Heat Waves

Global Warming Science EPS101

Eli Tziperman

https://courses.seas.harvard.edu/climate/eli/Courses/EPS101/

What are Heat Waves?

- Heat wave: unusually hot weather lasting at least a few days. Definition is relative to normal conditions; thresholds of temperature & duration vary from region to region.

Two-year-old Kaori Renè cooled off in the water sprinklers at Herbert Von King Park in Brooklyn on Sunday. Yana Paskova for NYTimes

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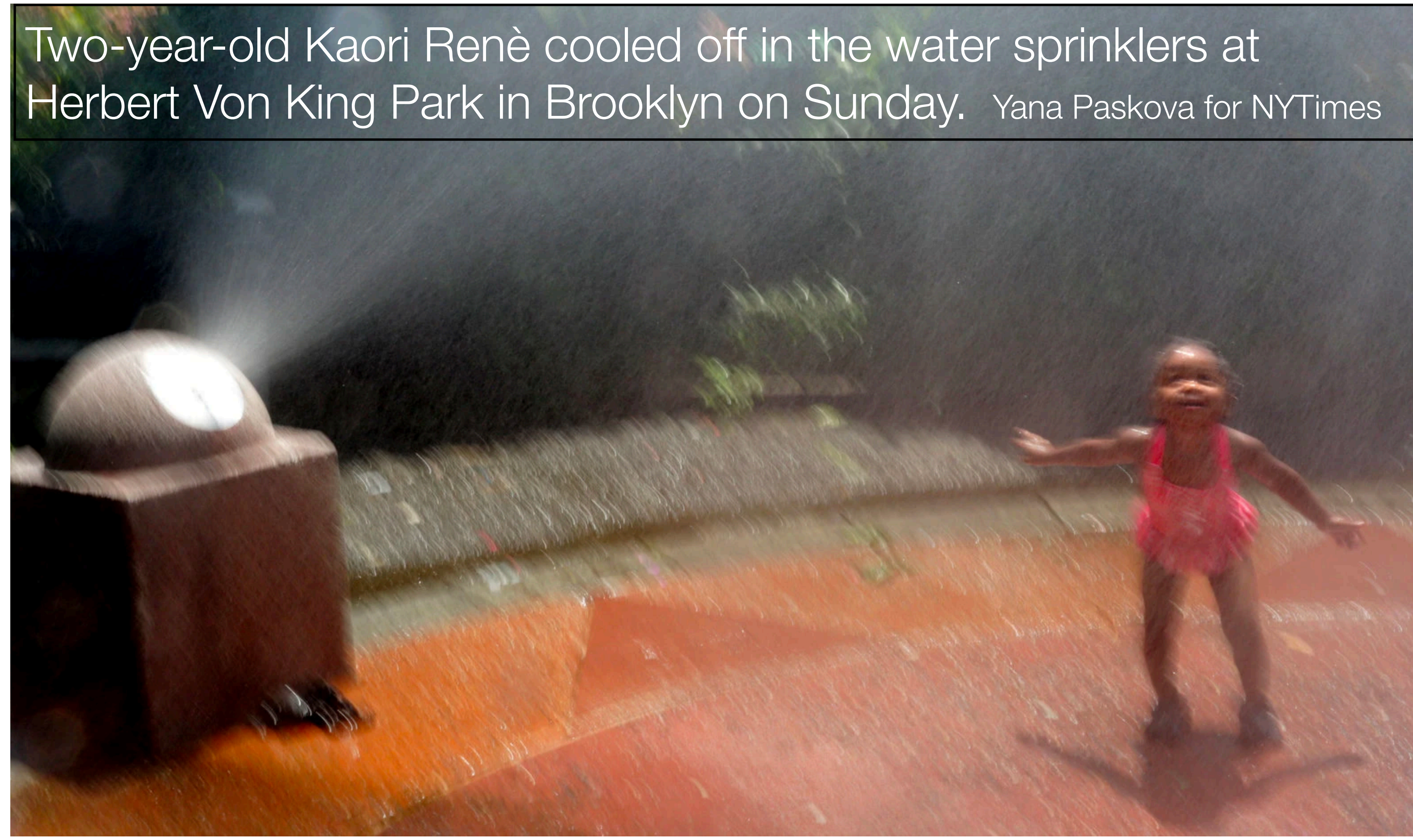

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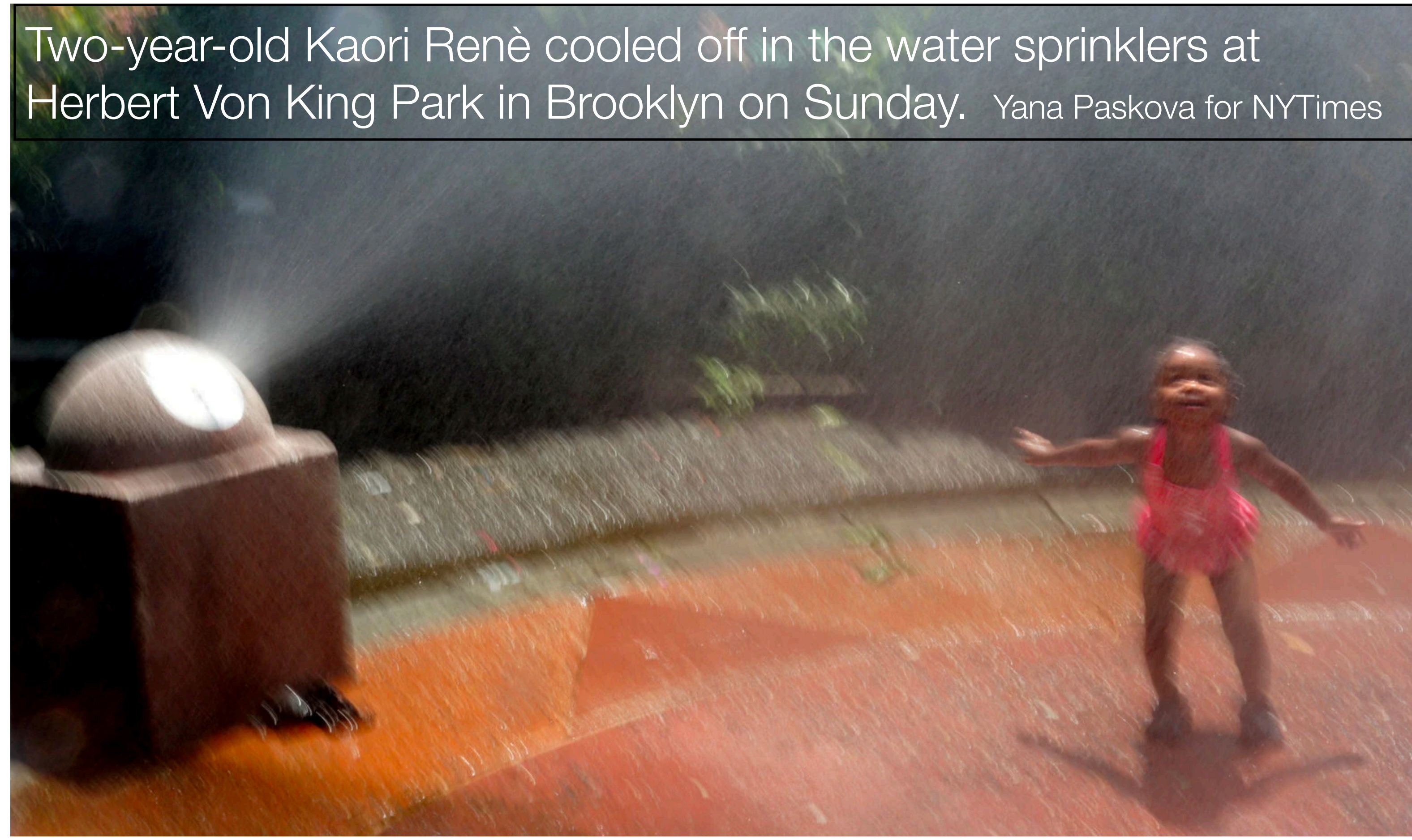
- Severe heat waves are natural disasters. Lead to failure of agricultural crops, power outages due to increased use of air conditioning, effects on human health, and death from heat stress & overheating.



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Heat Waves in the news

That Siberian Heat Wave? Yes, Climate Change Was a Big Factor

https://www.nytimes.com/2020/07/15/climate/siberia-heat-wave-climate-change.html

An analysis of recent record temperatures found that climate change made this year's long hot spell 600 times more likely.

The smoldering remains of a forest fire in the Yakutia region of Siberia in June. Yevgeny Sofroneyev\TASS, via Getty Images; NYTimes

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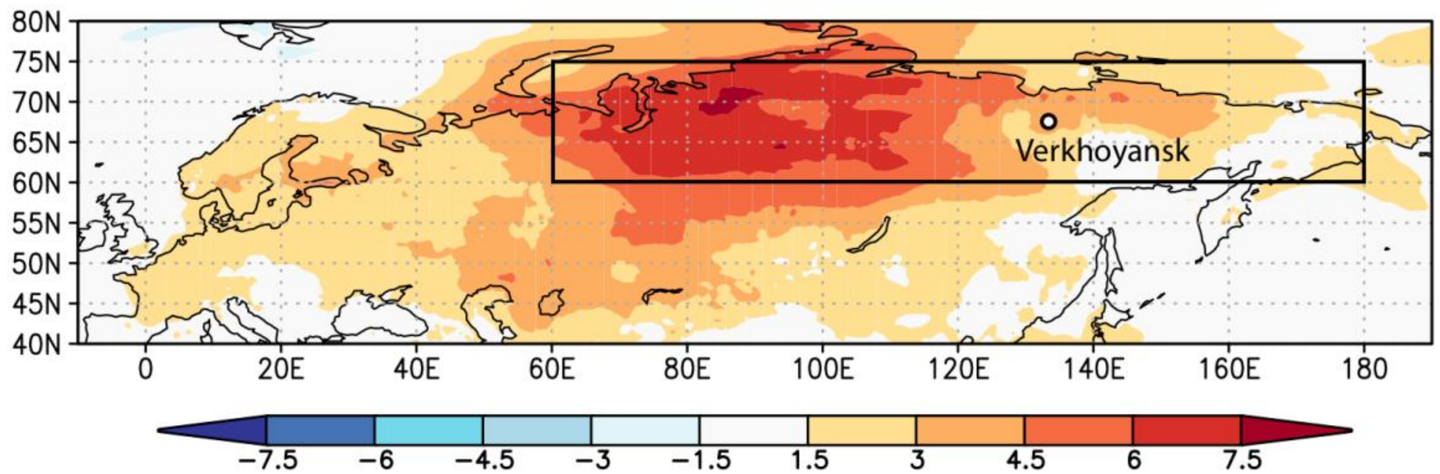

Figure 1: ERA5 near surface temperature (T2m) anomalies [°C] for Jan-Jun 2020. Reference period: 1981-2010. The rectangle represents the study region at 60-75°N, 60-180°E.

https://www.worldweatherattribution.org/wp-content/uploads/WWA-Prolonged-heat-Siberia-2020.pdf

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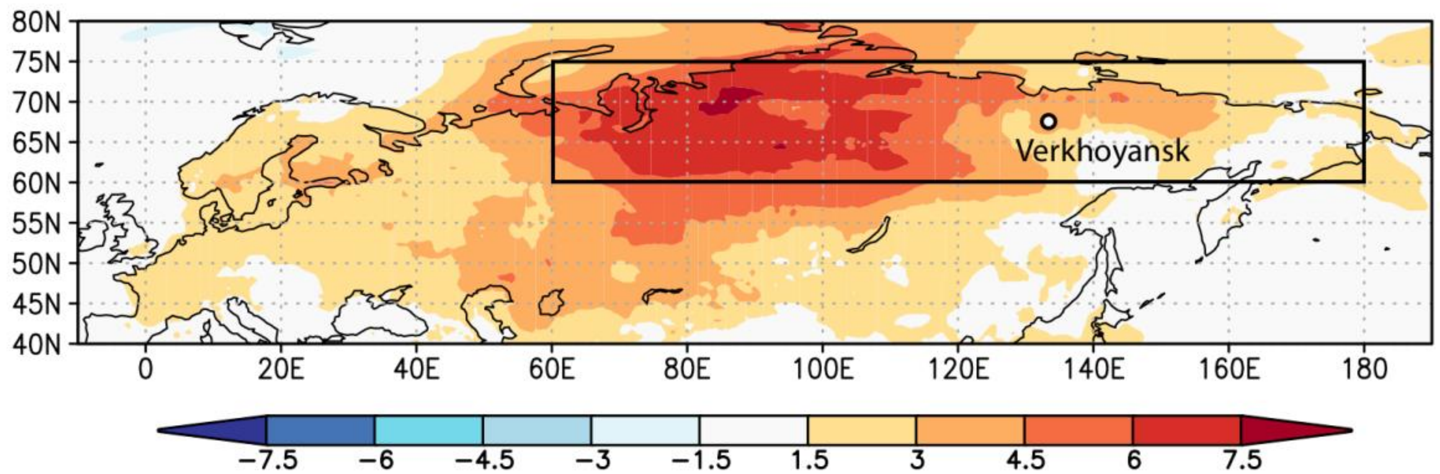

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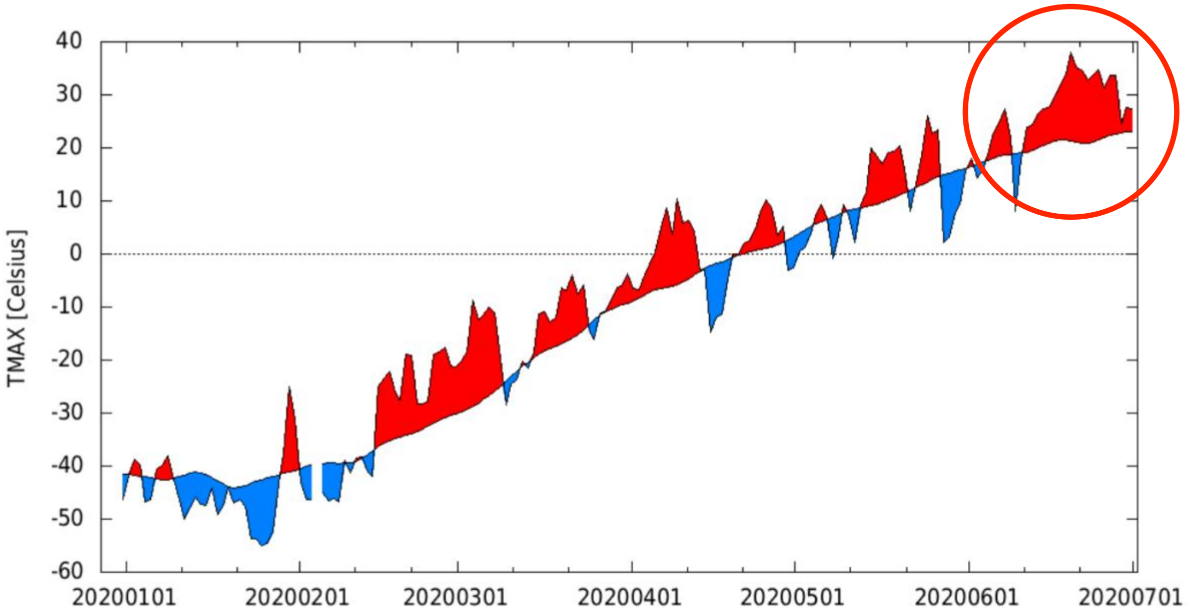

Figure 2: Daily maximum temperature (TX) observations [°C] from January-June 2020 at station Verkhoyansk with positive and negative departures from the 1981-2010 climatological mean shaded red and blue respectively. TX peaks at 38°C on June 20.

Arctic Siberian town hit with record heatwave

https://www.youtube.com/watch?v=pluxAS6w9_8

youtube disclaimer: "Al Jazeera is funded in whole or in part by the Qatari government: https://en.wikipedia.org/wiki/Al_Jazeera"

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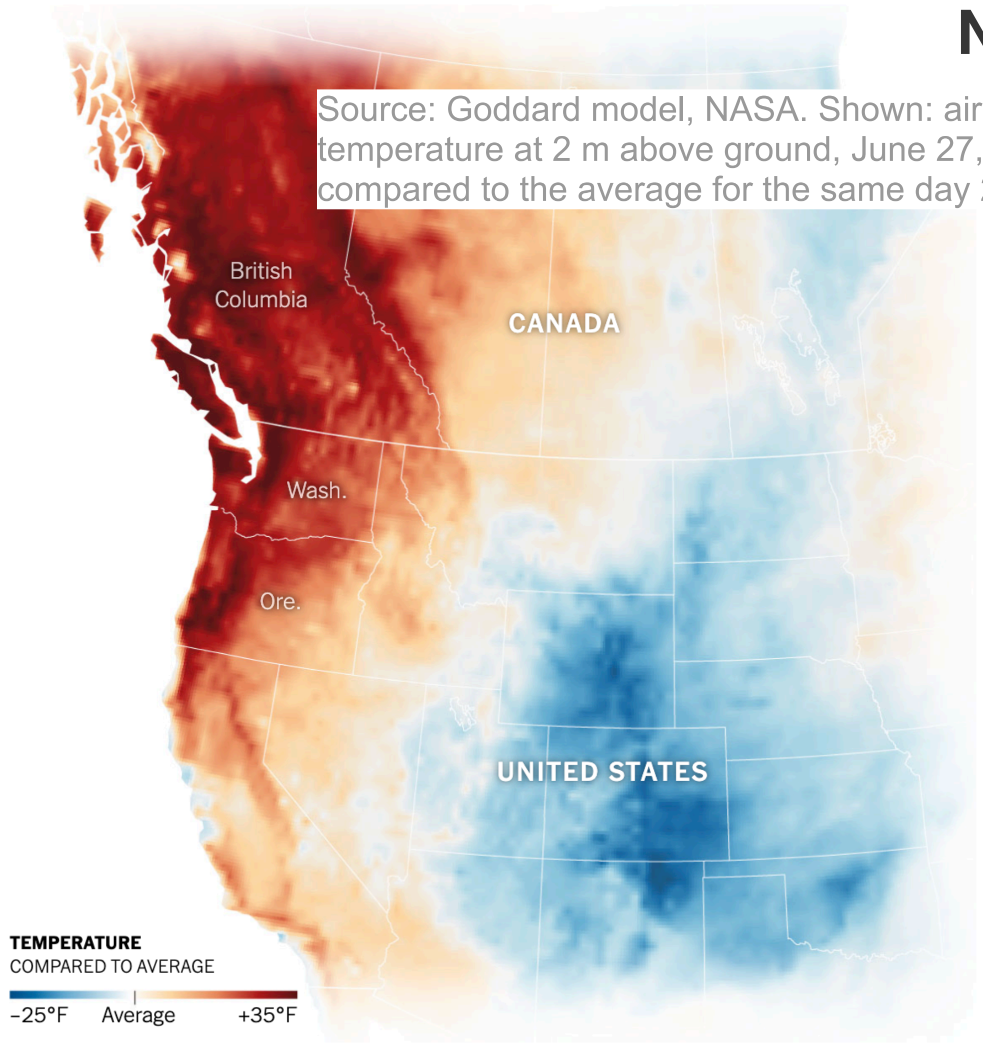
Hidden Toll of the Northwest Heat Wave: Hundreds of Extra Deaths

NYTimes Aug. 11, 2021



Source: Goddard model, NASA. Shown: air temperature at 2 m above ground, June 27, 2020, compared to the average for the same day 2014–2020.

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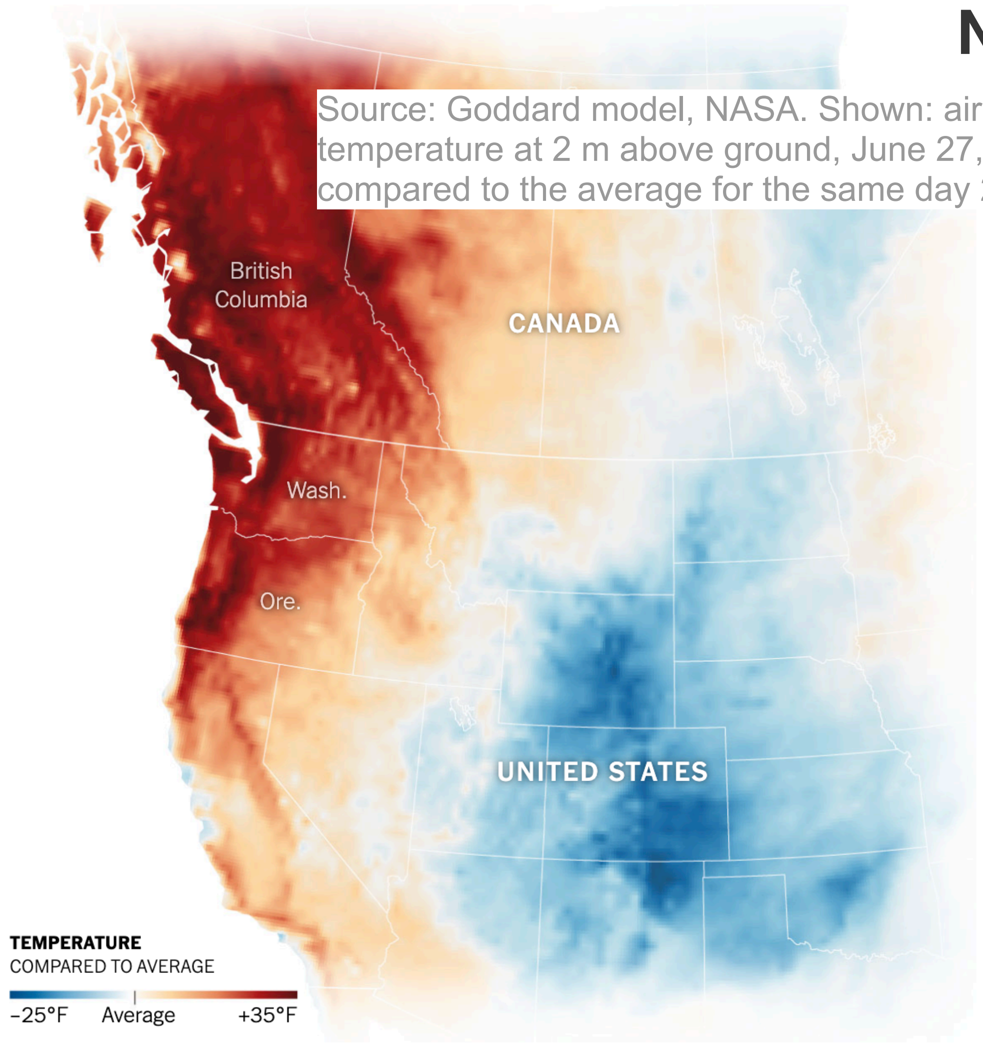

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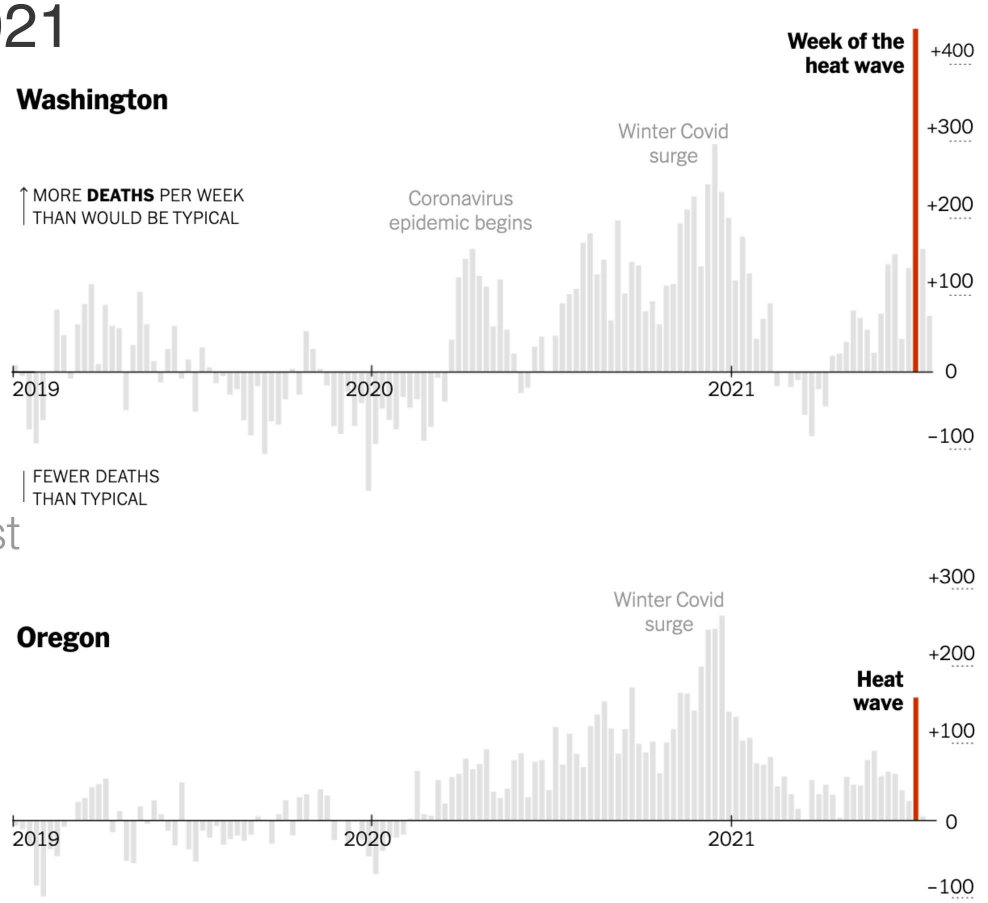
Source: Centers for Disease Control and Prevention. Deaths in recent weeks are most likely undercounted because of lags in reporting.



