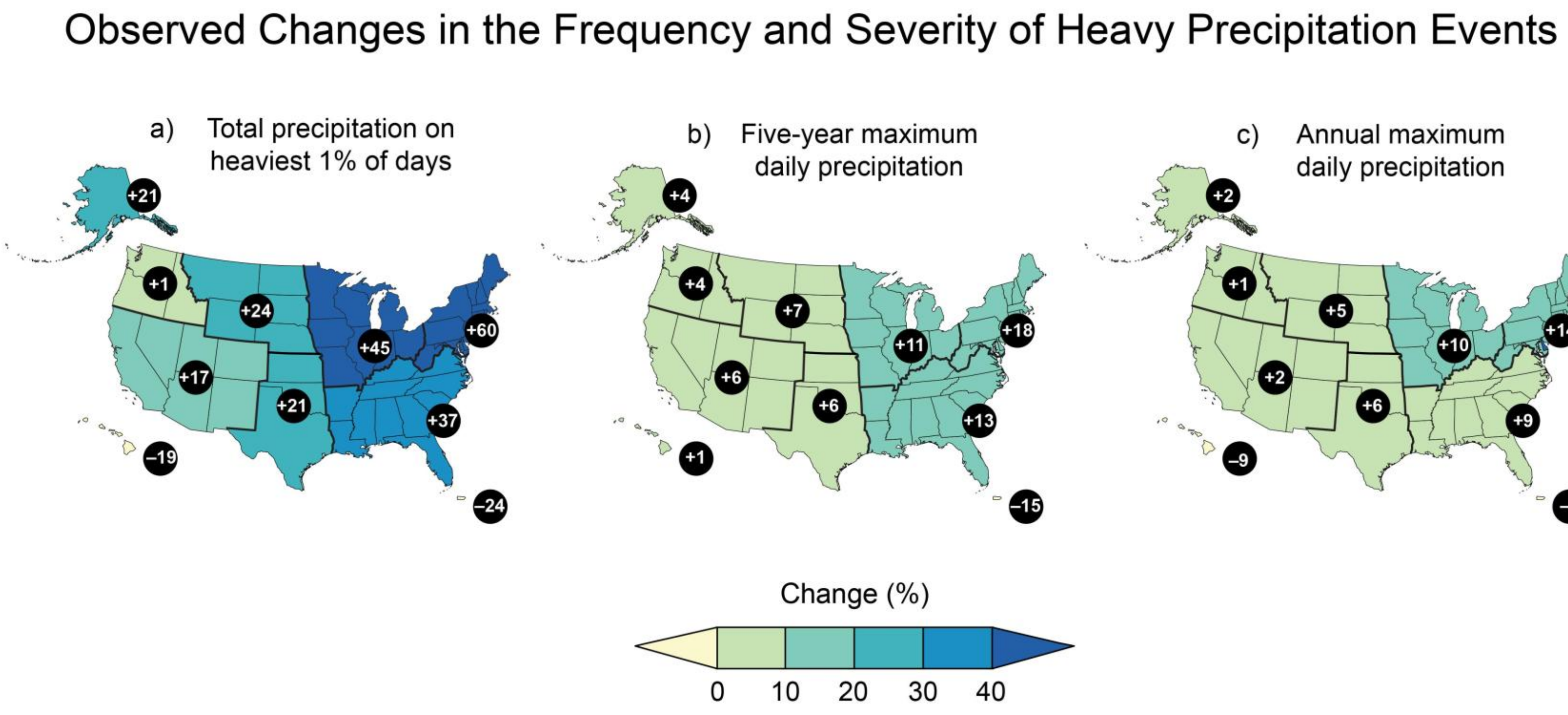
- Data: Hourly observations from NCEI
- Create <u>annual maximum series (AMS):</u> *the hottest (x) duration of each year.*
  - 13 durations: 2, 6, & 12 hours; 1 to 10 days
- Fit AMS with a distribution.
- Calculate temperatures at cumulative probabilities/return periods of interest