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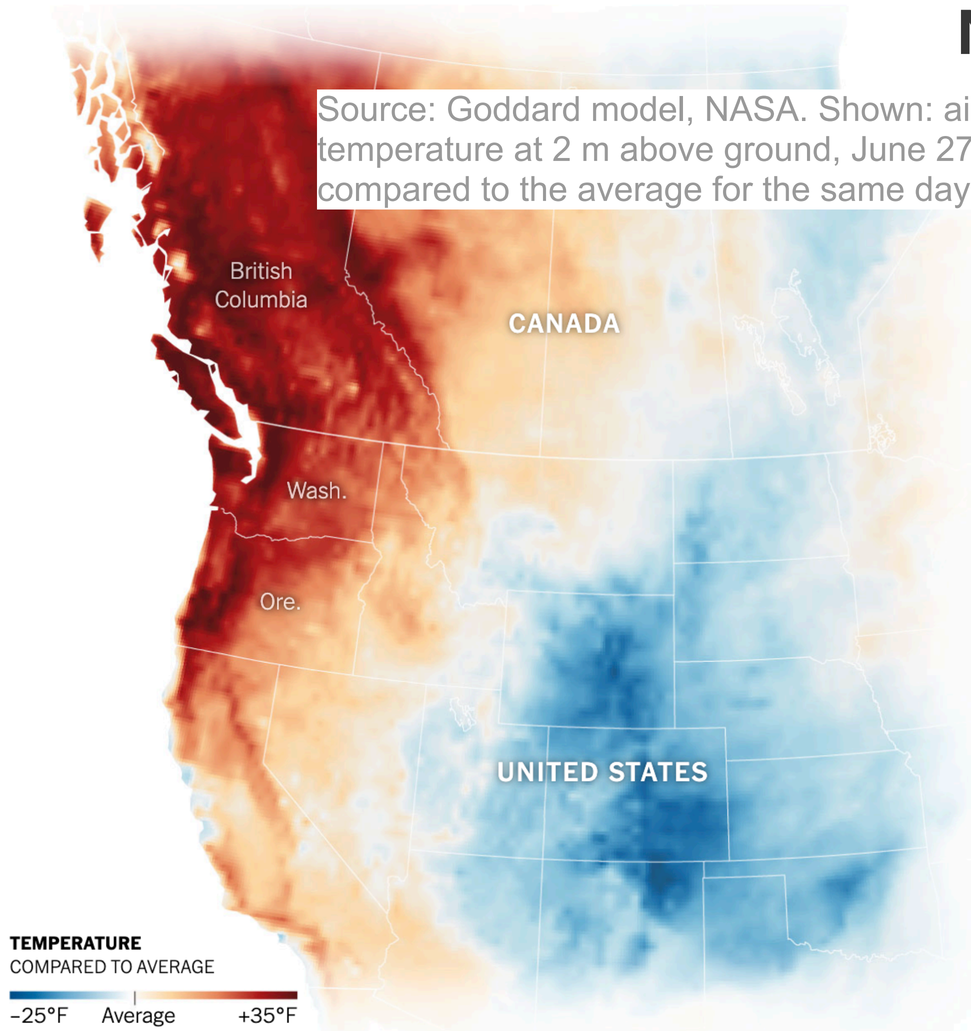

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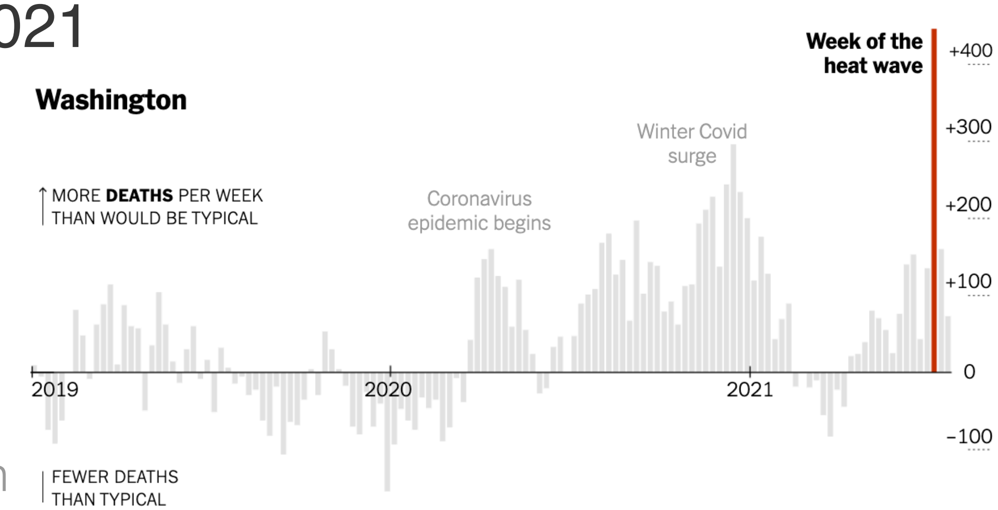

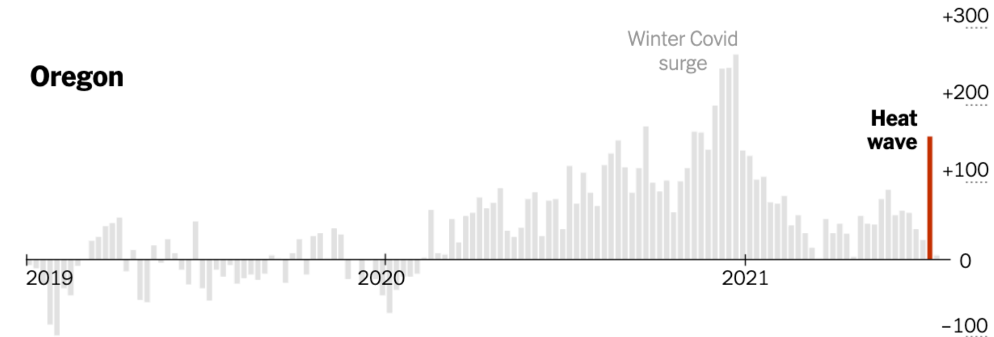

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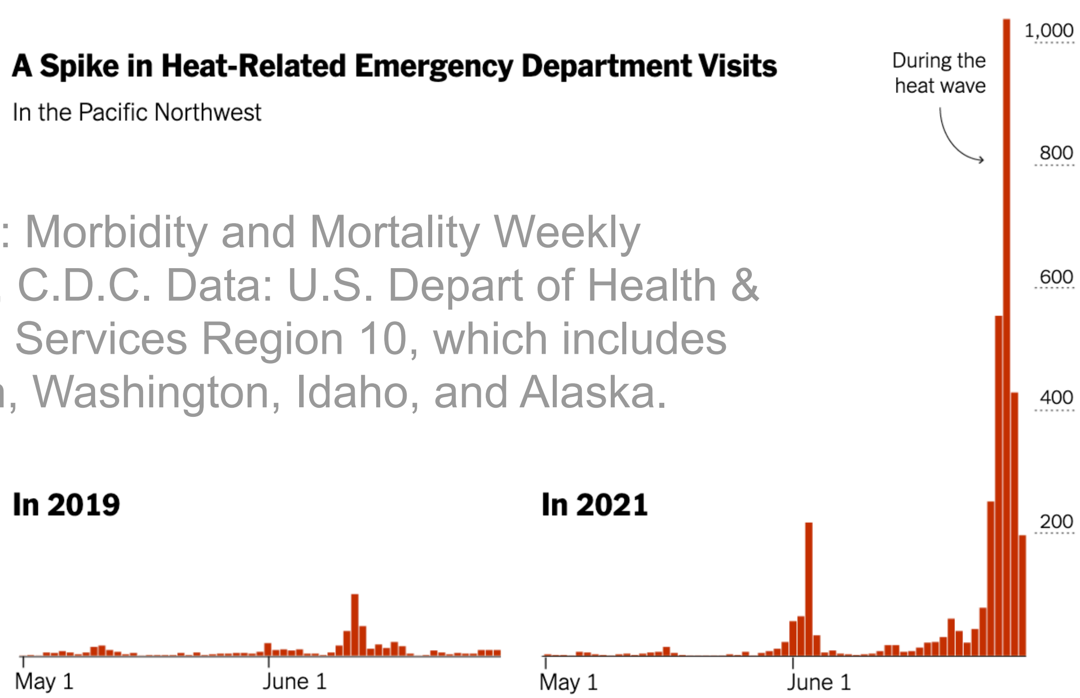

Source: Morbidity and Mortality Weekly Report, C.D.C. Data: U.S. Depart of Health & Human Services Region 10, which includes Oregon, Washington, Idaho, and Alaska.

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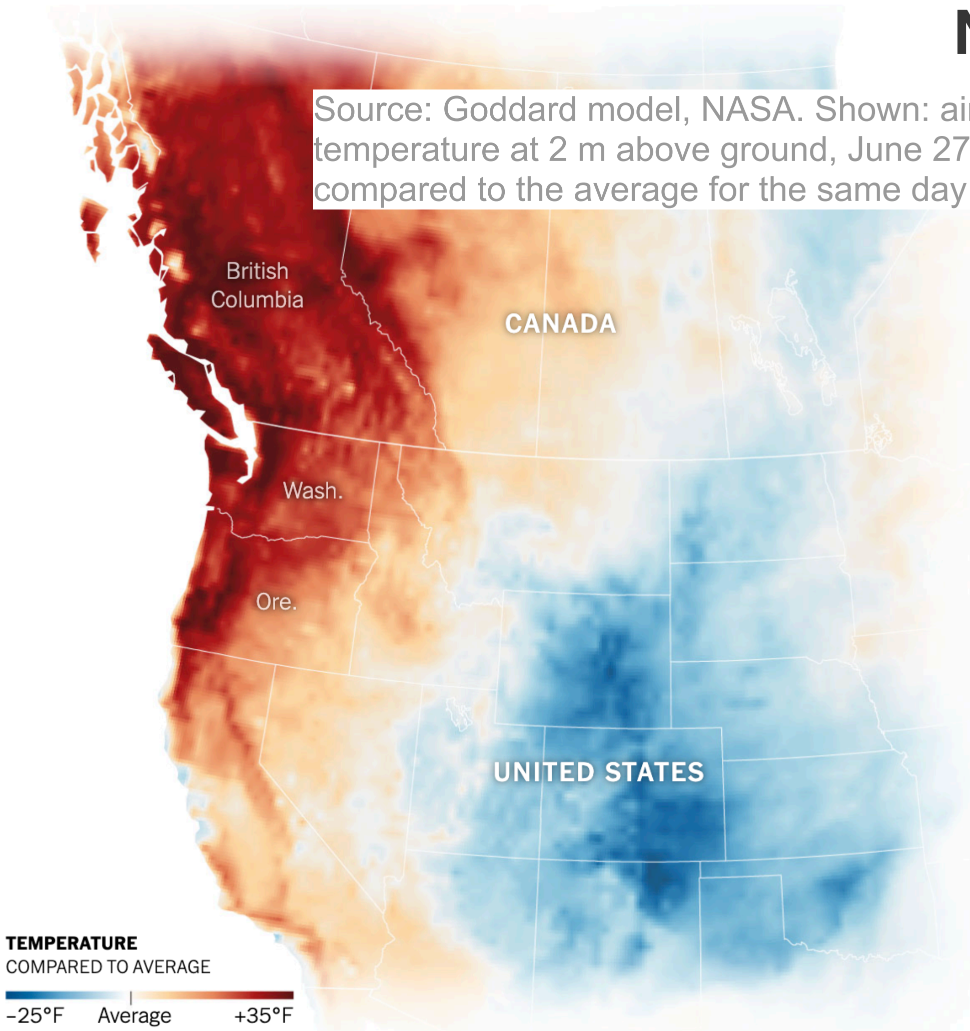

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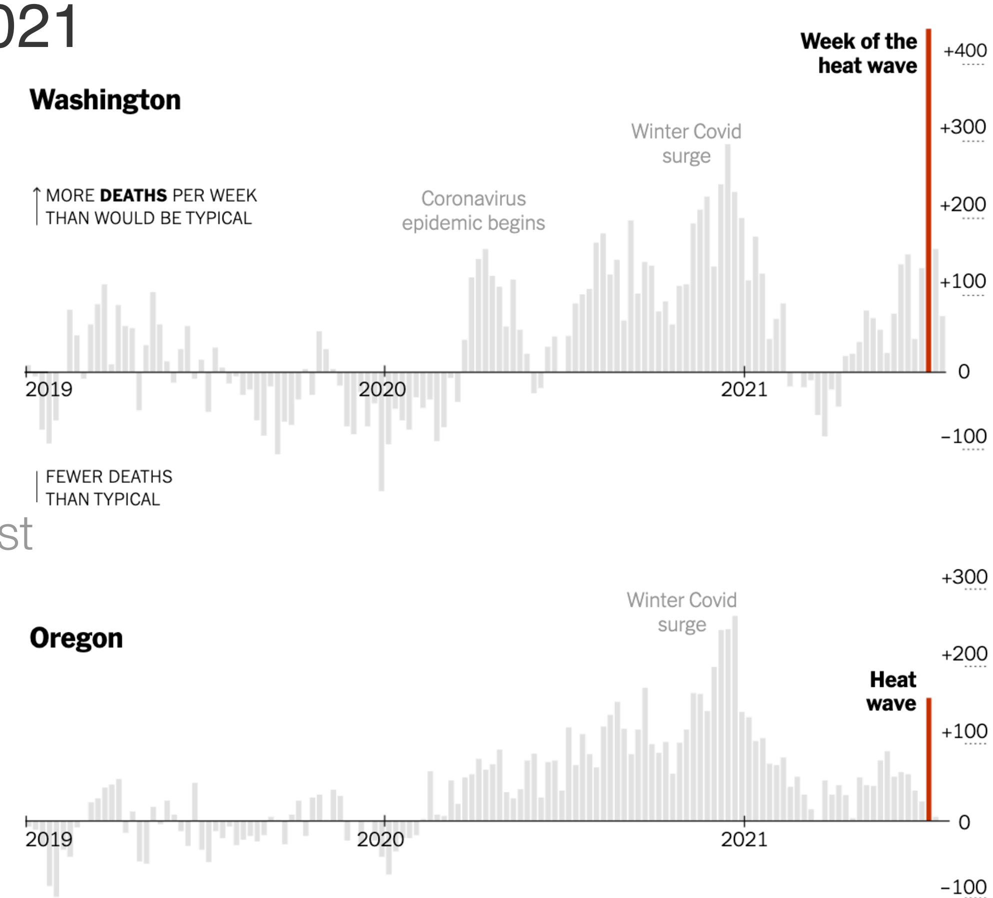

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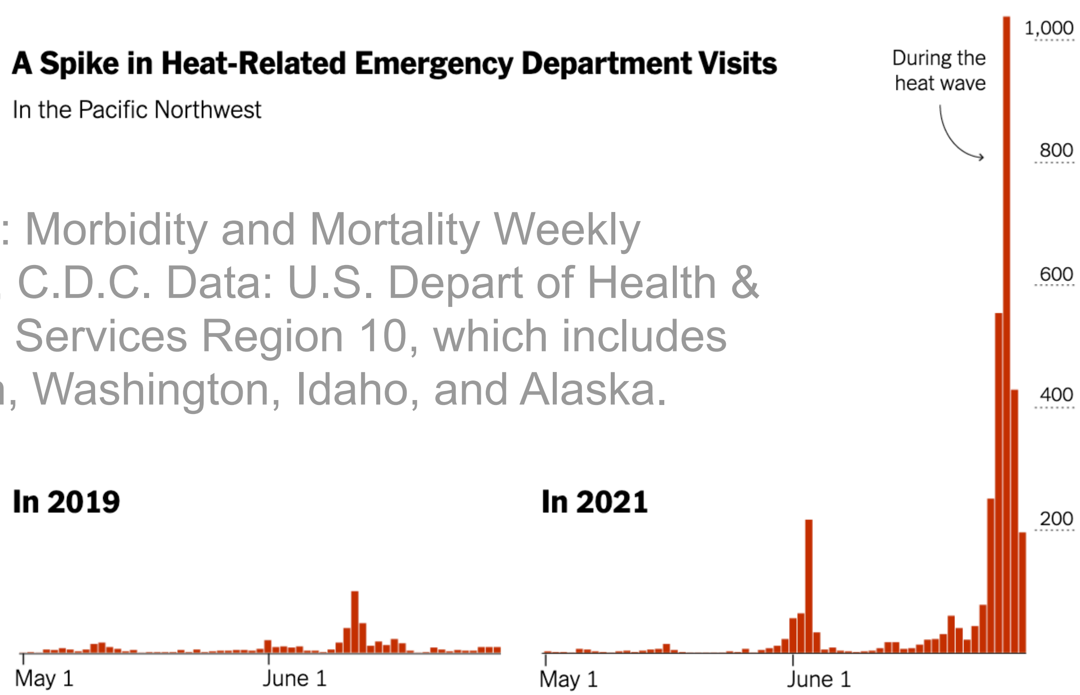

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"During the deadly heat wave that blanketed Oregon and Washington in late June, about 600 more people died than would have been typical…

The number is three times as high as the states' official estimates of heat-related deaths so far. It suggests that the true toll of the heat wave, which affected states and provinces across the Pacific Northwest, may be much larger than previously reported."

https://www.nytimes.com/interactive/2021/08/11/climate/deaths-pacific-northwest-heat-wave.html

Heat Waves in the news

Heat Waves in the Age of Climate Change: Longer, More Frequent and More Dangerous

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“ … a warming of 1C … can lead to a 10-fold increase in the frequency of 100 degree days in NYC for example,” said Dr. Mann. … since the 1960s the average number of heat waves — two or more consecutive days where daily lows exceeded historical July-August temperatures — in 50 major American cities has tripled… from two per year in the 1960s to current average of nearly six per year.

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Climate change makes heat waves more frequent

… by changing the jet stream … when heat waves arrive, they stay in place longer.

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Heat deaths may soon surpass deaths from cold weather

https://www.nytimes.com/2019/07/18/climate/heatwave-climate-change.html

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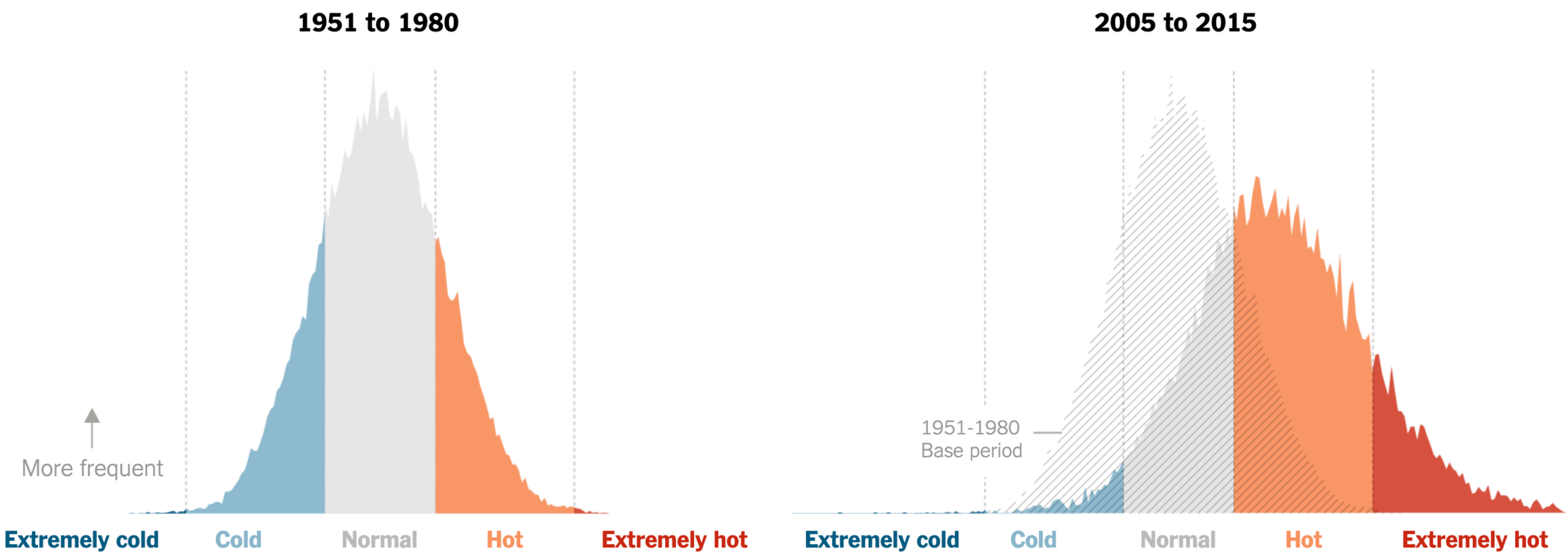
"It's Not Your Imagination. Summers Are Getting Hotter."

NADJA POPOVICH & ADAM PEARCE JULY 28, 2017, NYTimes



Summer temperatures
in the Northern Hemisphere

https://www.nytimes.com/interactive/2017/07/28/climate/more-frequent-extreme-summer-heat.html

Heat waves: goals

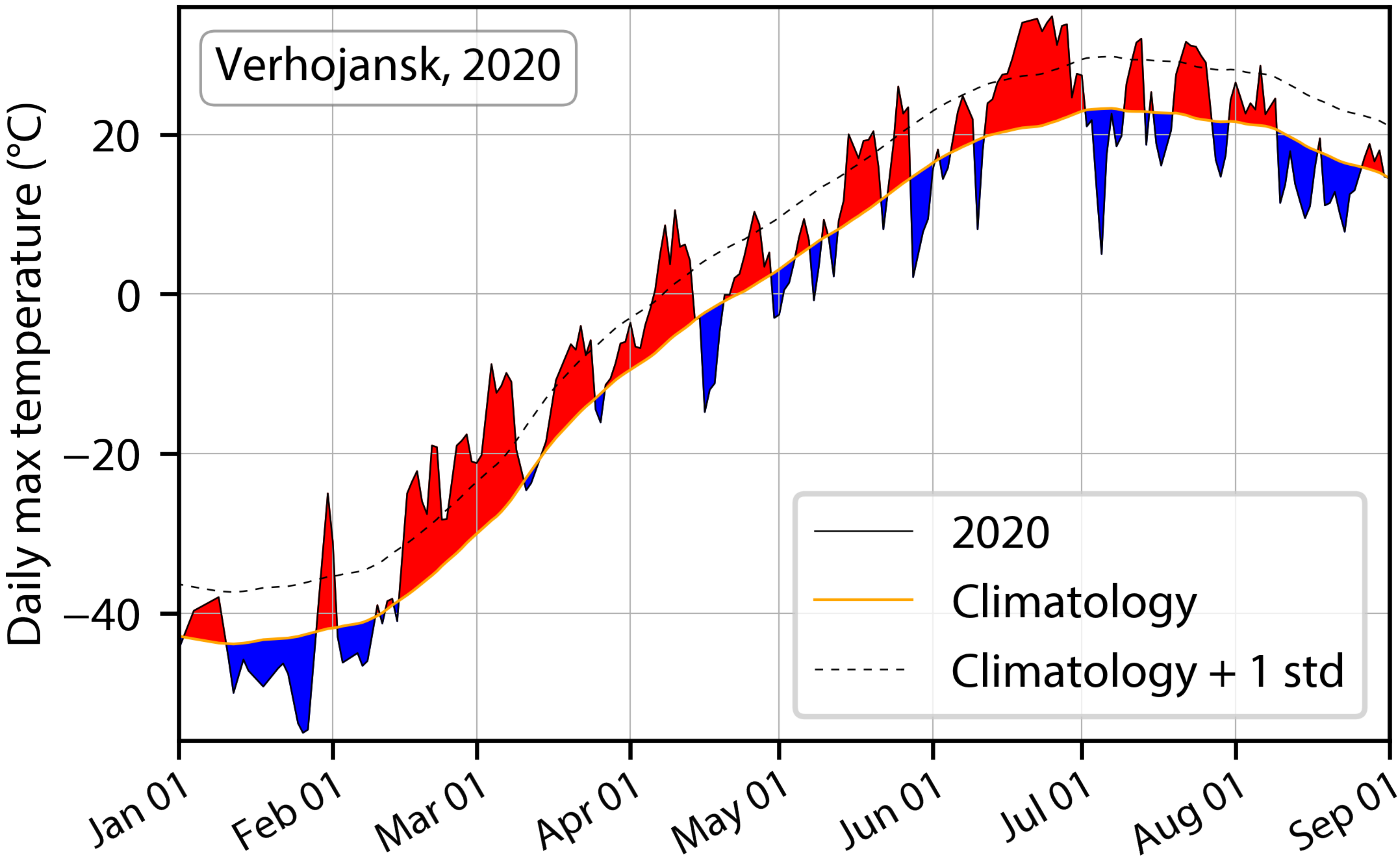
Our goal is to understand the following issues:

- Mechanism of heat waves
- Health effects, in particular heat stress and the role of humidity
- Learning to interpret heat wave statistics in a changing climate

Workshop #1

The Siberian heat wave of summer 2020

Workshop #1

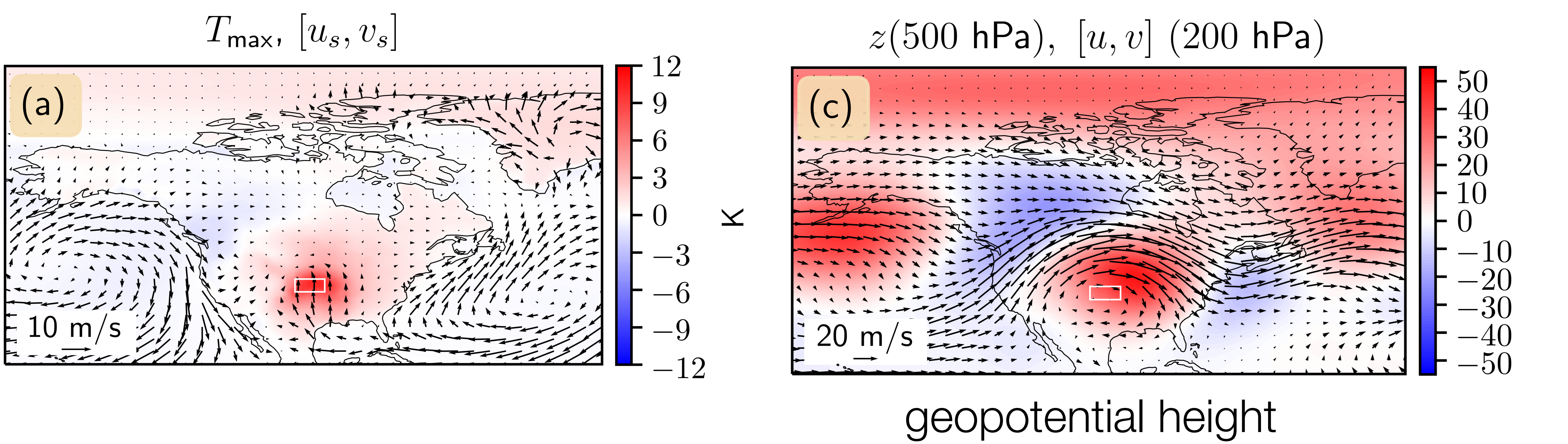


Verhojansk, 2020
Daily max temperature (°C)
20
0
−20
−40
2020
Climatology
Climatology + 1 std
Jan 01
Feb 01
Mar 01
Apr 01
May 01
Jun 01
Jul 01
Aug 01
Sep 01

Notes section 13.1
Mechanism of Heat Waves
(use following slides)

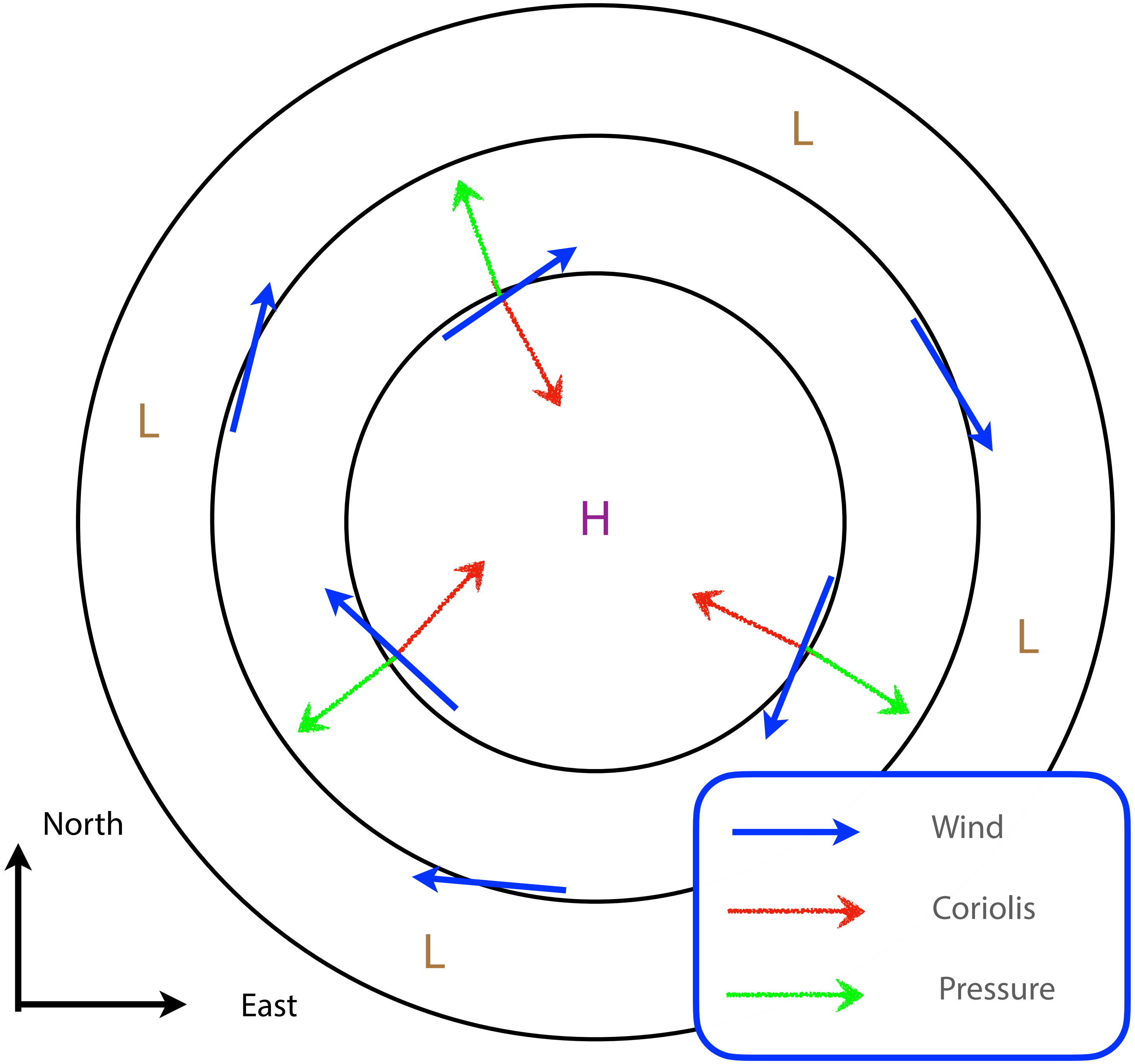
Mechanism of Heat Waves

1. Persistent high pressure aloft leads to subsidence and thus to a warming of the sinking air.
2. High pressure diverts precipitating storms, preventing soil moistening & latent heat cooling.
3. The warming of the air due to the subsidence lowers its relative humidity and leads to cloud-free clear sky which allows more short wave radiation to reach the surface.
4. The clear sky also enhances the radiative cooling of air and strengthens the subsidence.
5. Lack of precipitation in the previous rainy season, and resulting drier soil, enhance the occurrence of heat waves by reducing cooling via surface evaporation/latent heat flux.
6. Surface winds bring warm air: from warmer lower latitudes, from high to low elevation (warming via subsidence), or from warm continental interior to coastal heat wave region.
7. Subsidence prevents atmospheric convection & mixing of surface air with stronger upper atmosphere winds. This lowers surface winds and weakens surface evaporation & cooling.



Heat flux composite over great plains in a climate model

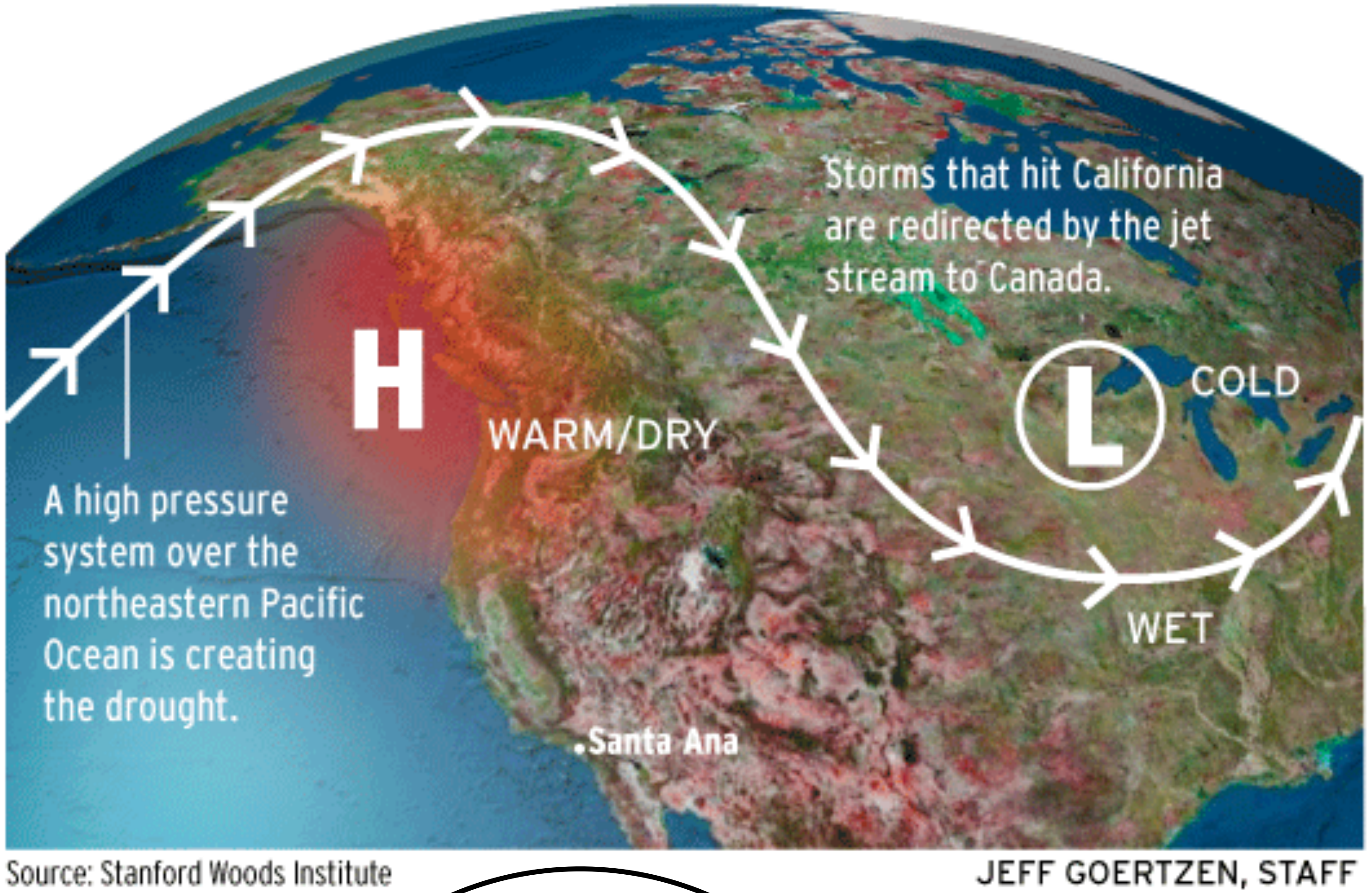
Effects of a regional high pressure



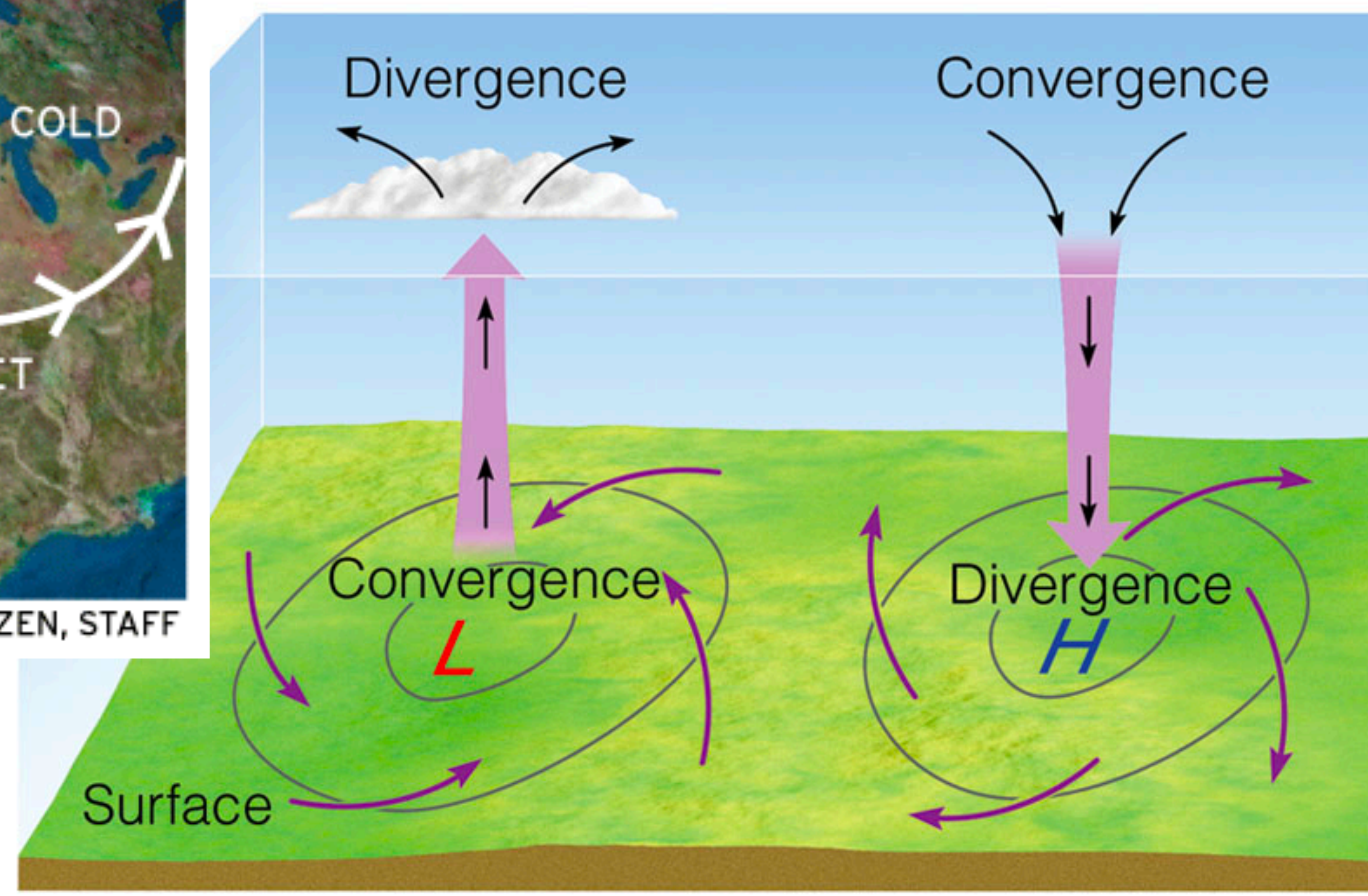
A Northern Hemisphere high-pressure schematic in the Northern Hemisphere.
The high pressure leads to a clockwise motion that is also slightly directed out of the high pressure.
As a result, subsidence occurs at the center to replace the air leaving.

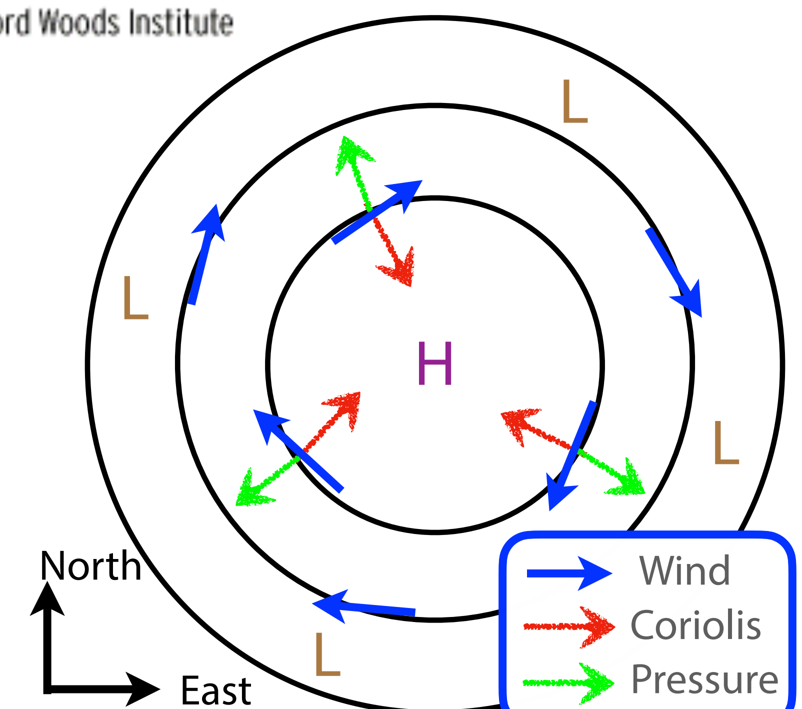
Effects of a regional high pressure

High sea level pressure: (1) diverts rain storms (2) causes subsidence and therefore drying



https://blog.weatherops.com/how-does-subsidence-affect-weather





A northern hemisphere high pressure schematic

Mechanism of Heat Waves

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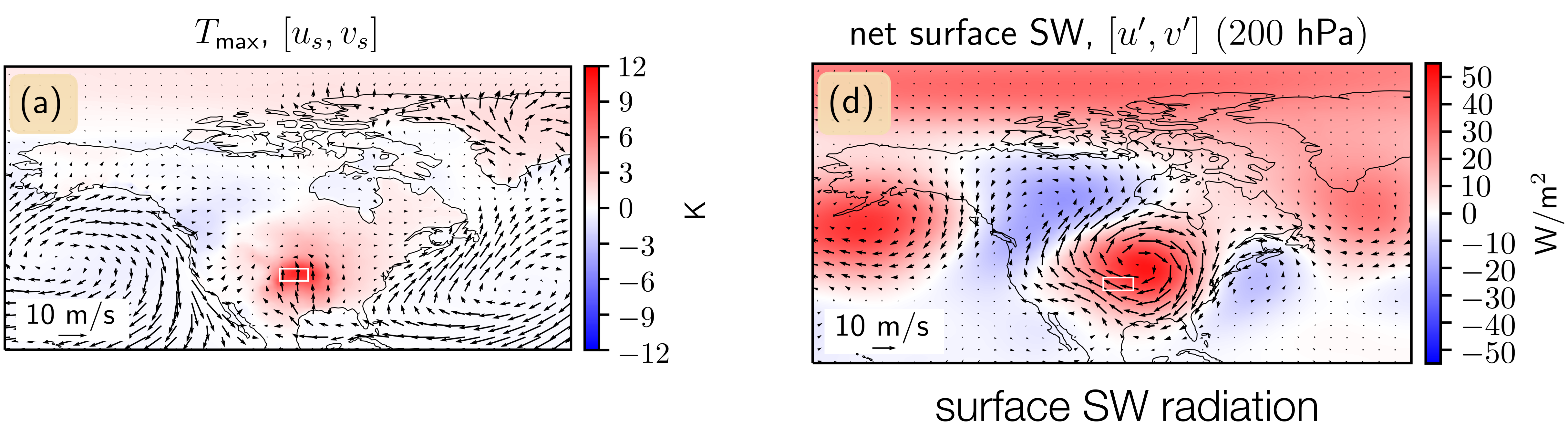

Heat flux composite over great plains in a climate model

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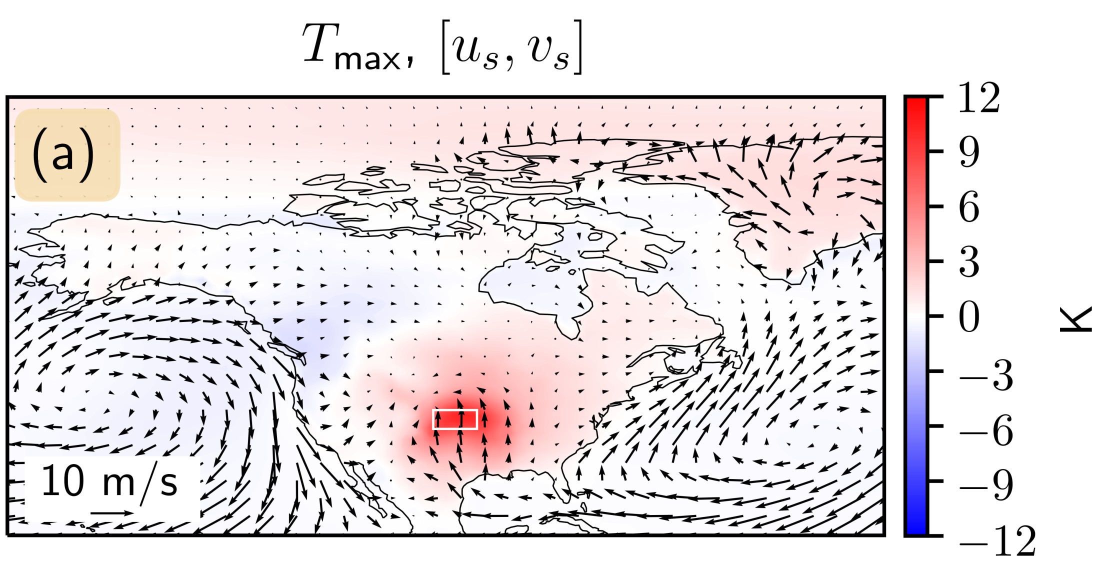

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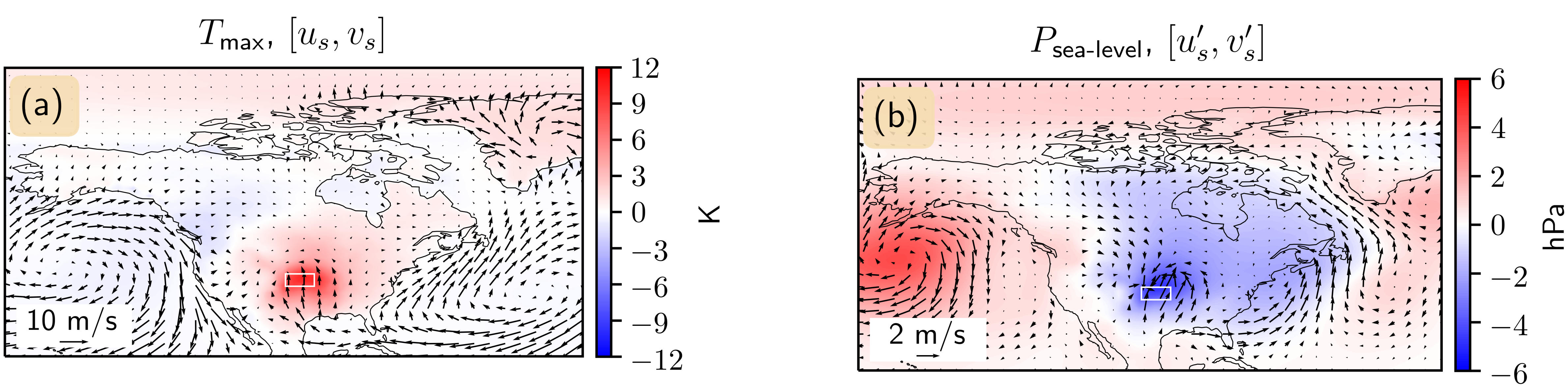
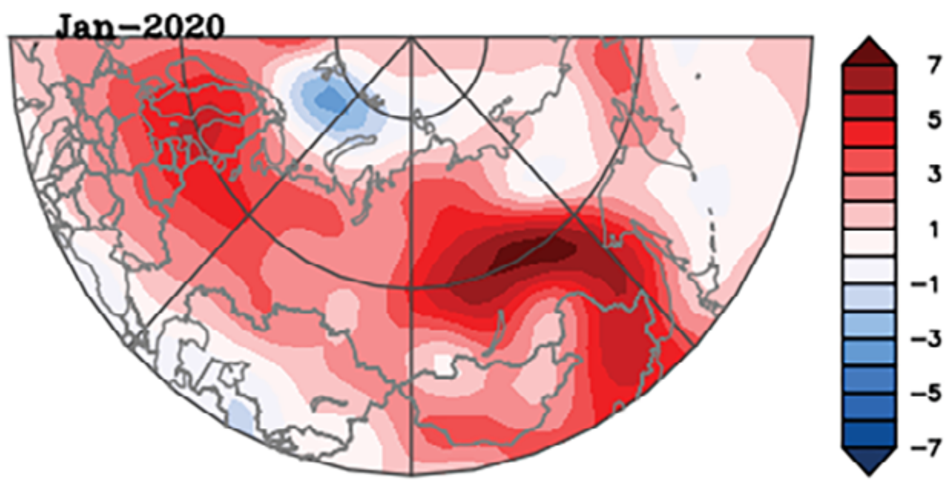


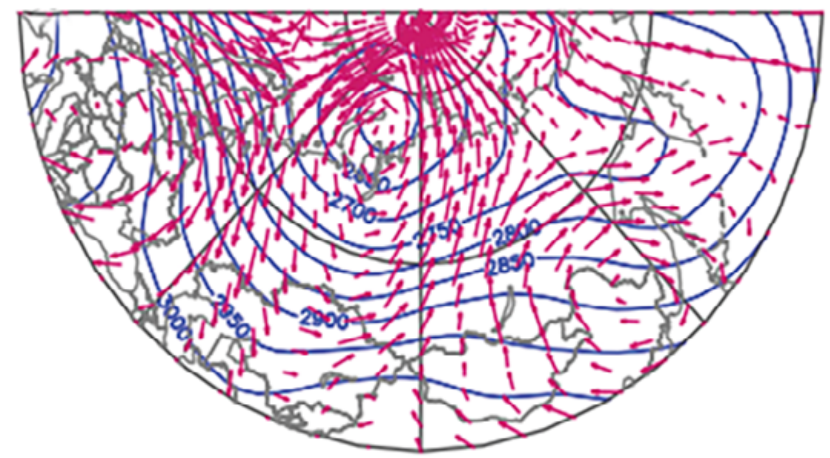
surface sea level pressure and surface winds

Heat flux composite over great plains in a climate model

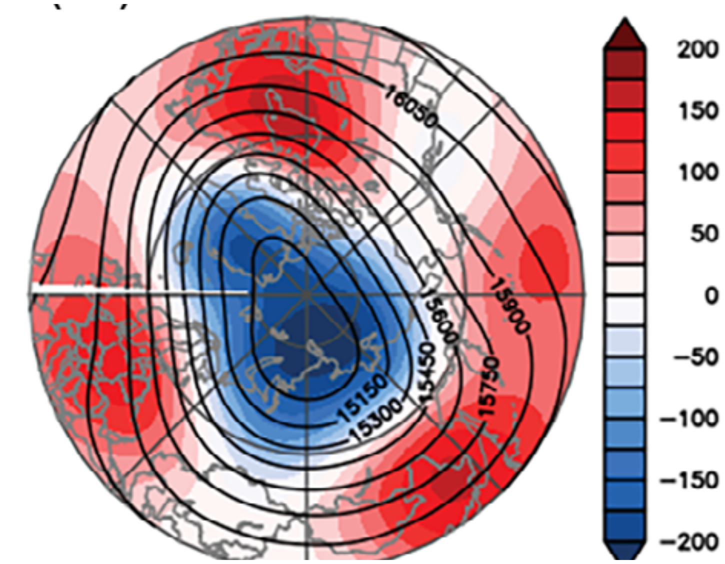
Example observed event: Siberian 2020 heat wave



low-level temperature



700 hPa winds and geopotential height



100 hPa height & anomalies

Jan

Heat wave lasted Jan–June, with peak temperatures in June. Mechanisms are different for Jan–Apr (stratospheric polar vortex, Arctic Oscillation) and for May–June.