Return Periods:



Rainfall Extremes are becoming more frequent and severe

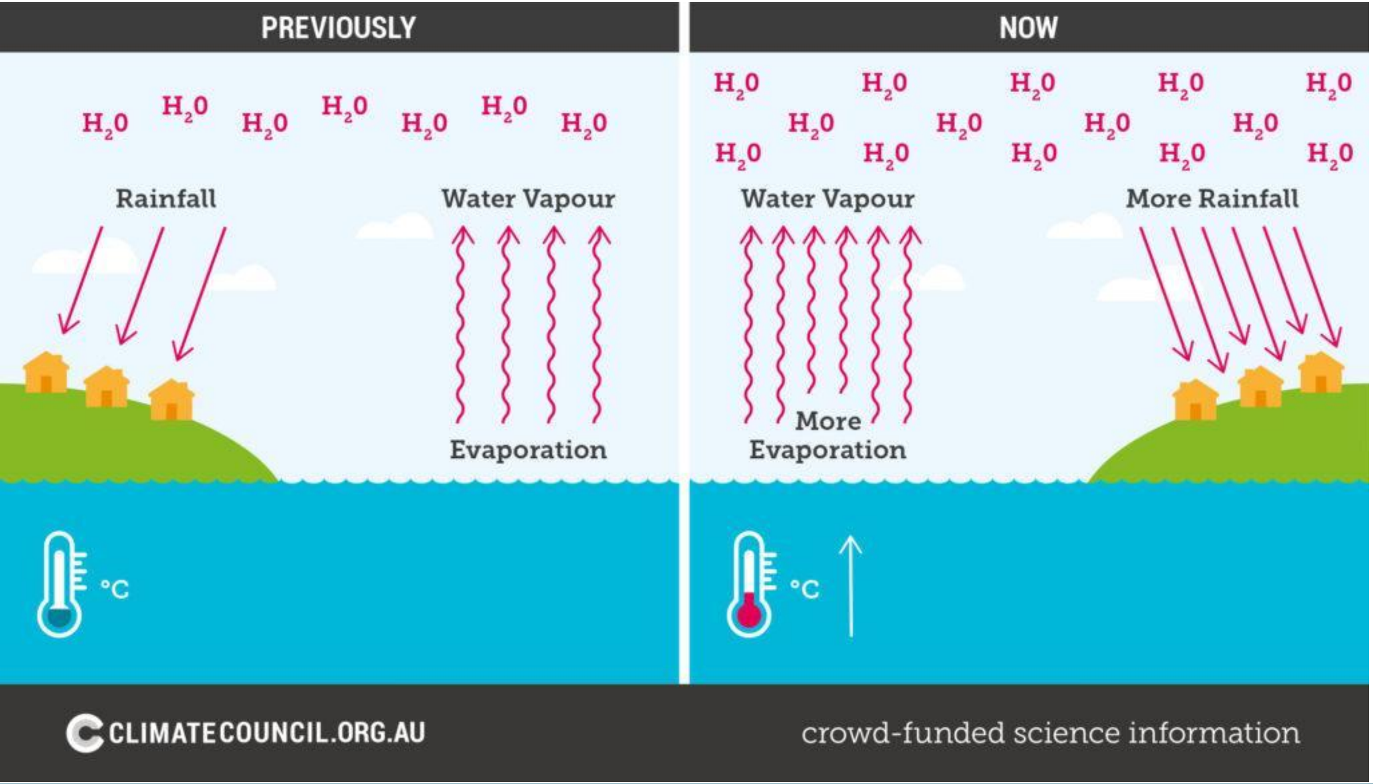


Get a point estimate of historical and future IDF values for different return periods