"The 2020 Siberian heat wave" Overland & Wang 2020; DOI: 10.1002/joc.6850

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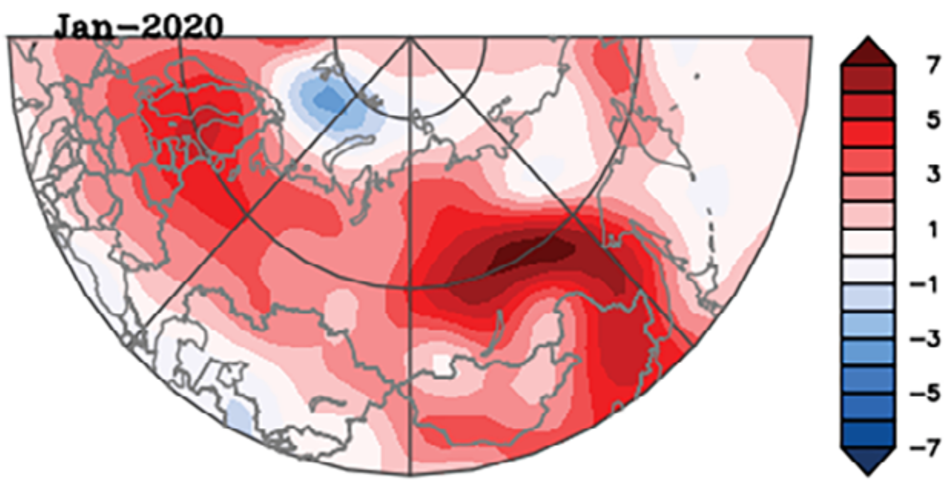

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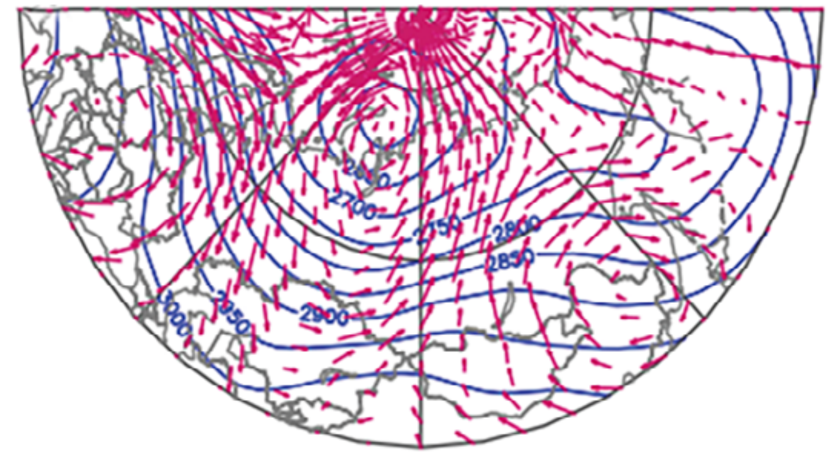

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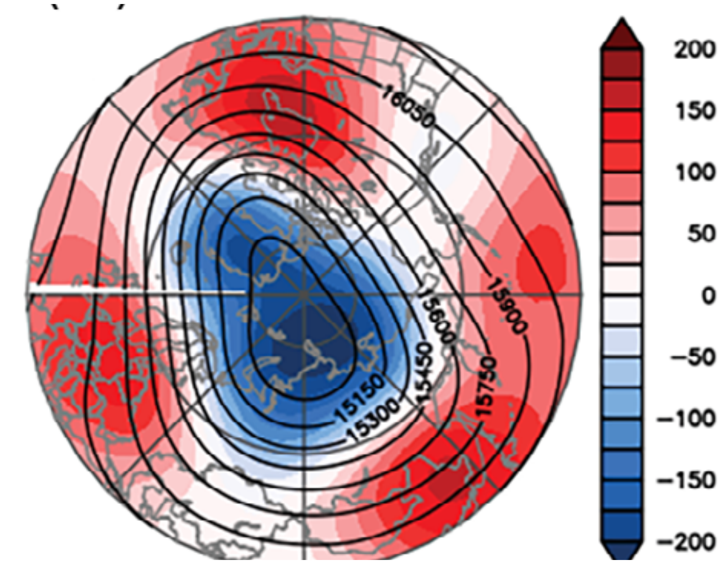

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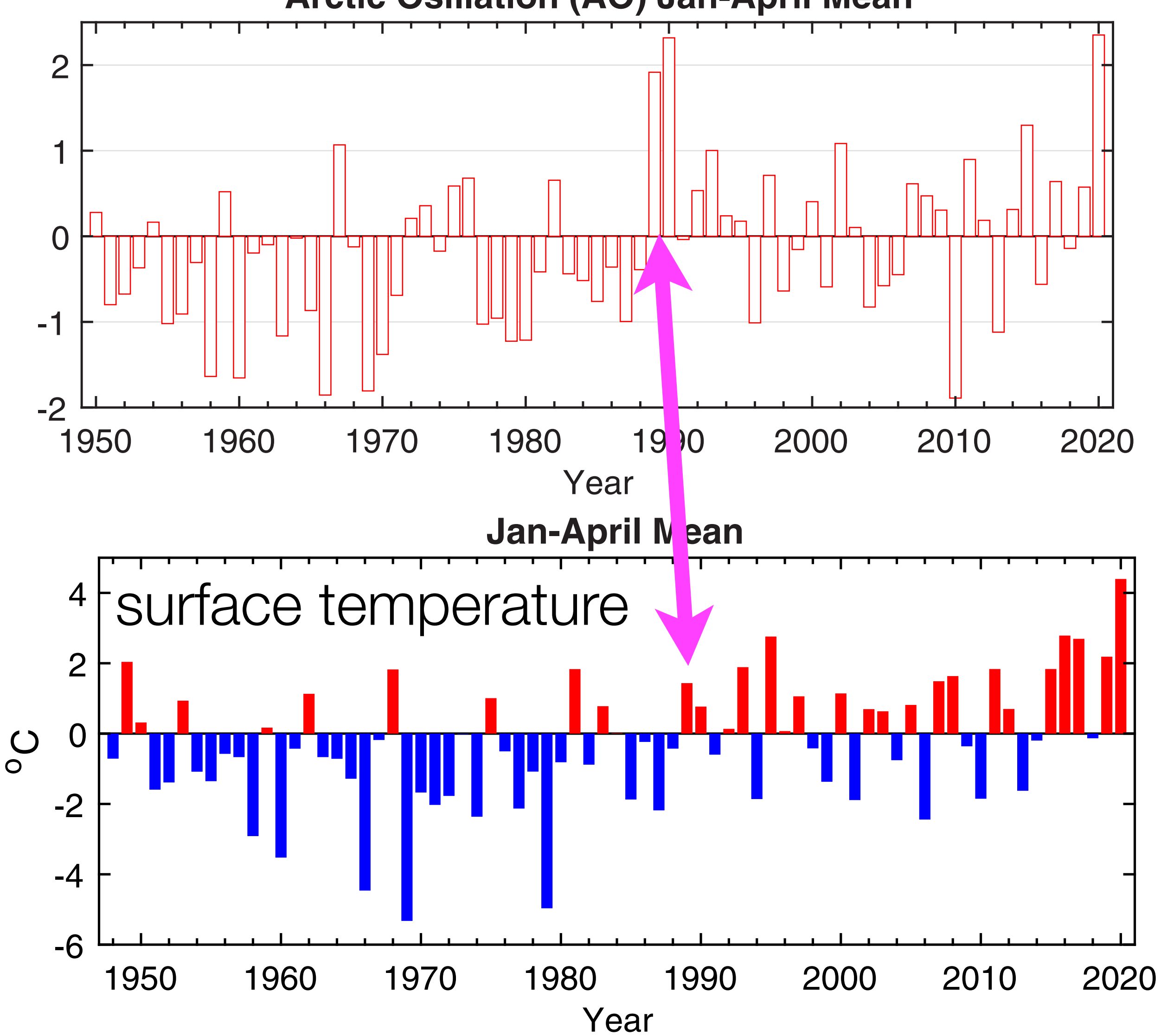

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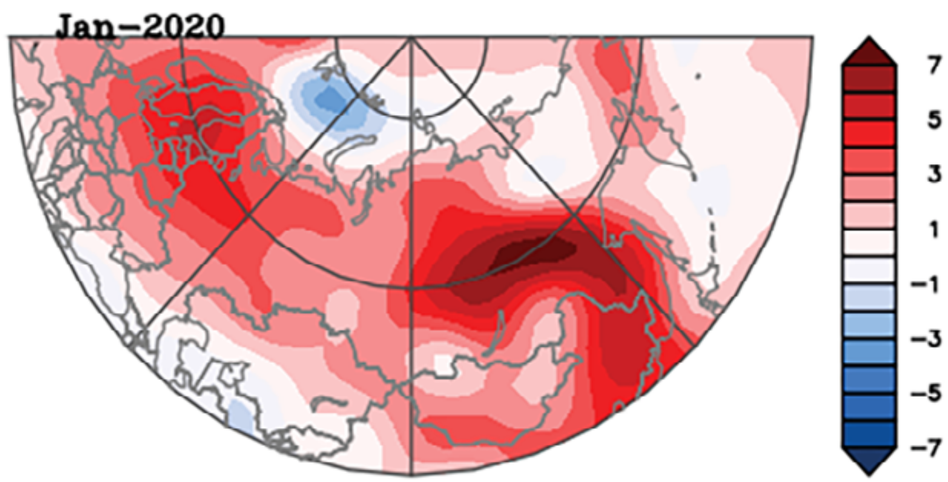
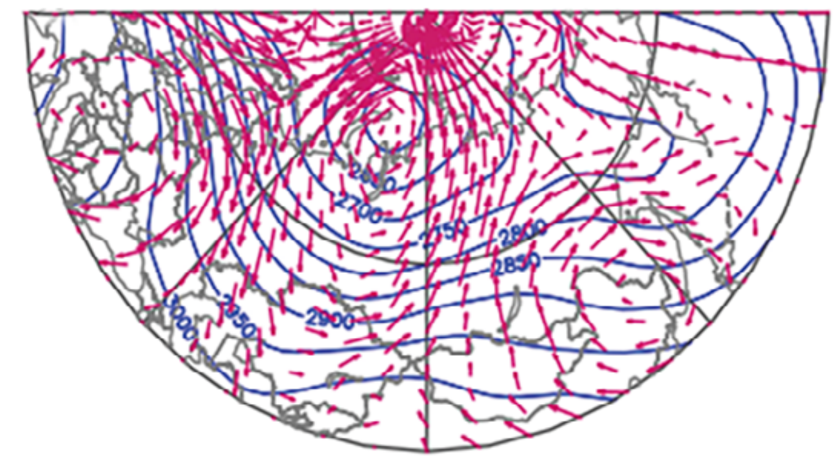


low-level temperature



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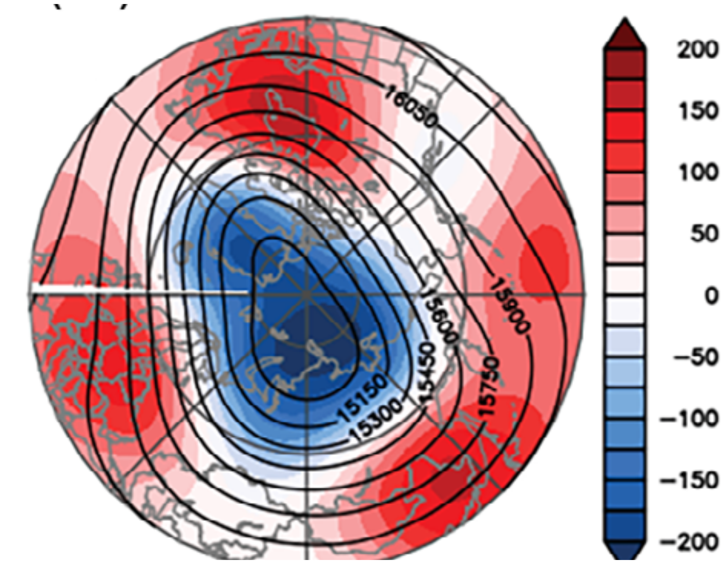

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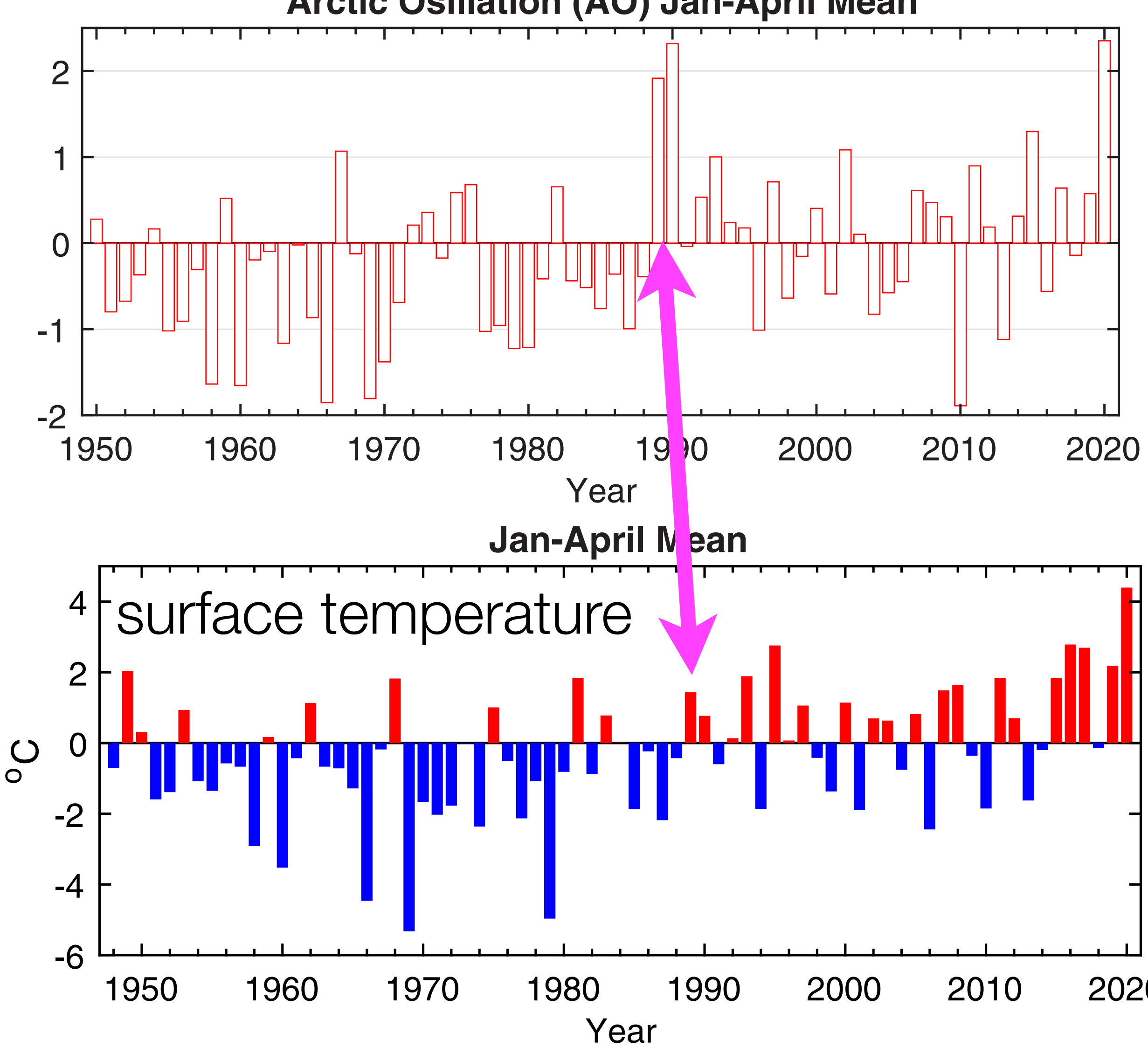

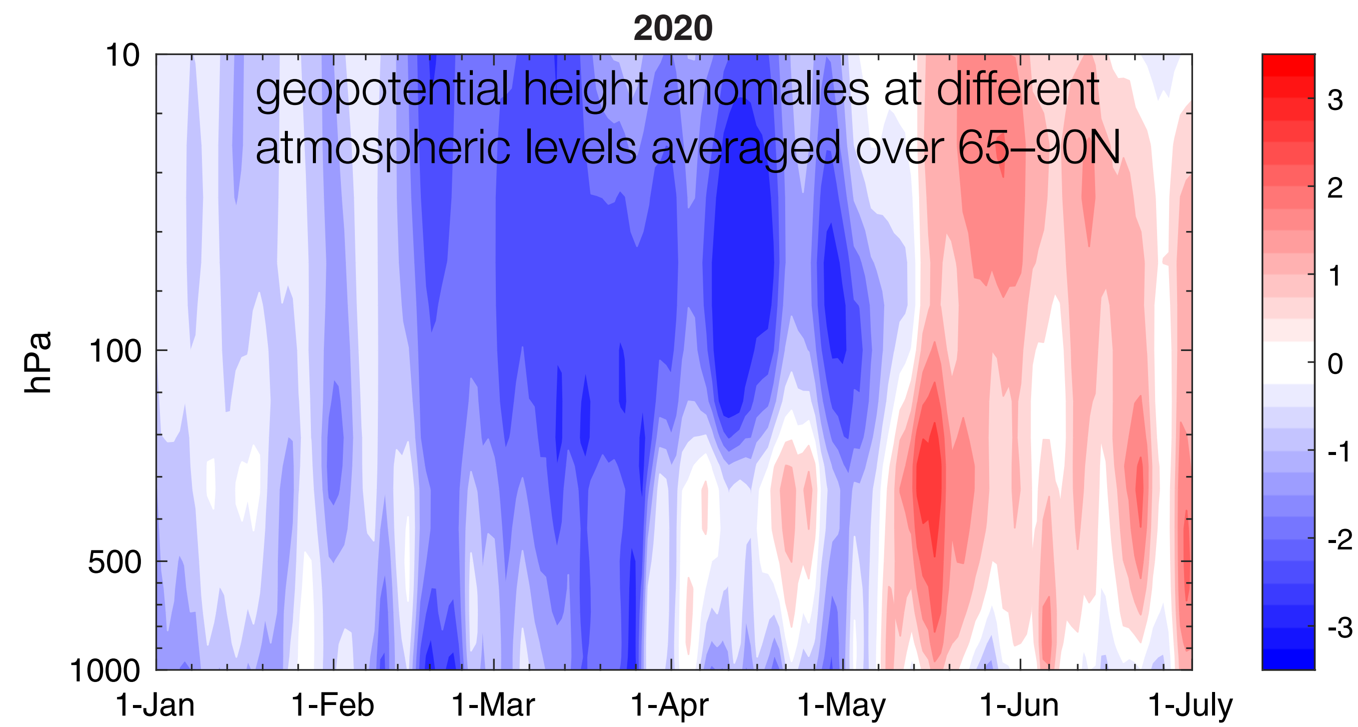

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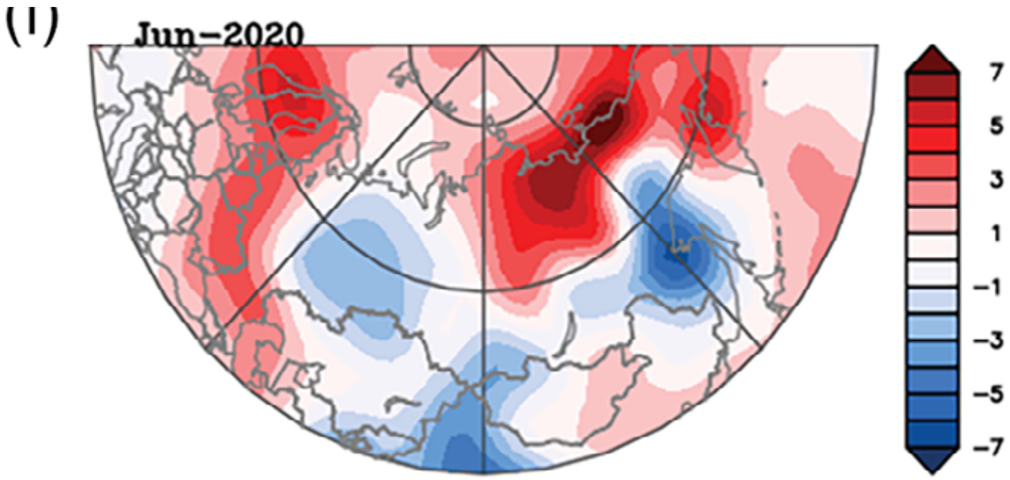
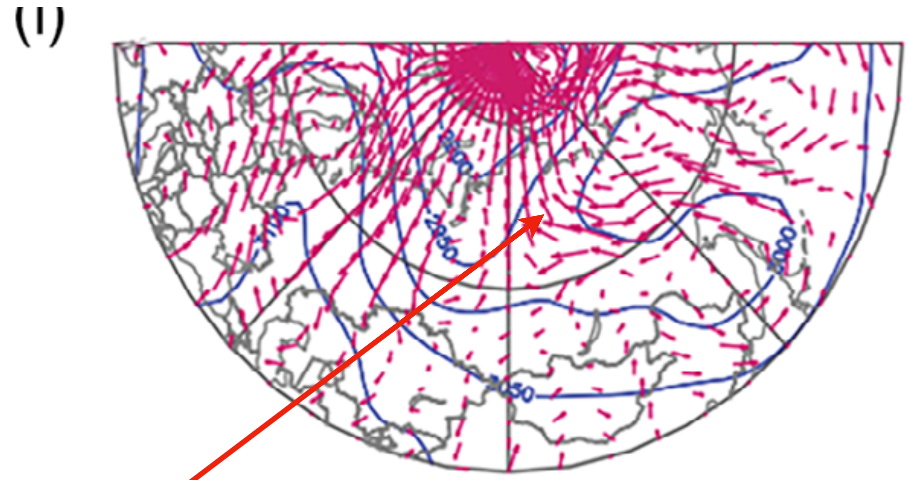
"The 2020 Siberian heat wave" Overland & Wang 2020; DOI: 10.1002/joc.6850

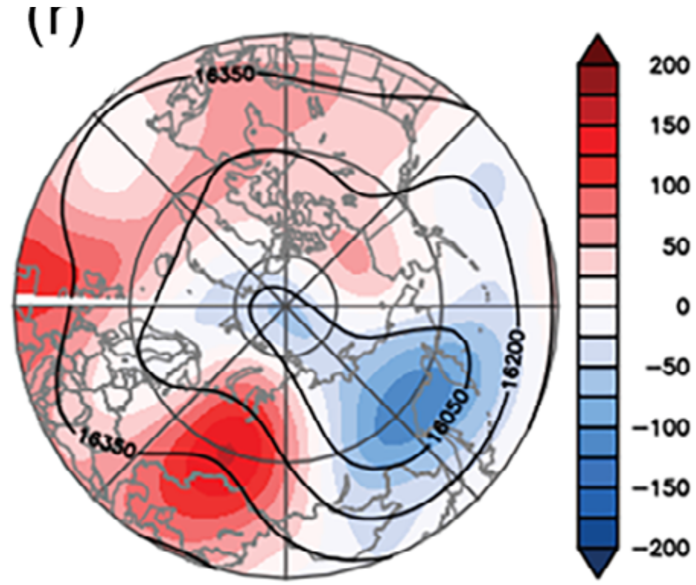
Example observed event: Siberian 2020 heat wave



low-level temperature



700 hPa winds and geopotential height

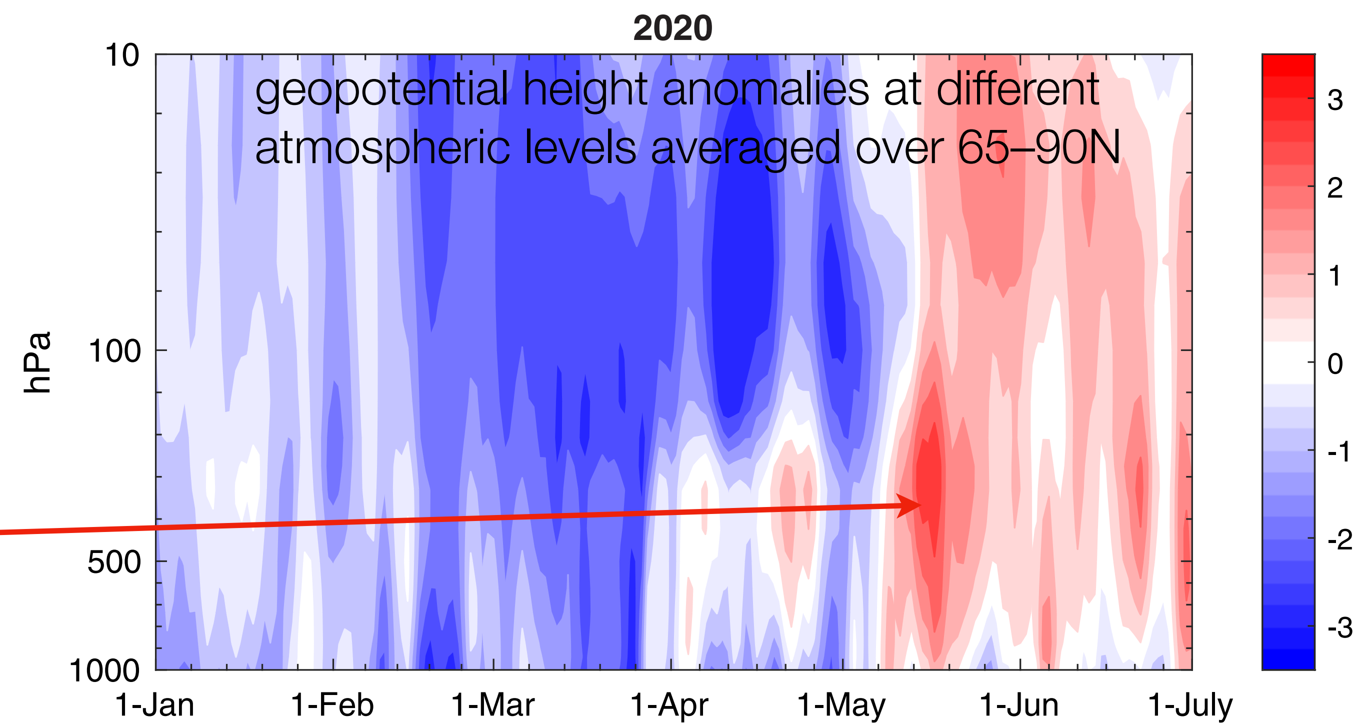


100 hPa height & anomalies

June

southerly low-level winds

high pressure



Heat wave lasted Jan–June, with peak temperatures in June. Mechanisms are different for Jan–Apr (stratospheric polar vortex, Arctic Oscillation) and for May–June.