Precip Depth (in) and Intensity (in/hr) estimates for 35.739246°N, -79.20659°E:
(This is the nearest grid point to your selected location of 35.7424°N, -79.2044°E)
Note: Intensity is calculated by precip depth (inches) divided by duration (hours)

Dataset	Duration	ARI 2 yr	ARI 5 yr	ARI 10 yr	ARI 25 yr	ARI 50 yr	ARI 100 yr	ARI 500 yr	ARI 1000 yr
Atlas 14	**1hr Depth (in)**	1.59	2.07	2.38	2.74	3	3.24	3.77	3.99
Atlas 14	**6hr Depth (in)**	2.4	3.17	3.71	4.39	4.92	5.45	6.73	7.32
Atlas 14	**12hr Depth (in)**	2.84	3.77	4.44	5.3	5.98	6.68	8.43	9.26
Atlas 14	**24hr Depth (in)**	3.29	4.37	5.13	6.11	6.86	7.63	9.51	10.37
RCP4.5 Mid Century (Mean)	**1hr Depth (in)**	1.67	2.19	2.54	2.93	3.23	3.53	4.26	4.59
RCP4.5 Mid Century (Mean)	**6hr Depth (in)**	2.52	3.36	3.97	4.7	5.31	5.94	7.6	8.41
RCP4.5 Mid Century (Mean)	**12hr Depth (in)**	2.98	4	4.75	5.67	6.46	7.28	9.53	10.65
RCP4.5 Mid Century (Mean)	**24hr Depth (in)**	3.46	4.64	5.48	6.53	7.41	8.31	10.75	11.92
RCP4.5 End of Century (Mean)	**1hr Depth (in)**	1.72	2.26	2.59	3.01	3.29	3.6	4.26	4.55
RCP4.5 End of Century (Mean)	**6hr Depth (in)**	2.6	3.46	4.04	4.83	5.41	6.05	7.6	8.34

Future Intensification of the Water Cycle



Warmer air temps → increased water vapor capacity

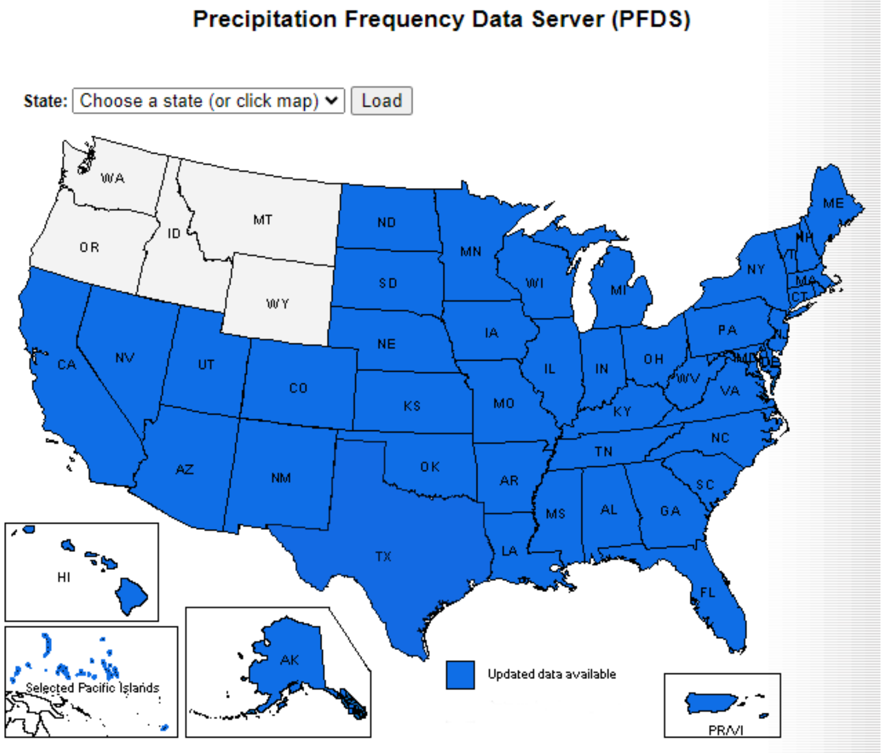
Warmer sea surface temperatures → more evaporation