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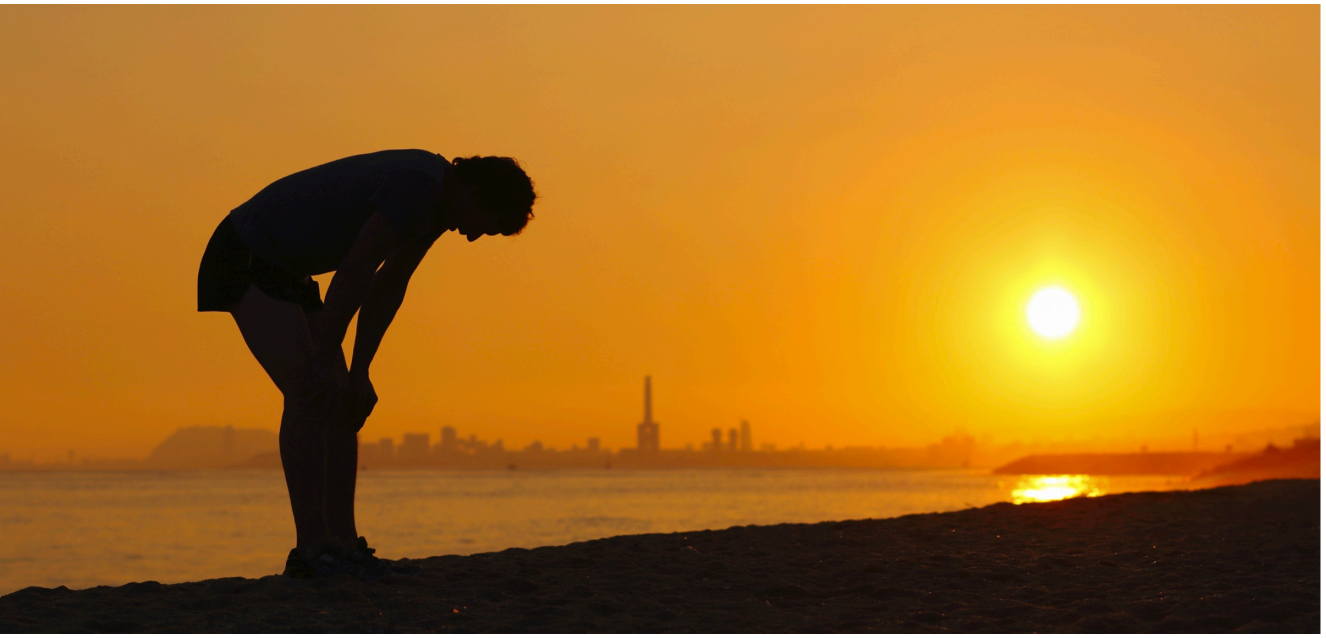
Health effects: wet bulb temperature & heat stress

National Oceanic and Atmospheric Administration

Excessive heat, a 'silent killer'

Heat exhaustion or heatstroke? Know the signs of heat illness.



https://www.noaa.gov/stories/excessive-heat-silent-killer

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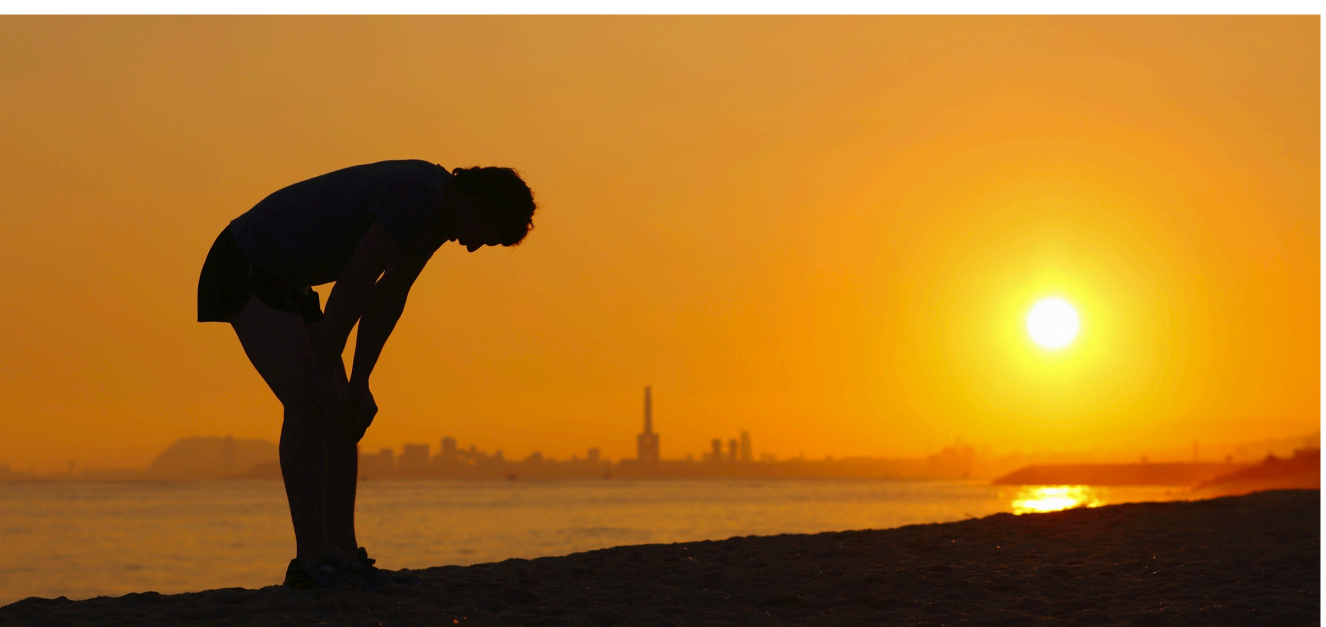

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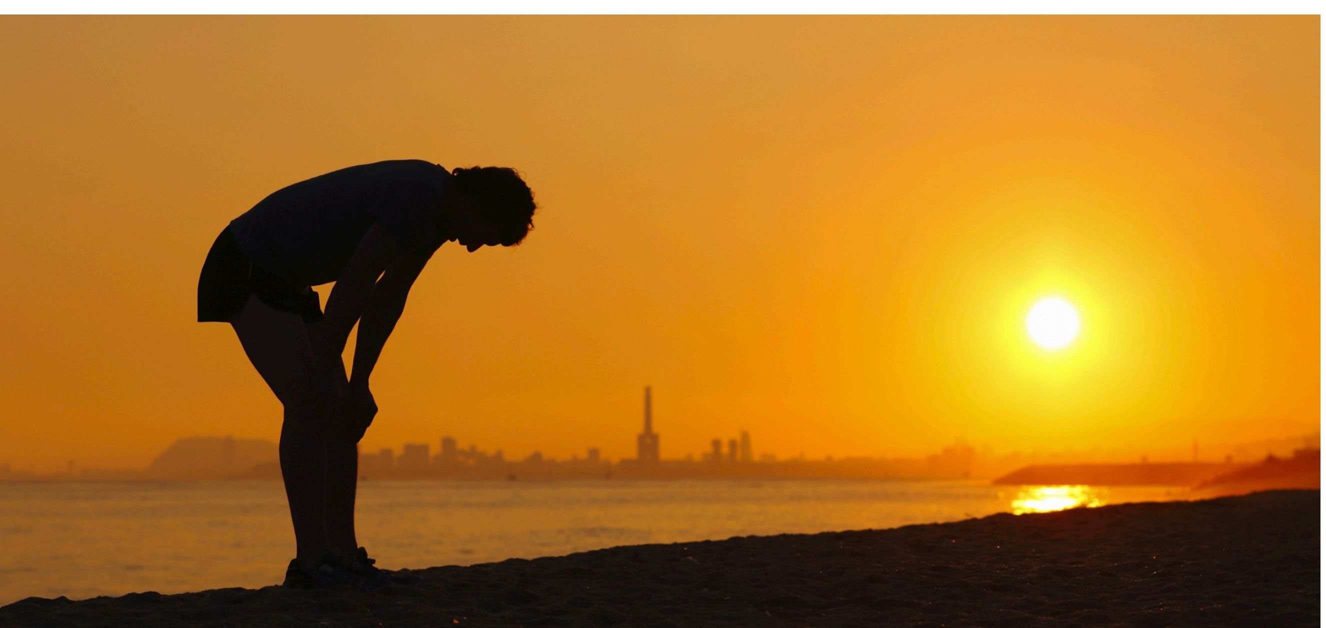

"Heat can be a silent killer because it doesn't topple trees or rip roofs off houses like tornadoes and hurricanes" Eli Jacks, chief of forecast services with NOAA's National Weather Service

https://www.noaa.gov/stories/excessive-heat-silent-killer

Notes section 13.2

Heat stress and the wet bulb temperature

(use following slide)

Health effects: wet bulb temperature & heat stress

- Heat waves can impact human health when the body is unable to maintain a healthy temperature: at a higher relative humidity the body cannot cool by evaporating sweat.

Health effects: wet bulb temperature & heat stress

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- A measure of this effect: "wet bulb temperature" (WBT, T_w) defined as temperature that an air parcel would have if cooled adiabatically until its RH is 100%, by evaporation of water into it, where latent heat required for evaporation is supplied by the air parcel.

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Parcel heat budget for calculating WBT:

$$c_p T + L \cdot RH \cdot q^*(T) = c_p T_W + L q^*(T_W)$$

$$\left(q(T) = RH \cdot q^*(T)\right)$$

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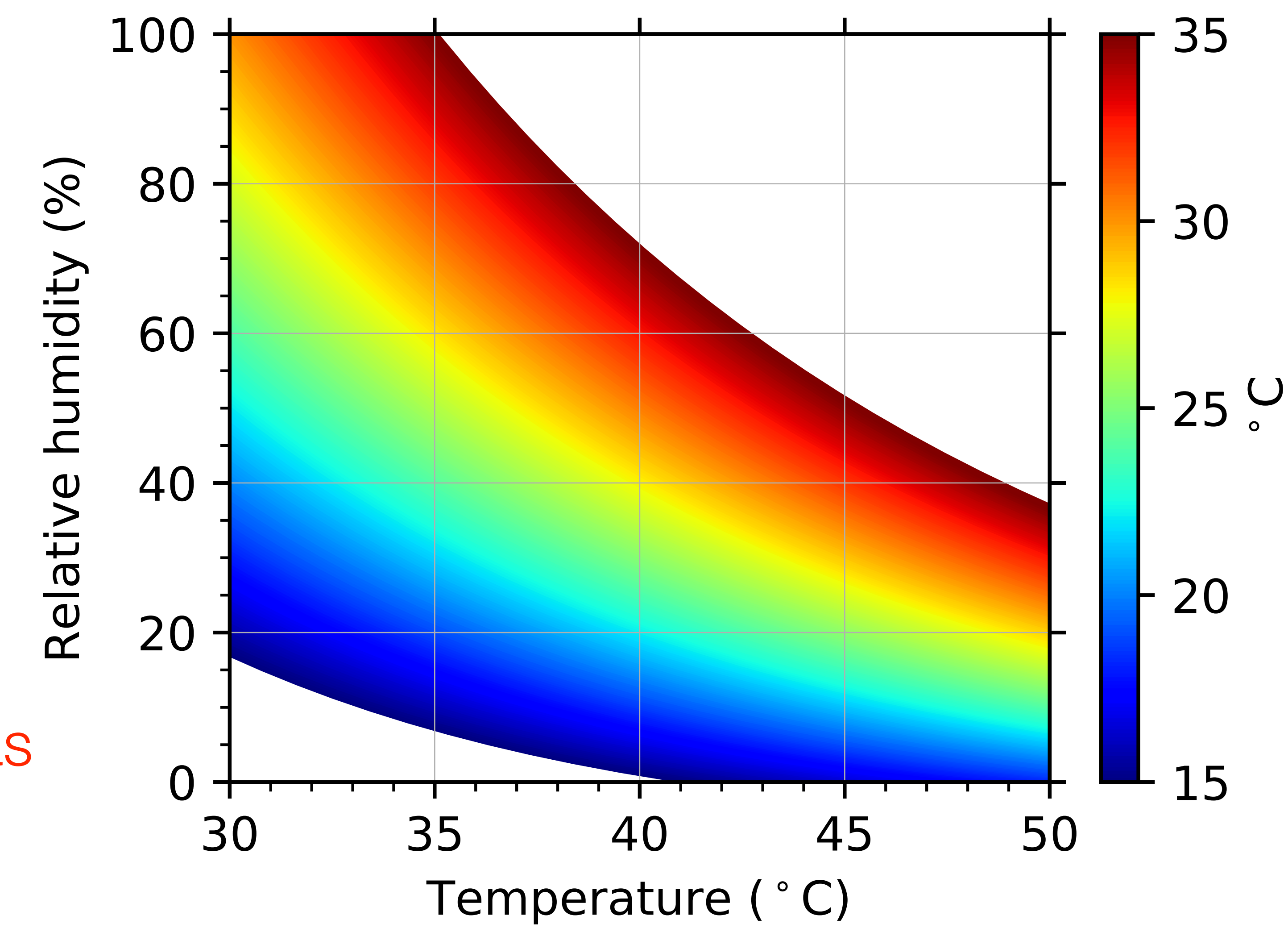


Figure 13.2: Wet bulb temperature (°C) as function of temperature and relative humidity. Figure after Sherwood (2018).

Workshops #2a

Heat stress and wet bulb temperature.

[Leave 2b for HW]

Understanding statistics of future heat wave projections

"Without human-caused climate change temperatures of 40 °C in the UK would have been extremely unlikely"

"Human-caused climate change made the event at least 10 times more likely."

"The same event would be about 2 °C less hot in a 1.2 °C cooler world"

https://www.worldweatherattribution.org/wp-content/uploads/UK-heat-scientific-report.pdf

Future projections, heat wave statistics

Great plains example in a climate model:

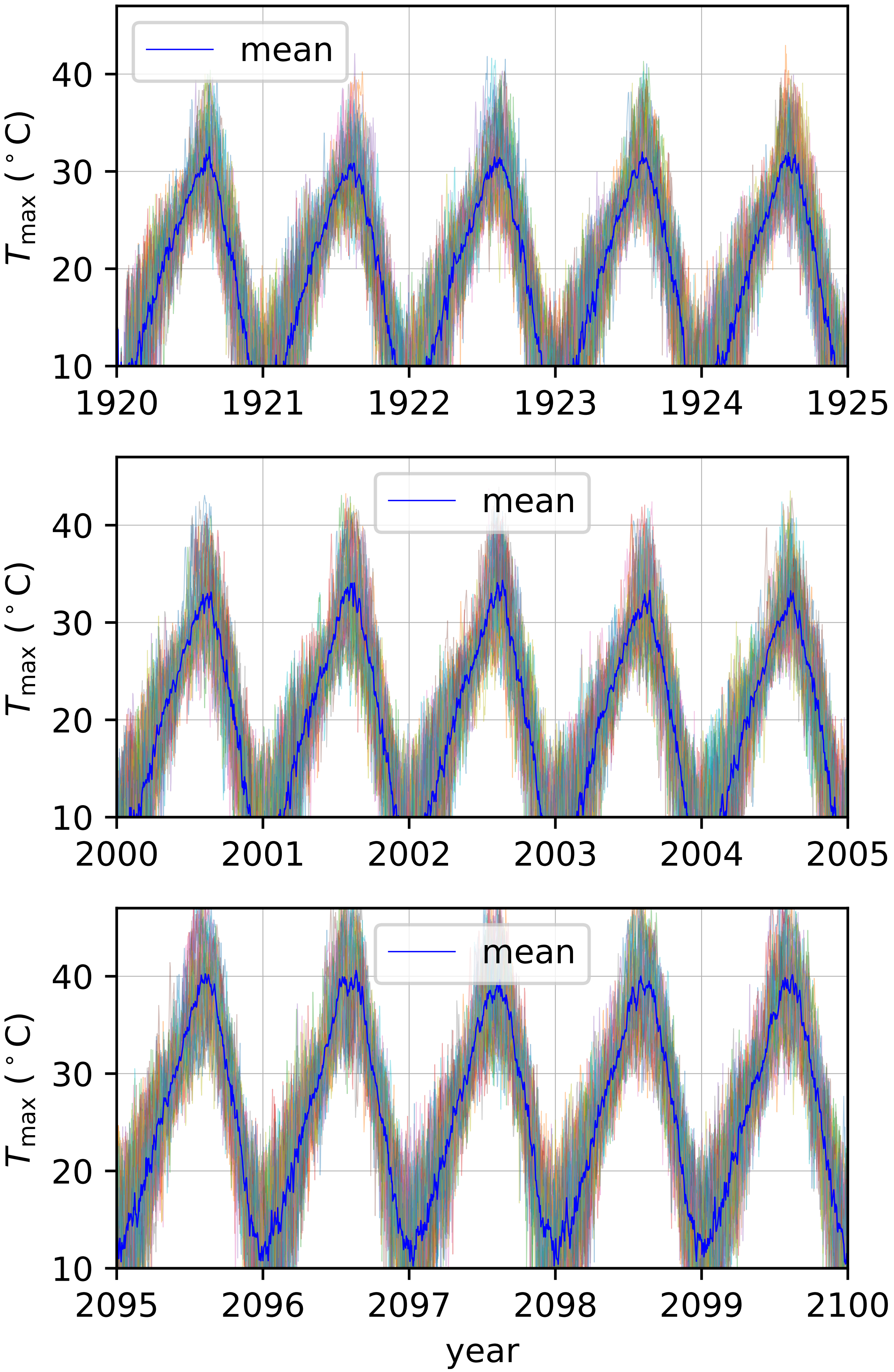
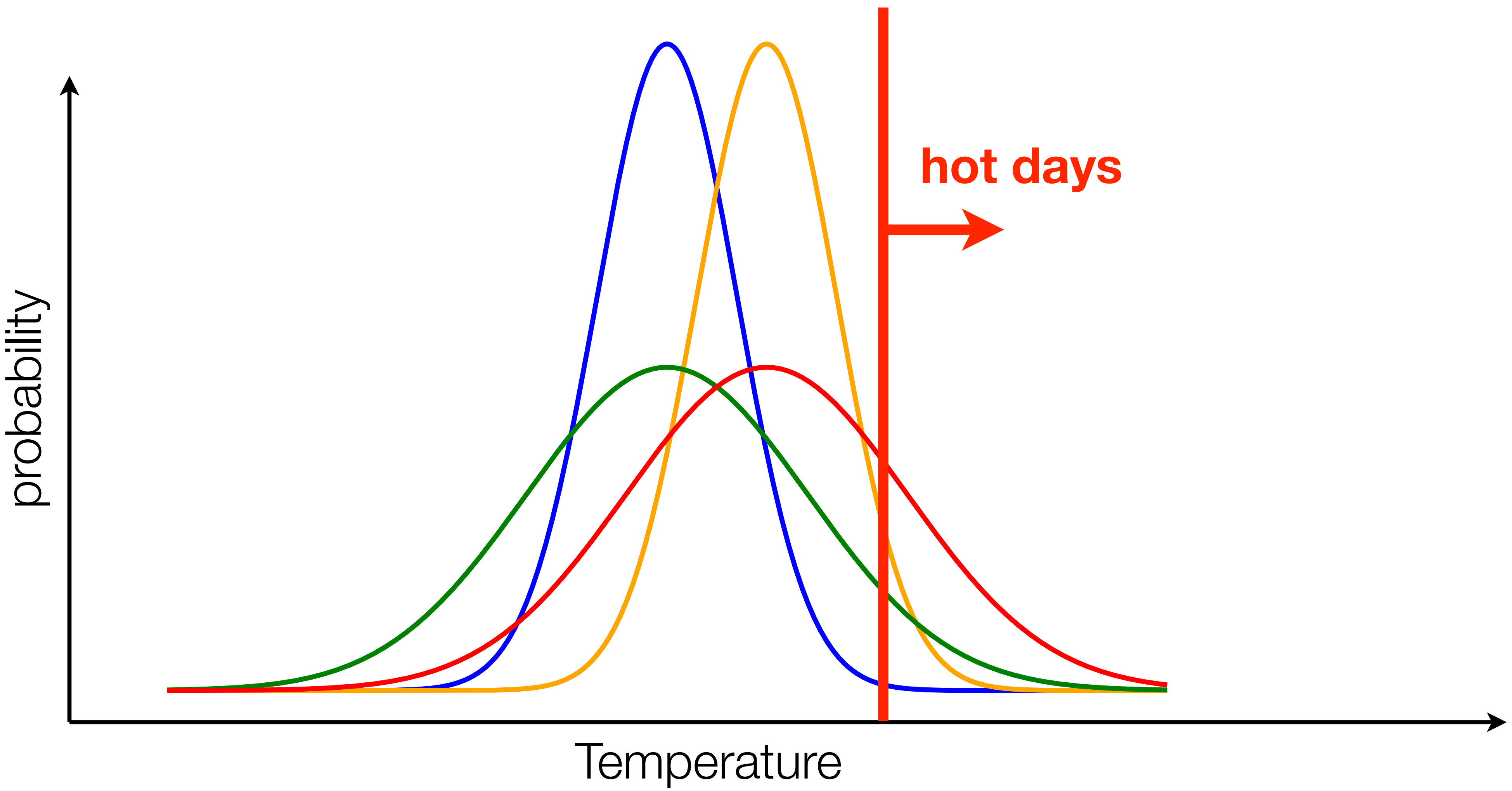


Figure 13.3: Maximum daily surface temperature over the great plains. *Shown:* results of 30 ensemble model runs 1920-2100, using observed greenhouse gas forcing until 2005, followed by RCP8.5 until 2100. Ensemble mean is shown in blue.

Very few cases of going over a threshold of 40 °C in the 1920s, vs persistent summer temperatures above this threshold toward 2100.

Understanding statistics of future heat wave projections

Heat waves are weather events occurring due to a combination of random (chaotic) circumstances/initial conditions. Their amplitude, duration, number of events per year, etc, can change in a warmer climate because the weather dynamics are different, or simply because the mean temperature is expected to be warmer. For example, there may be a shift from **blue** (preindustrial) to **orange** or to green **green** (or both, **red**). All options involve more hot days:



So which scenario will it be? How does one tell?

Understanding statistics of future heat wave projections

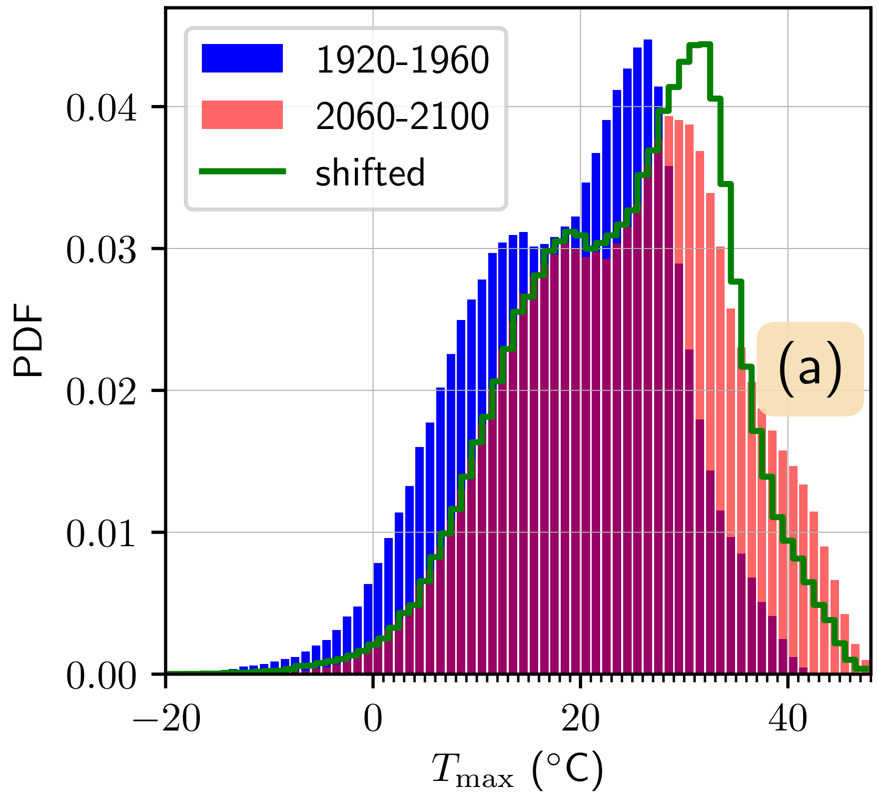


Figure 13.5: Comparing preindustrial and RCP8.5 heat wave statistics.

(a) A probability distribution function for simulated daily maximum temperature for 1920–1960 over great plains region, and for 2060–2100 in an RCP8.5 warming scenario.

PDFs for 1920–1960 are in blue, for projected 2060–2100 in red. Green: PDFs calculated from 1920–1960 time series of daily maximum temperatures, with an added constant temperature equal to the mean difference between 1920–1960 & 2060–2100.

Understanding statistics of future heat wave projections

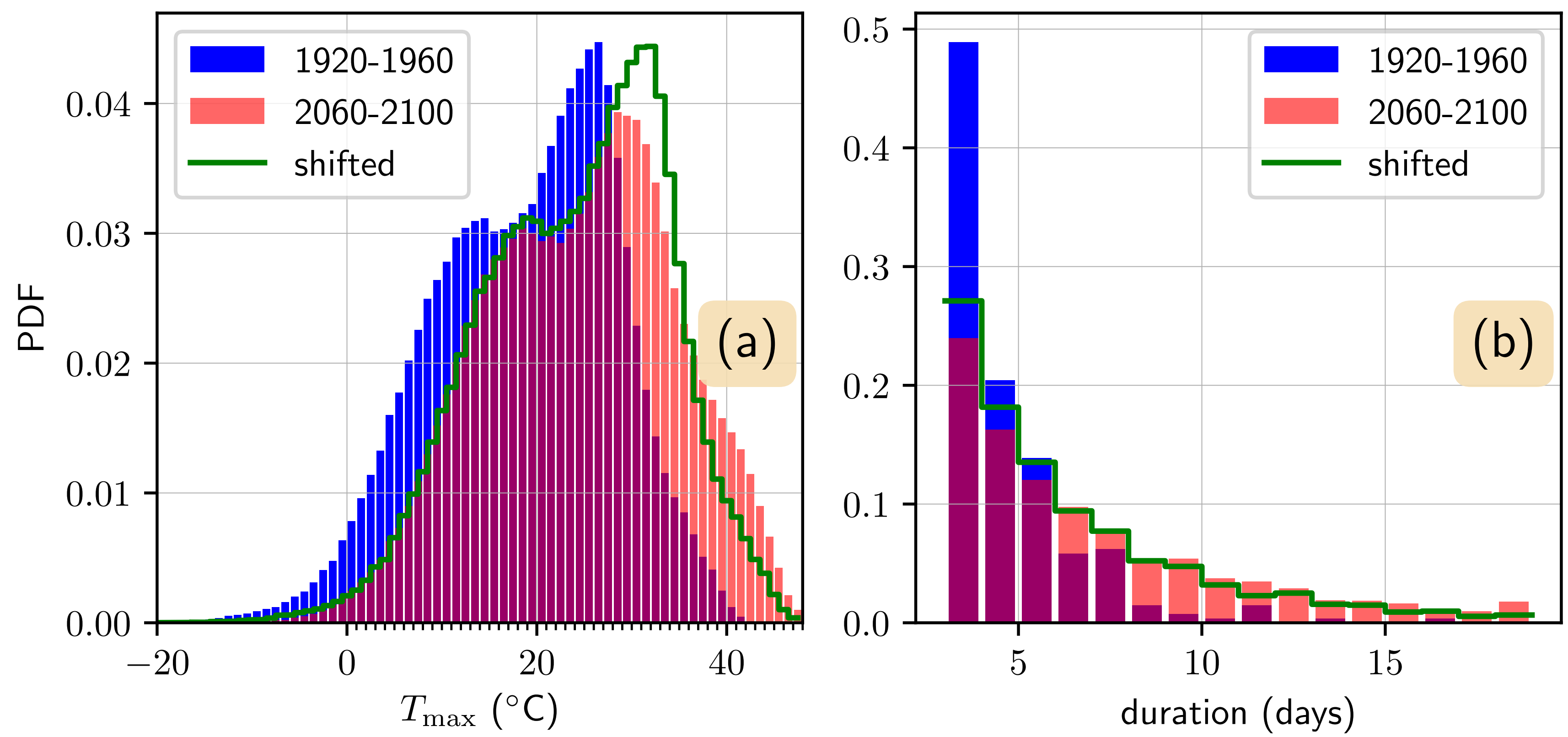


Figure 13.5: Comparing preindustrial and RCP8.5 heat wave statistics.

(a) A probability distribution function for simulated daily maximum temperature for 1920–1960 over great plains region, and for 2060–2100 in an RCP8.5 warming scenario.

(b) Probability distribution function for heat wave duration.

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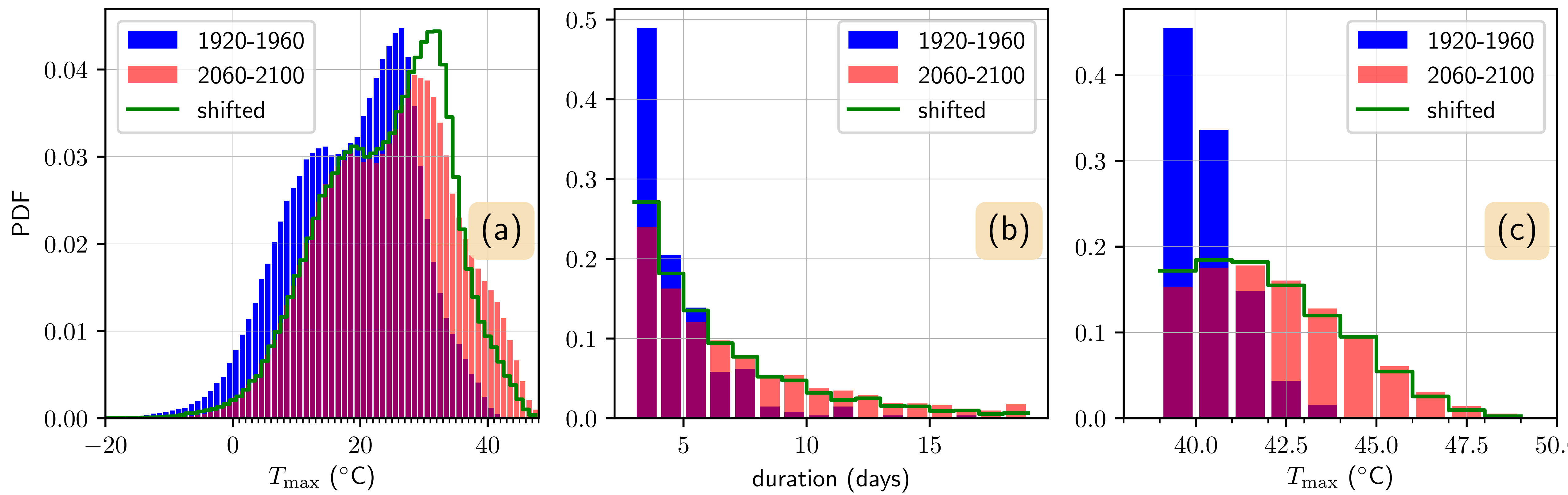
Understanding statistics of future heat wave projections



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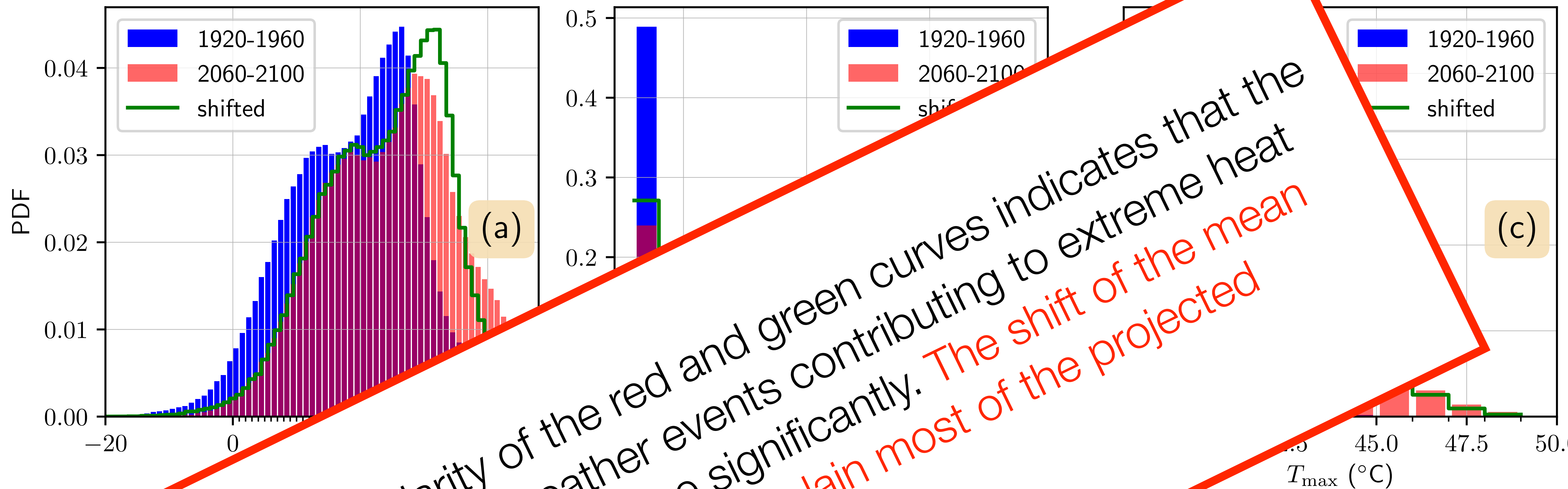
(a) A probability distribution function for simulated daily maximum temperature for 1920–1960 over great plains region, and for 2060–2100 in an RCP8.5 warming scenario.

(b) Probability distribution function for heat wave duration.

(c) PDF for average daily maximum temperature during heat wave events.

PDFs for 1920–1960 are in blue, for projected 2060–2100 in red. Green: PDFs calculated from 1920–1960 time series of daily maximum temperatures, with an added constant temperature equal to the mean difference between 1920–1960 & 2060–2100.

Understanding statistics of future heat wave projections



The similarity of the red and green curves indicates that the dynamics of weather events contributing to extreme heat waves did not change significantly. The shift of the mean temperature alone can explain most of the projected changes to heat wave statistics.

Figure 13.5: Co… …eat wave statistics.

(a) A probability d… …ated daily maximum temperature for 1920–1960 over great plains r… …2100 in an RCP8.5 warming scenario.

(b) Probability distrib… …n for heat wave duration.

(c) PDF for average d… maximum temperature during heat wave events.

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Projected change to extreme event statistics

"Heat wave that occurred over XX is now 100 times more likely due to climate change"

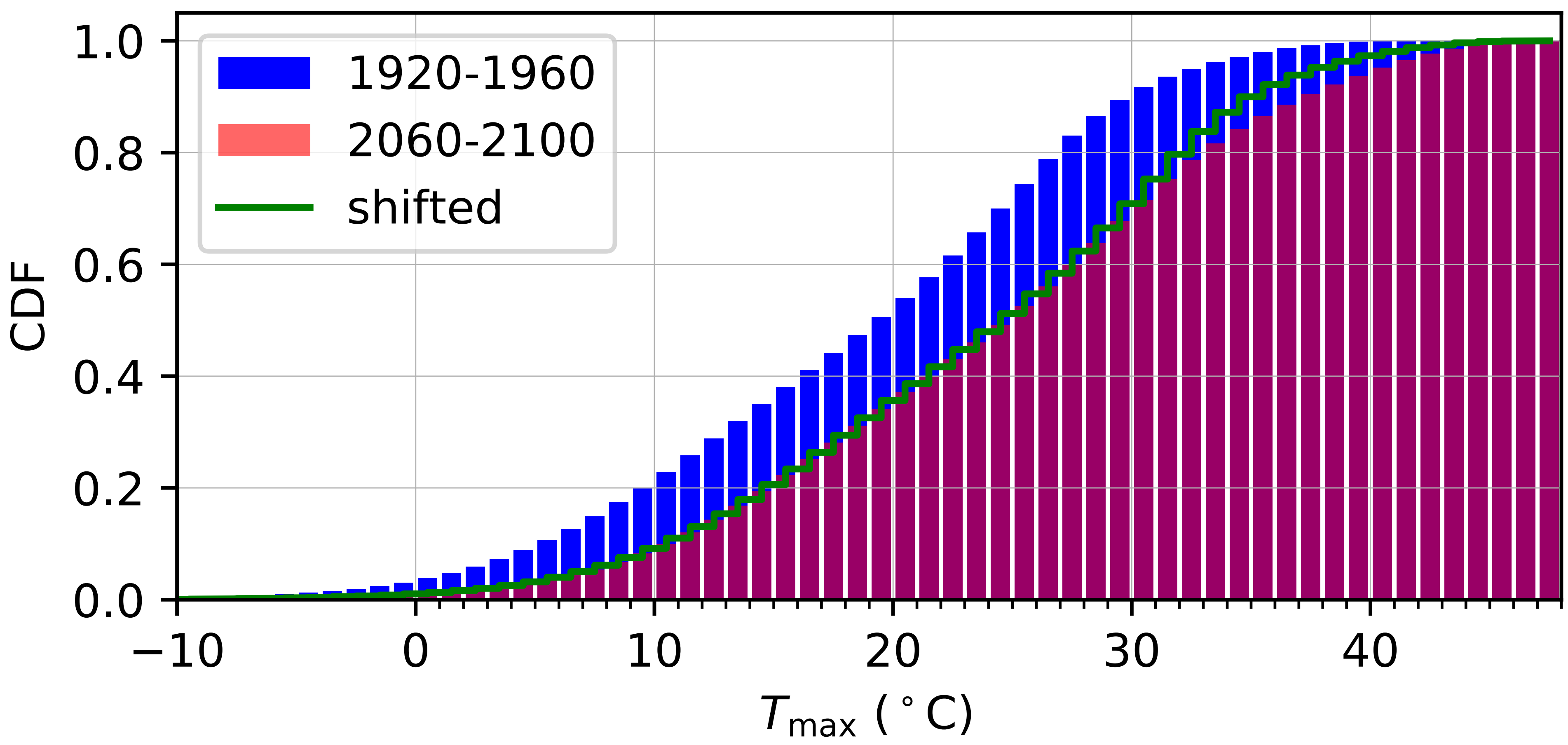

Figure 13.6: The cumulative probability distribution function for the simulated daily maximum temperatures for the period 1920–1960 (blue), and for 2060–2100 in an RCP8.5 warming scenario (red) over the great plains region marked by white rectangles in Figure 13.1. The CDF shown by the green line is calculated as in Figure 13.5.

Projected change to extreme event statistics

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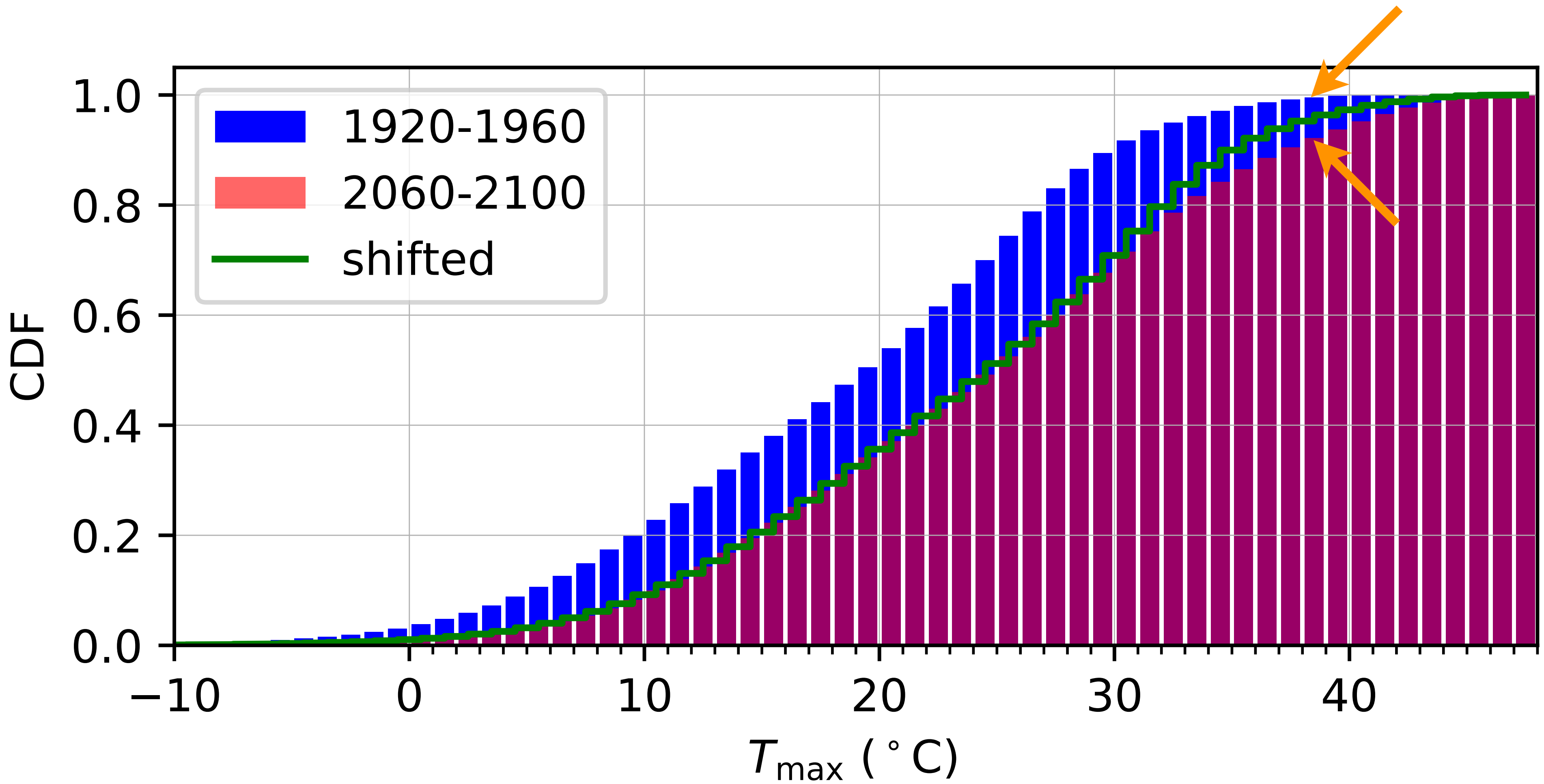

An event that was warmer than 99.9% of days is now warmer only more than 95% and therefore much more likely to happen.

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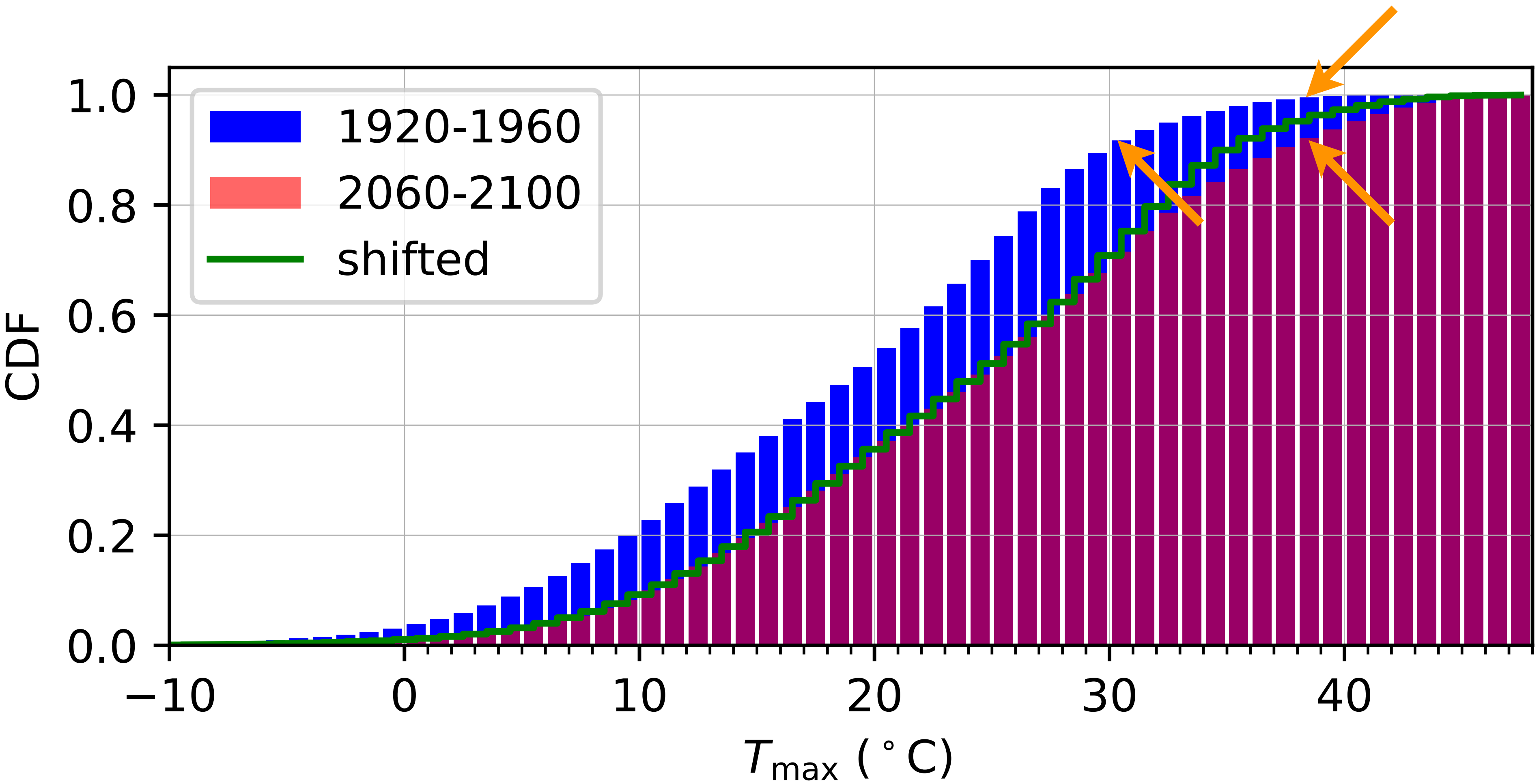


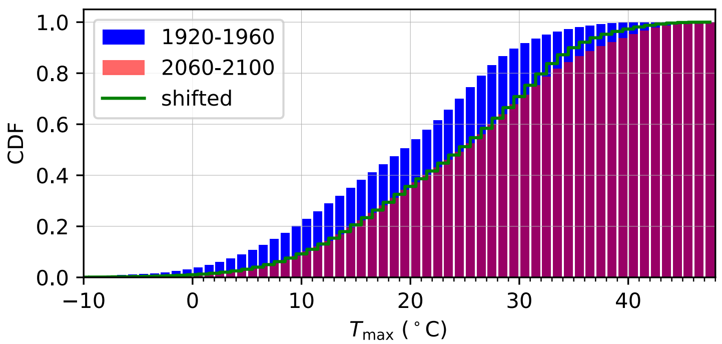
An event that was warmer than 99.9% of days is now warmer only more than 95% and therefore much more likely to happen.

On the other hand, if the mean warming is 7 °C, this event is as likely to occur as an event that is 7 °C colder was likely to happen before the warming.

Figure 13.6: The cumulative probability distribution function for the simulated daily maximum temperatures for the period 1920–1960 (blue), and for 2060–2100 in an RCP8.5 warming scenario (red) over the great plains region marked by white rectangles in Figure 13.1. The CDF shown by the green line is calculated as in Figure 13.5.

Understanding statistics of future heat wave projections I

"The heat wave that just occurred is now 10 times more likely due to climate change"

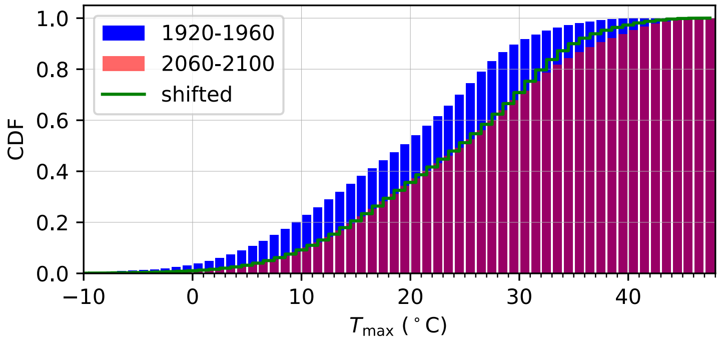


Blue $CDF(T)$ is the probability that the daily maximum temperature was less than T during 1920–1960. A value of **0.9999** means that the daily maximum temperature was above that range during 0.01% of the days. This means an event that exceeds T occurred (365*10)*0.0001=0.365 days in a decade, which implies a return time of 10/0.365=27.4 years, which is the average wait time between such events.

IPCC AR6 Ch 11: "Changes in extremes have been examined from two perspectives: changes in the frequency for a given magnitude of extremes; or changes in the magnitude for a particular return period (frequency)."

Understanding statistics of future heat wave projections I

"The heat wave that just occurred is now 10 times more likely due to climate change"



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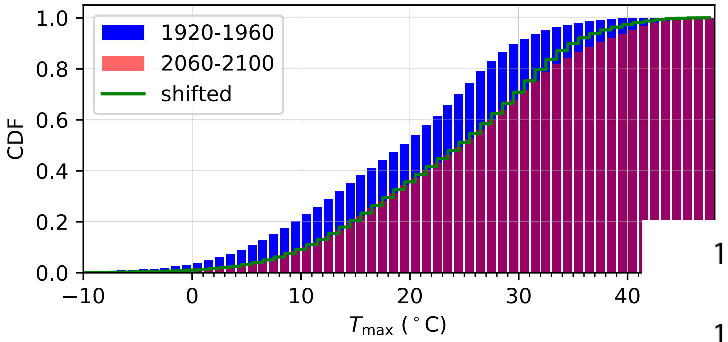
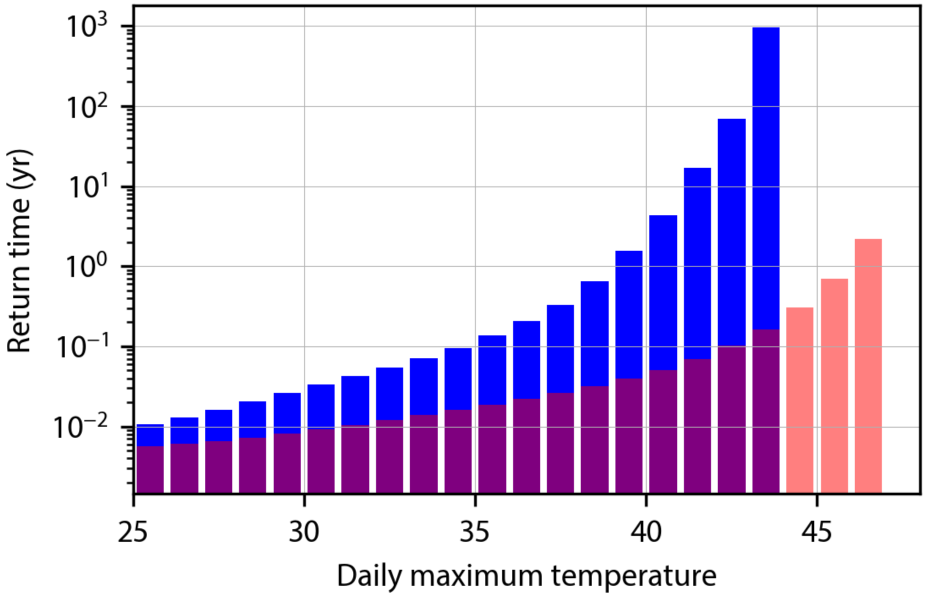
Suppose the red CDF, for 2060–2100 for the same T, is **0.999**. This would imply a return time of 2.74 years. A heat wave exceeding T would then become 10 times more likely to happen.