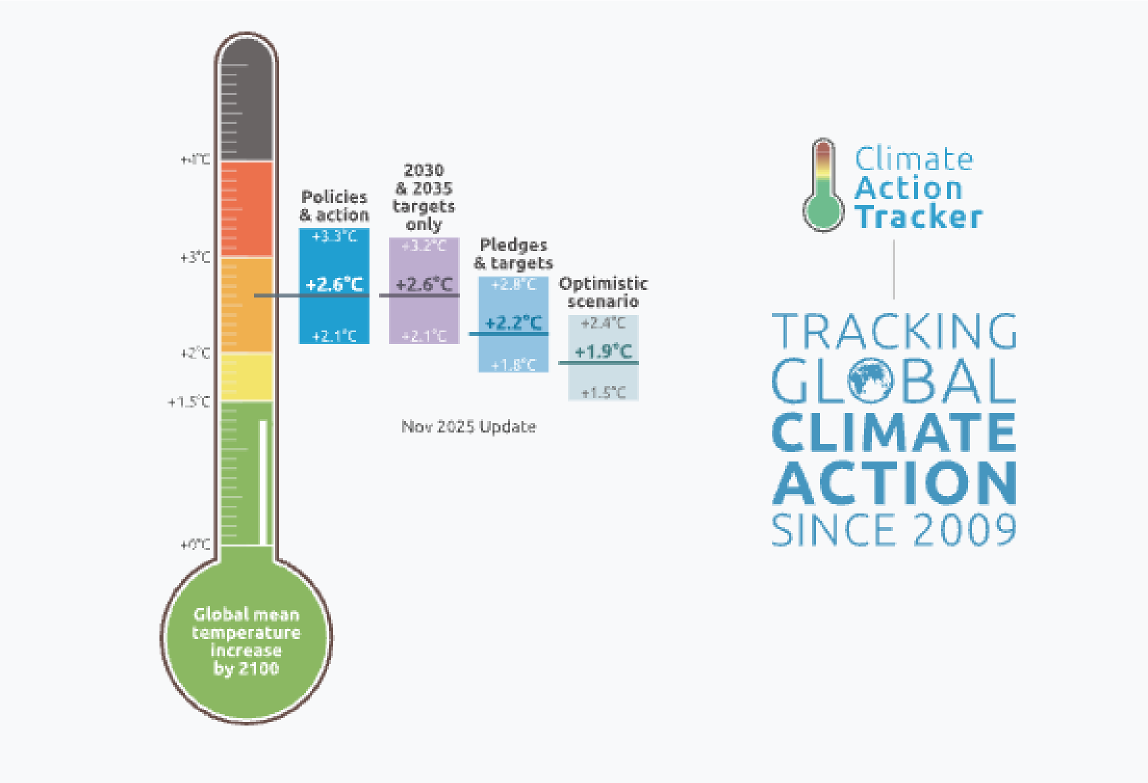
More evaporation → more water vapor

More water vapor → potential for more rain

NOAA Atlas 14 U.S. Standard Reference Precipitation IDF Curves

Static: doesn't consider changes in rainfall (historical trends / plausible future changes)





+4°C
+3°C
+2°C
+1.5°C
+0°C
Global mean temperature increase by 2100
Policies & action
+3.3°C
+2.6°C
+2.1°C
2030 & 2035 targets only
+3.2°C
+2.6°C
+2.1°C
Pledges & targets
+2.8°C
+2.2°C
+1.8°C
Optimistic scenario
+2.4°C
+1.9°C
+1.5°C
Nov 2025 Update
Climate Action Tracker
TRACKING GLOBAL CLIMATE ACTION SINCE 2009

Thank you
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