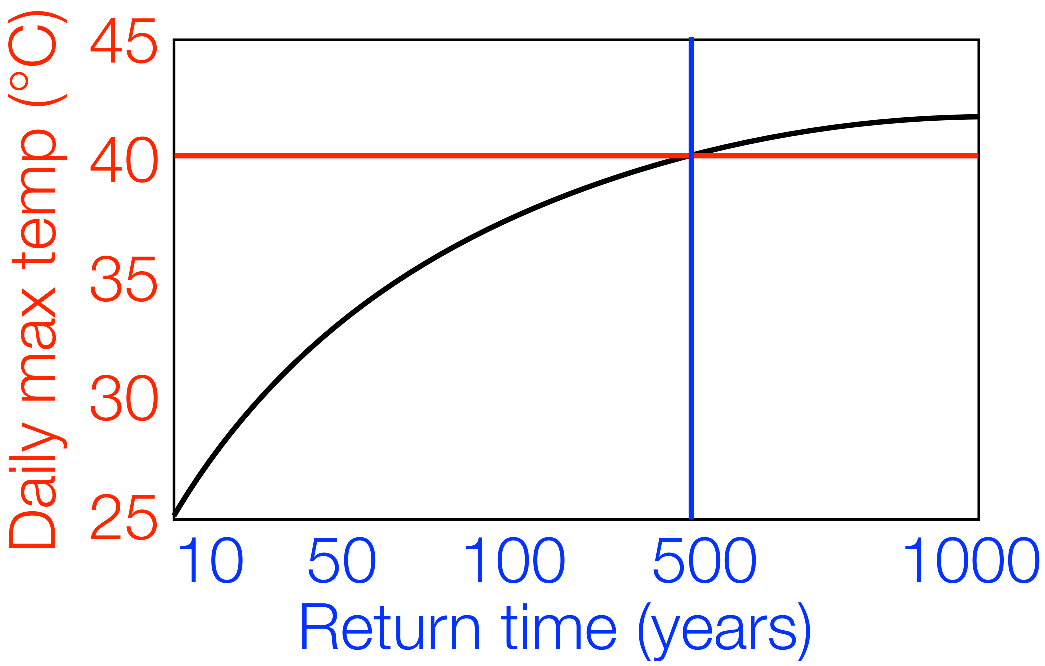
IPCC AR6 Ch 11: "Changes in extremes have been examined from two perspectives: changes in the frequency for a given magnitude of extremes; or changes in the magnitude for a particular return period (frequency)."

Understanding statistics of future heat wave projections I

"The heat wave that just occurred is now 10 times more likely due to climate change"







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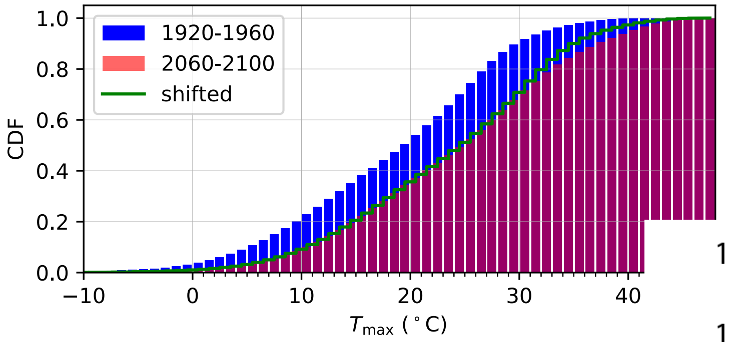
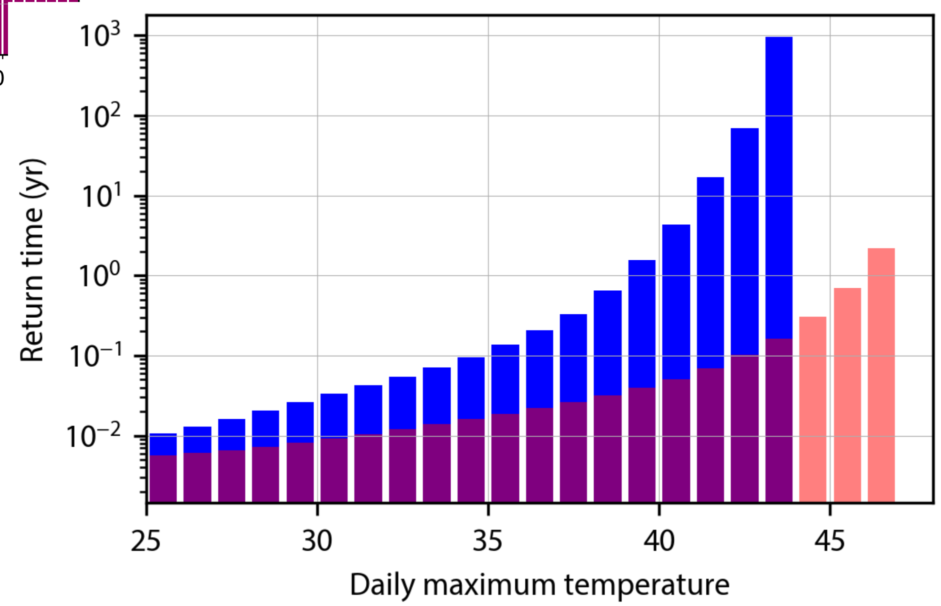
Suppose the red CDF, for 2060–2100 for the same T, is **0.999**. This would imply a return time of 2.74 years. A heat wave exceeding T would then become 10 times more likely to happen.

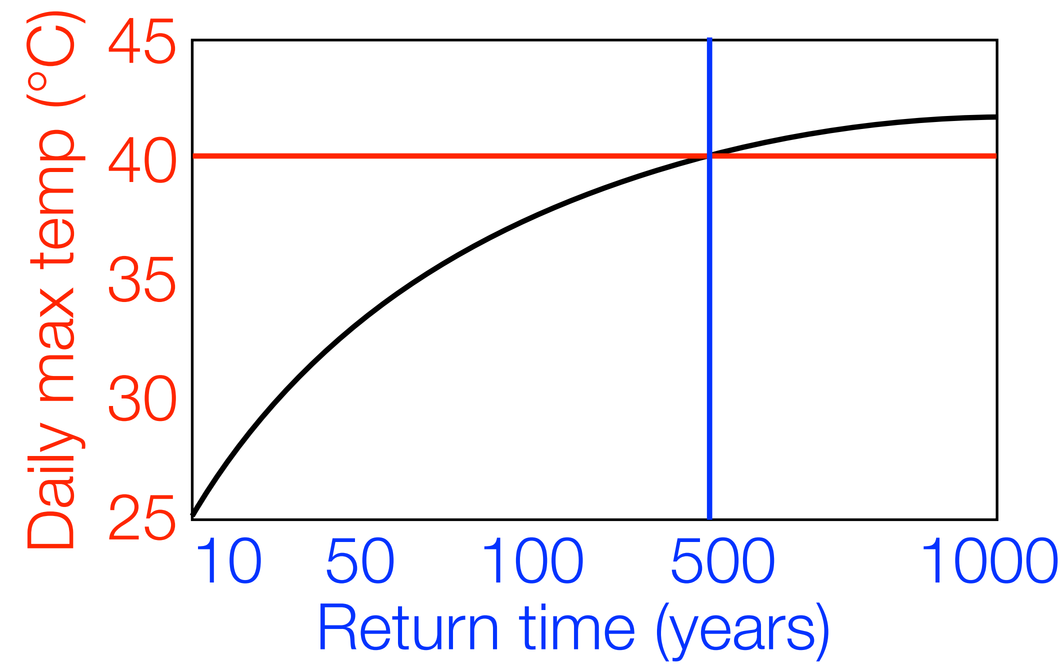
IPCC AR6 Ch 11: "Changes in extremes have been examined from two perspectives: changes in the frequency for a given magnitude of extremes; or changes in the magnitude for a particular return period (frequency)."

Understanding statistics of future heat wave projections II

"A heat wave that occurs every 10 years is now 2 degrees warmer than it used to be"







Blue $CDF(T)$ is the probability that the daily maximum temperature was less than T during 1920–1960. Suppose the CDF is 0.9999 for $T = 42$ °C. this means that the temperature exceeds this temperature every 27.4 years, which is the average wait time between such events.

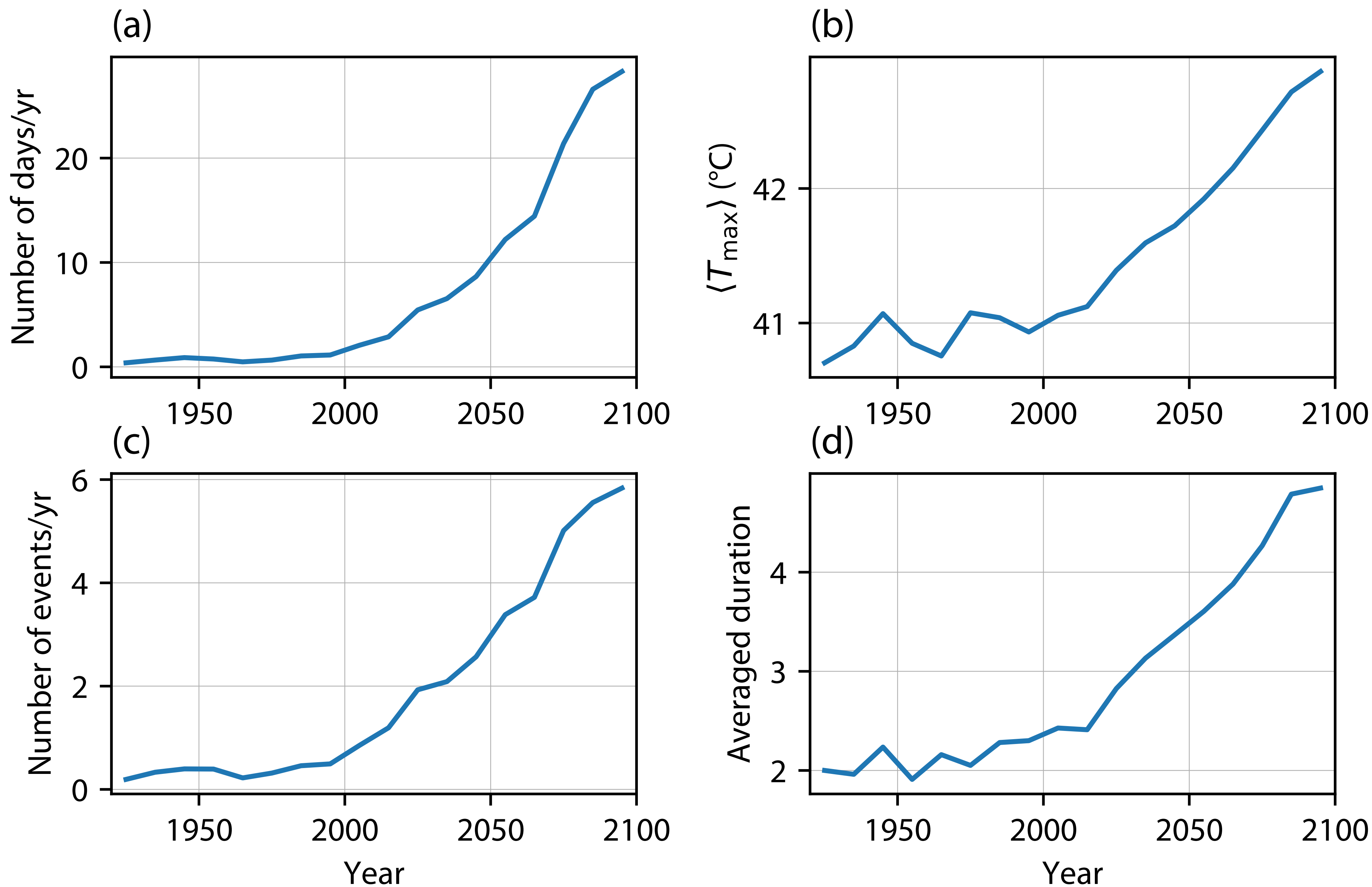
Suppose the red CDF for 2060–2100 has the same value of 0.9999 for $T = 45$ °C. This implies that an event with a return time of 2.74 years is projected to be 3 °C warmer than it used to be.

IPCC AR6 Ch 11: "Changes in extremes have been examined from two perspectives: changes in the frequency for a given magnitude of extremes; or changes in the magnitude for a particular return period (frequency)."

Workshop #3

Understanding heat wave statistics for an RCP8.5 projection.

Future projections: decadal statistics time series



(great plains)

Figure 13.4: Time series of decadal statistics of heat waves over the great plains area analyzed in Figure 13.1 from 1920 to 2100. (a) Averaged number of heat wave days per year. (b) Averaged maximum daily temperature in a heat wave. (c) Averaged number of heat waves per year. (d) Averaged heat wave duration in days.

Workshop #4

Heat wave composite analysis in the region of your city of birth

Composite analysis: Heat waves over central plains

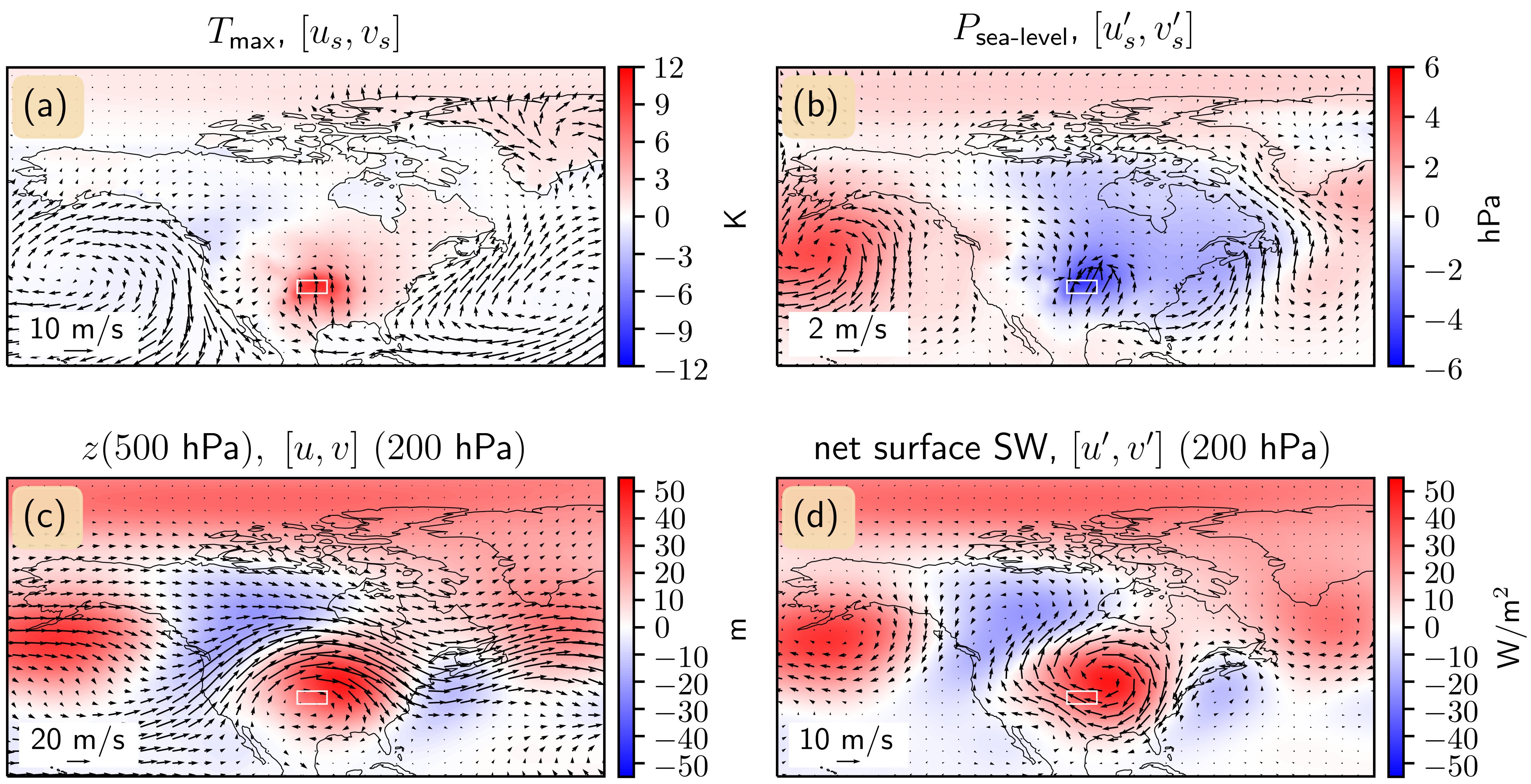


Figure 13.1: Heat waves in a climate model run, over latitudes 40 ≥ θ ≥ 37 and longitudes −95 ≥ ϕ ≥ −102, marked by white rectangles in the figures. Shown are averaged fields over periods corresponding to heat waves (that is, heat wave composites) where a heat wave is defined as the daily maximum temperature being above 39°C for at least 3 days. (a) Maximum daily surface temperature (T_{max}) anomaly (deviation from the August mean) and surface winds. (b) Sea-level pressure anomaly and surface wind anomalies. (c) Geopotential height anomaly at 500 hPa and winds at 200 hPa. (d) Net surface short wave radiation anomaly and anomaly winds at 200 hPa. Note that panels a,c show the surface and 200 hPa wind fields averaged over heat wave events, while b,d show the deviation of these wind fields from their August means.

Workshop #5

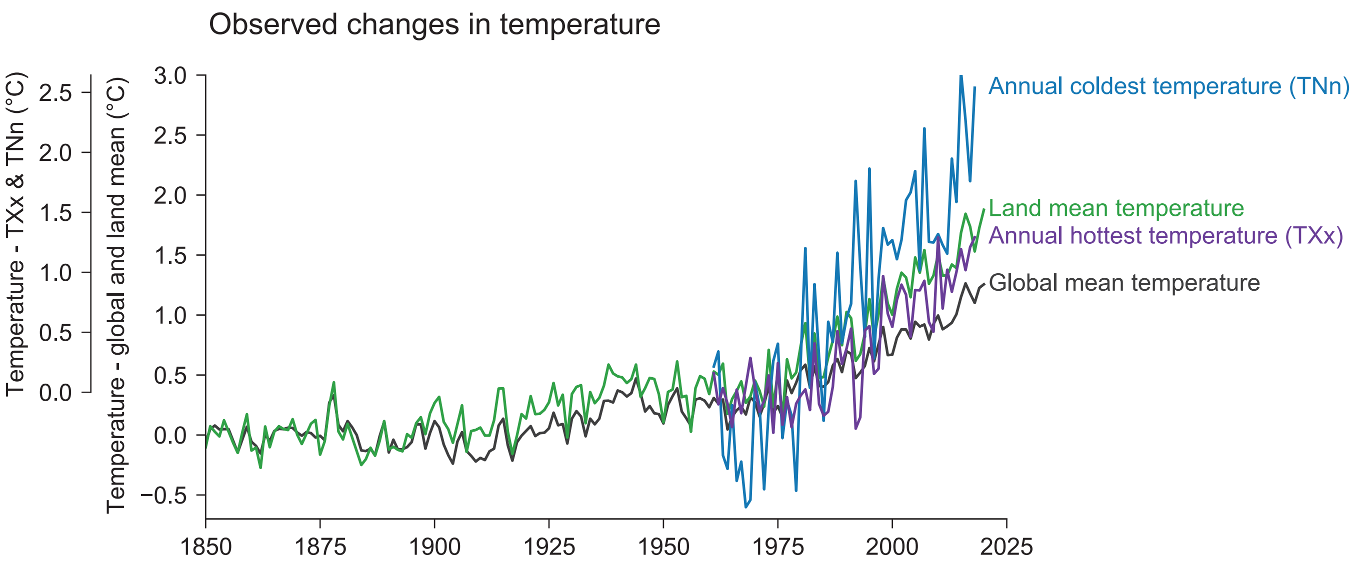
Decadal time series of the heatwave statistics

Observations and projections of heat waves

It is *virtually certain* that … heatwaves have become more frequent and intense across most land regions since the 1950s … *high confidence* that human-induced climate change is the main driver.

Figure 11.2 | Observed global average annual mean temperature anomalies (black), land average annual mean (green), land average annual hottest daily maximum (TXx, purple), and land average annual coldest daily minimum (TNn, blue).

Global and land mean anomalies are relative to 1850–1900. TXx and TNn are relative to 1961–1990.



IPCC AR6 2022

Observations and projections of heat waves

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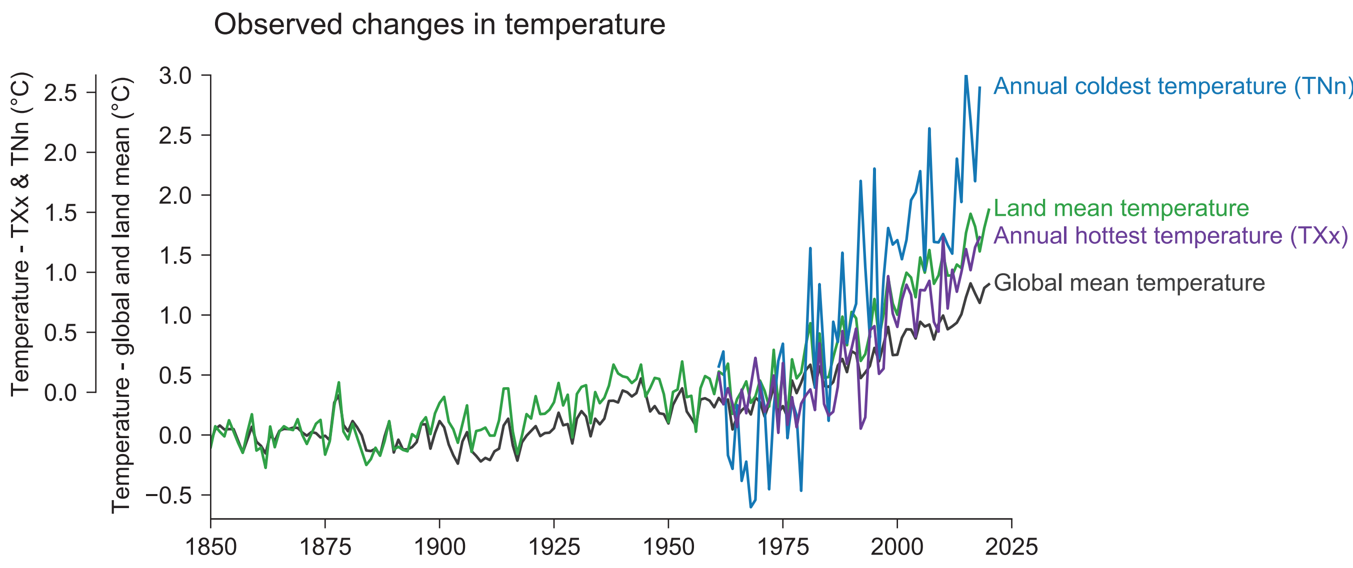

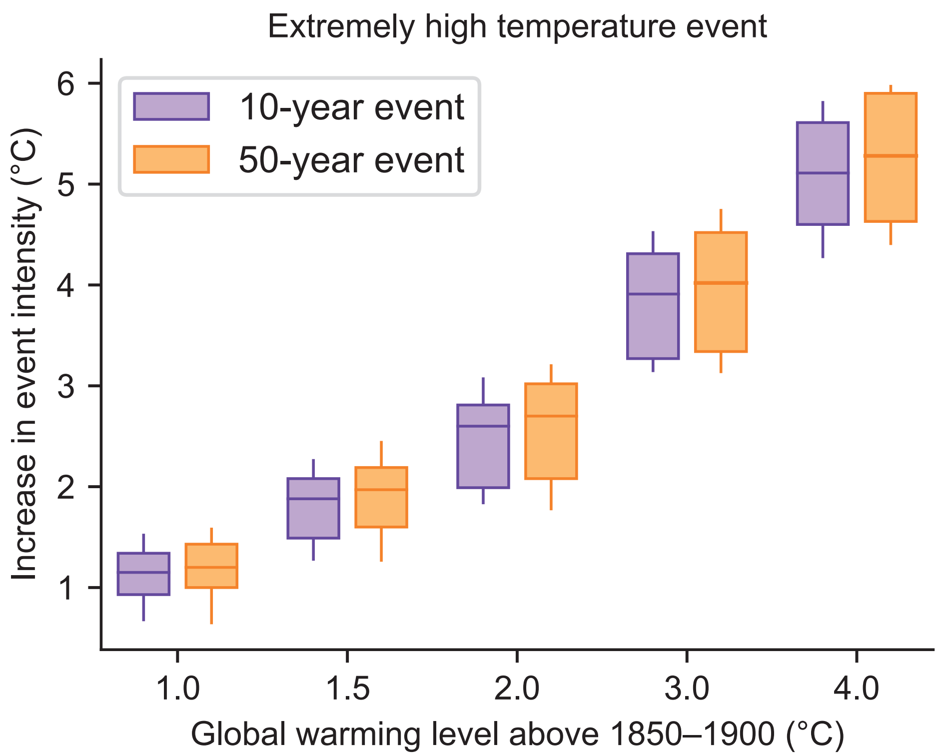

Figure 11.12 | Projected changes in extreme temperature events under different global warming levels relative to 1850–1900.

Extreme temperature events are defined as the daily maximum temperatures (TXx) that were exceeded on average once during a 10-year period (10-year event, blue) and a 50-year period (orange) during 1850–1900. Shown for global land. The horizontal line and box represent the median and central 66% uncertainty range across the multi-model CMIP6 ensemble; 'whiskers' indicate 90% range.

IPCC AR6 2022

Observations and projections of heat waves

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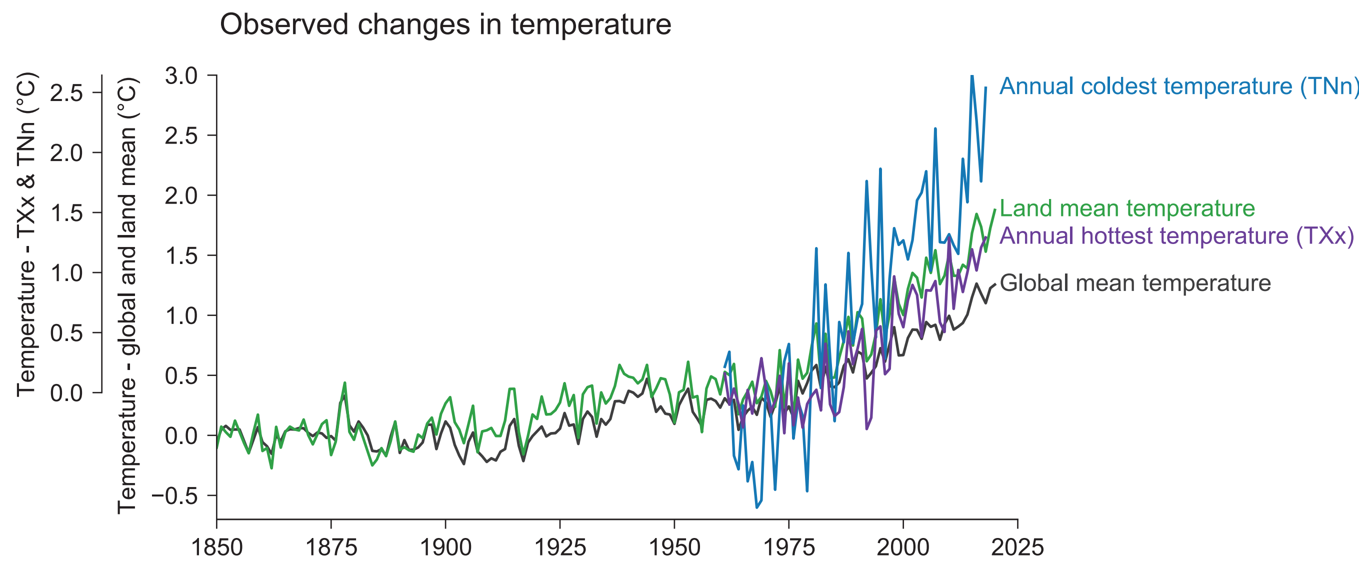


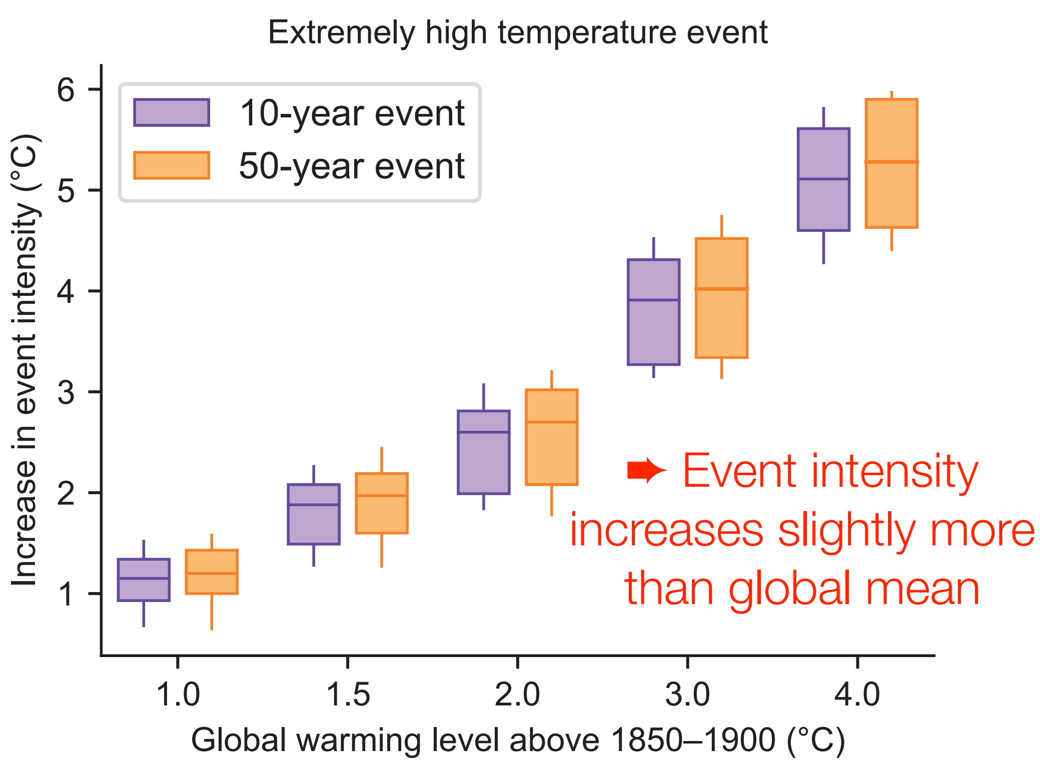


Figure 11.12 | Projected changes in extreme temperature events under different global warming levels relative to 1850–1900.

Extreme temperature events are defined as the daily maximum temperatures (TXx) that were exceeded on average once during a 10-year period (10-year event, blue) and a 50-year period (orange) during 1850–1900. Shown for global land. The horizontal line and box represent the median and central 66% uncertainty range across the multi-model CMIP6 ensemble; 'whiskers' indicate 90% range.

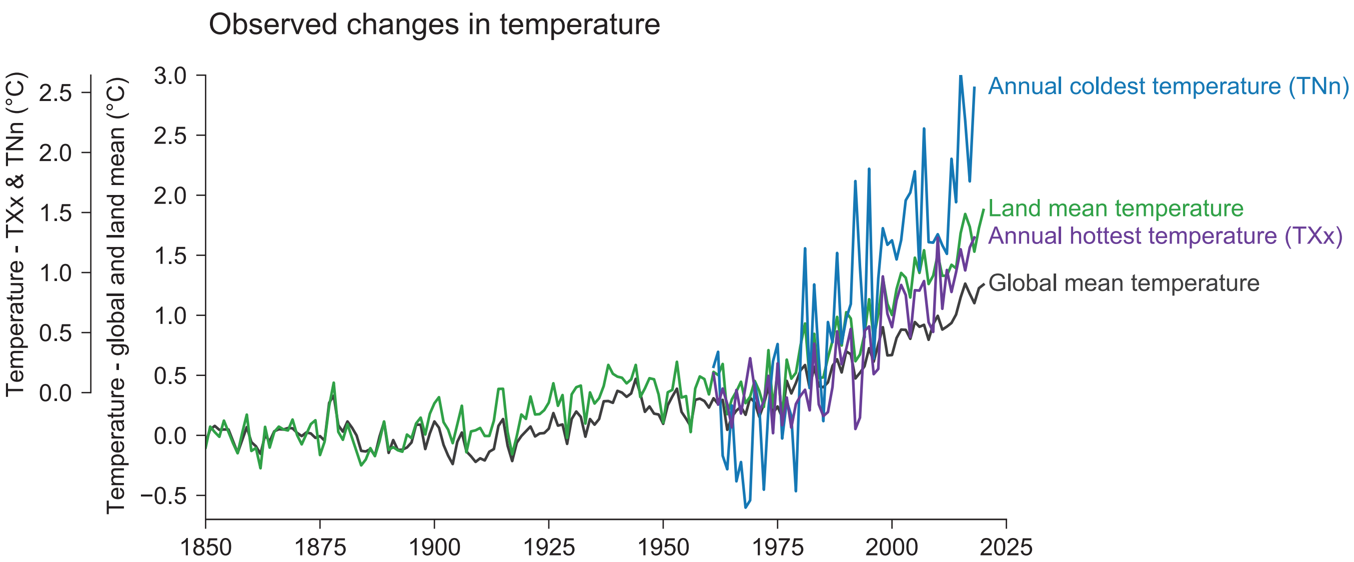
IPCC AR6 2022

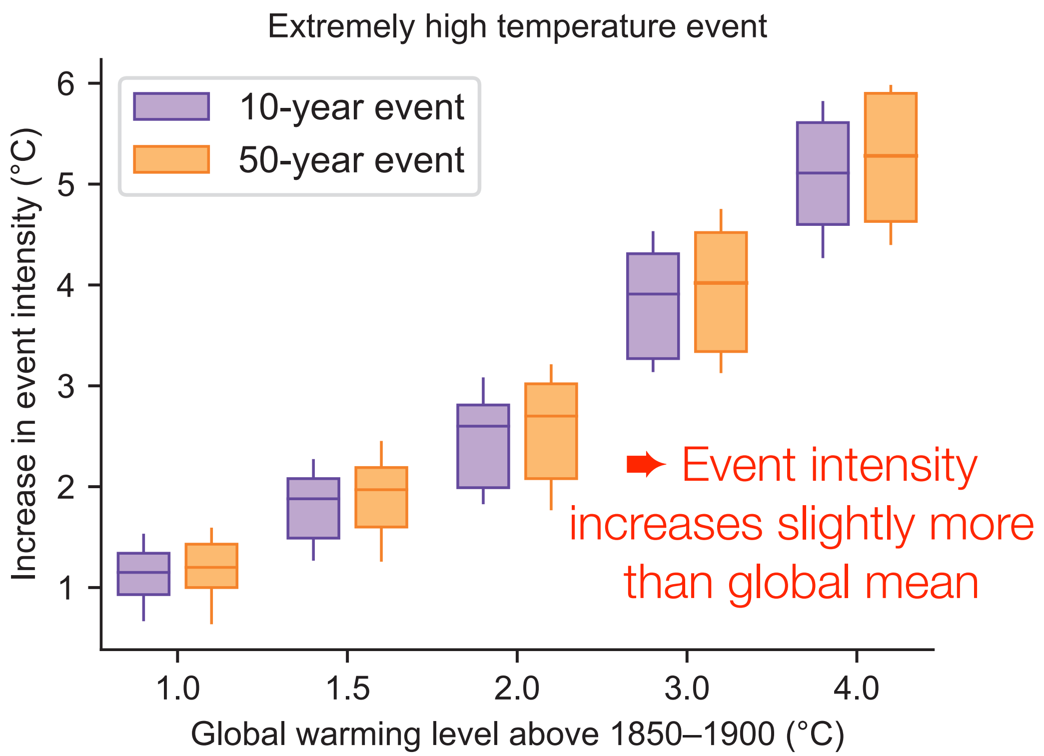
Observations and projections of heat waves

It is *virtually certain* that … heatwaves have become more frequent and intense across most land regions since the 1950s … *high confidence* that human-induced climate change is the main driver.

Figure 11.2 | Observed global average annual mean temperature anomalies (black), land average annual mean (green), land average annual hottest daily maximum (TXx, purple), and land average annual coldest daily minimum (TNn, blue).

Global and land mean anomalies are relative to 1850–1900. TXx and TNn are relative to 1961–1990.





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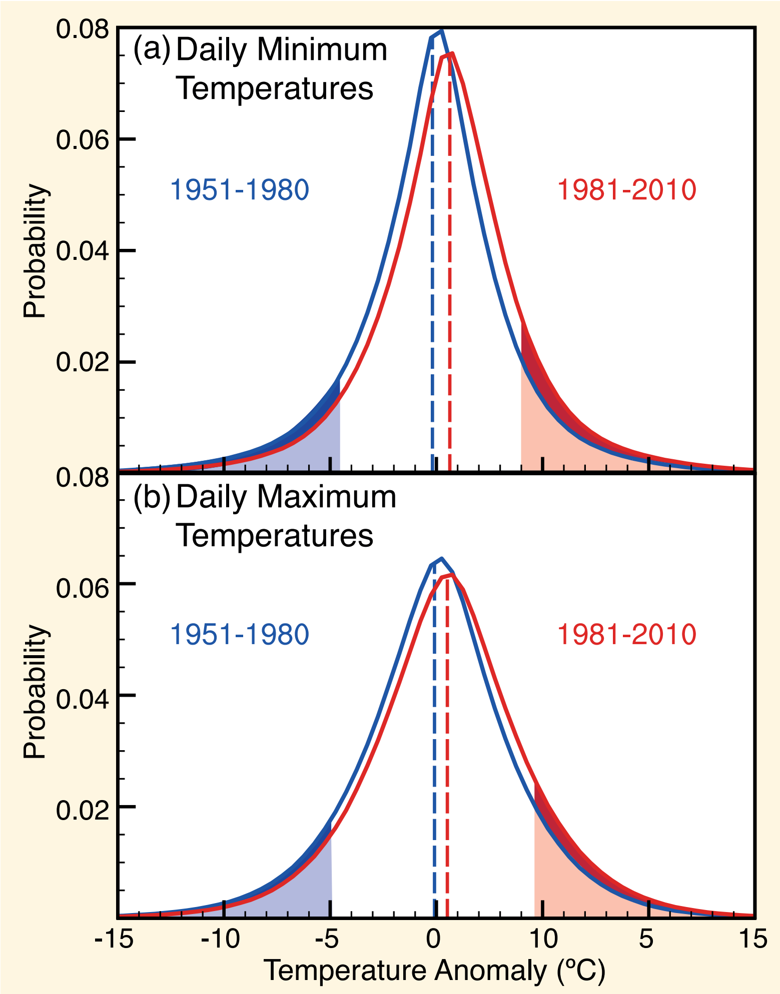
IPCC AR6 2022

"Future urbanization will amplify the projected air temperature change in cities regardless of the characteristics of the background climate, resulting in a warming signal on minimum temperatures that could be as large as the global warming signal (*very high confidence*)."

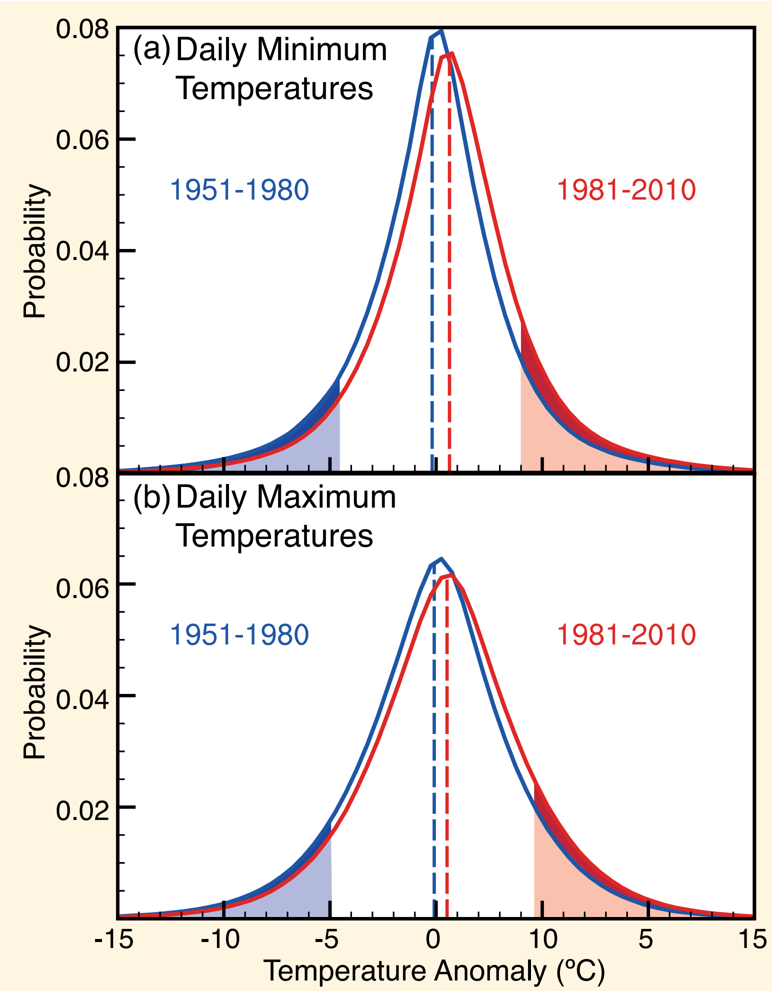
Observations and projections of heat waves



FAQ 2.2, Figure 1 | Distribution of (a) daily minimum and (b) daily maximum temperature anomalies relative to1961–1990 for: 1951–1980 (blue) & 1981–2010 (red). Shaded blue and red represent coldest 10% and warmest 10% of (a) nights & (b) days during 1951–1980. darker shading: by how much number of coldest days & nights has reduced (dark blue) and warmest days & nights increased (dark red) during 1981–2010 compared to 1951–1980.

IPCC AR5 2013

Observations and projections of heat waves



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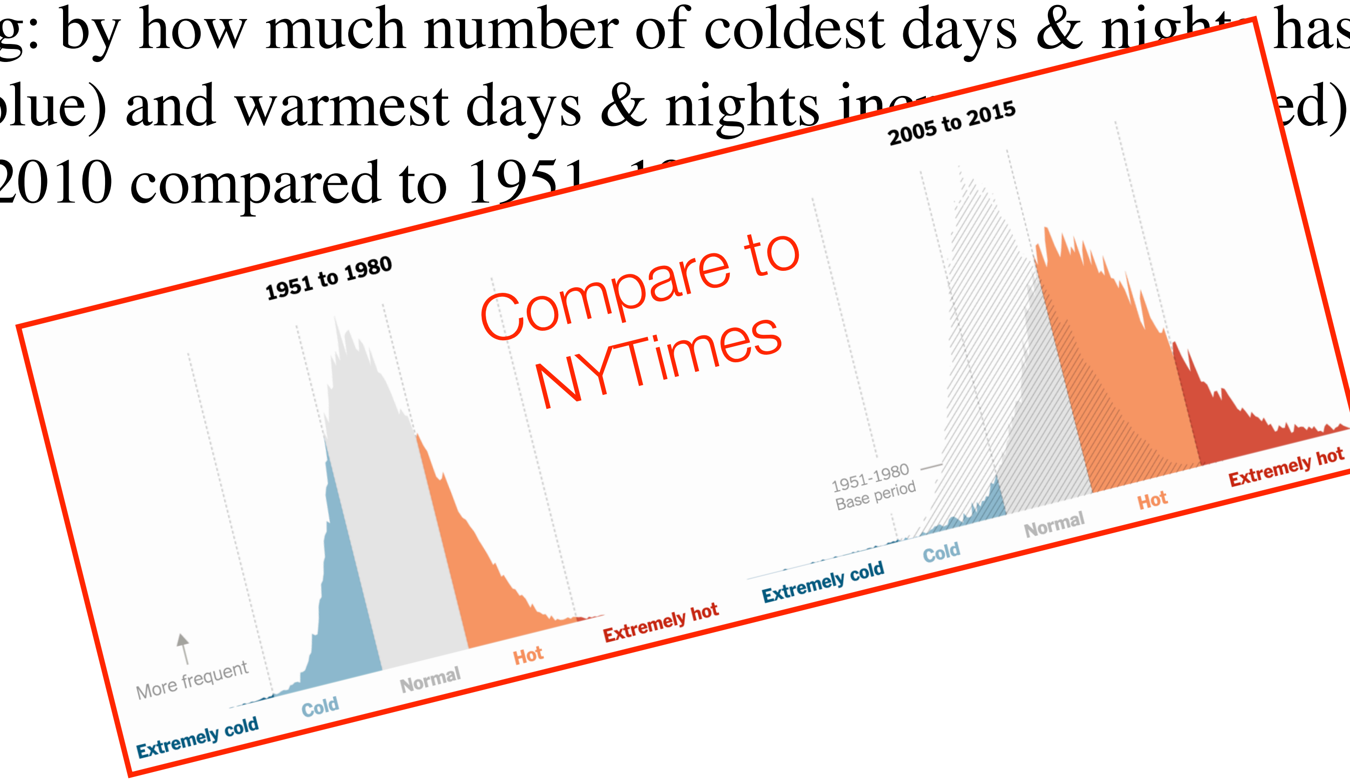

IPCC AR5 2013

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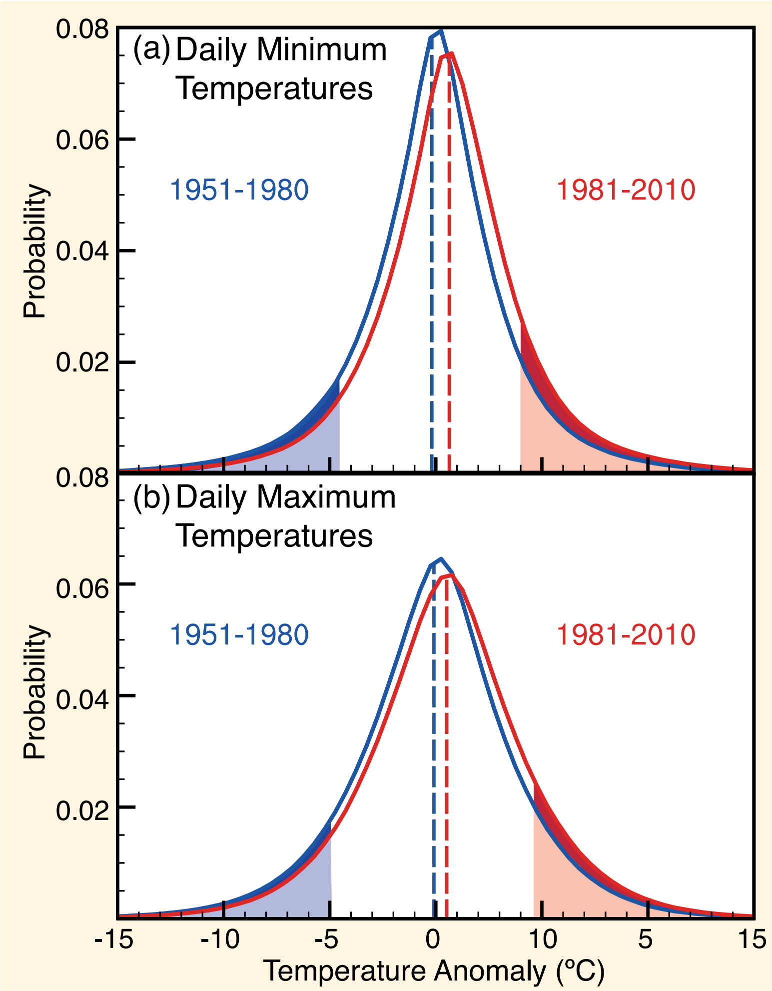

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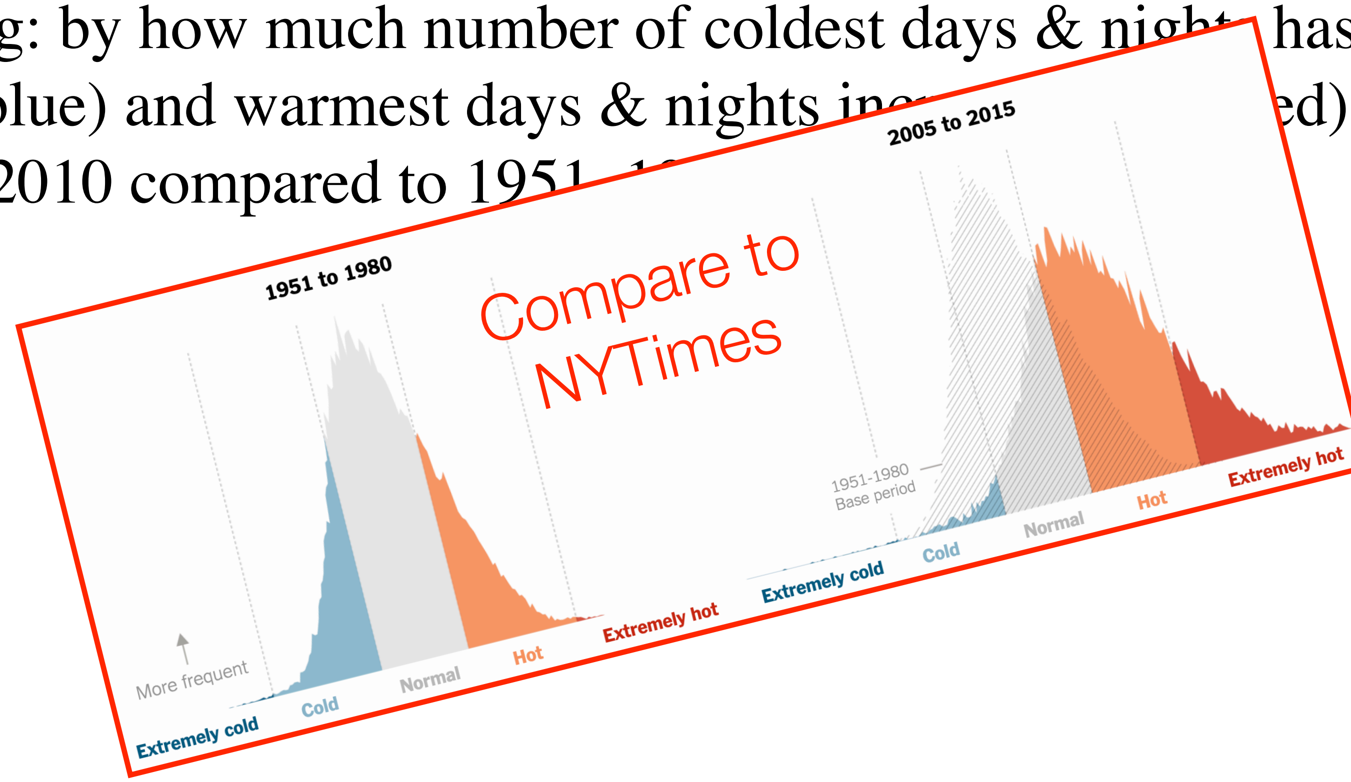

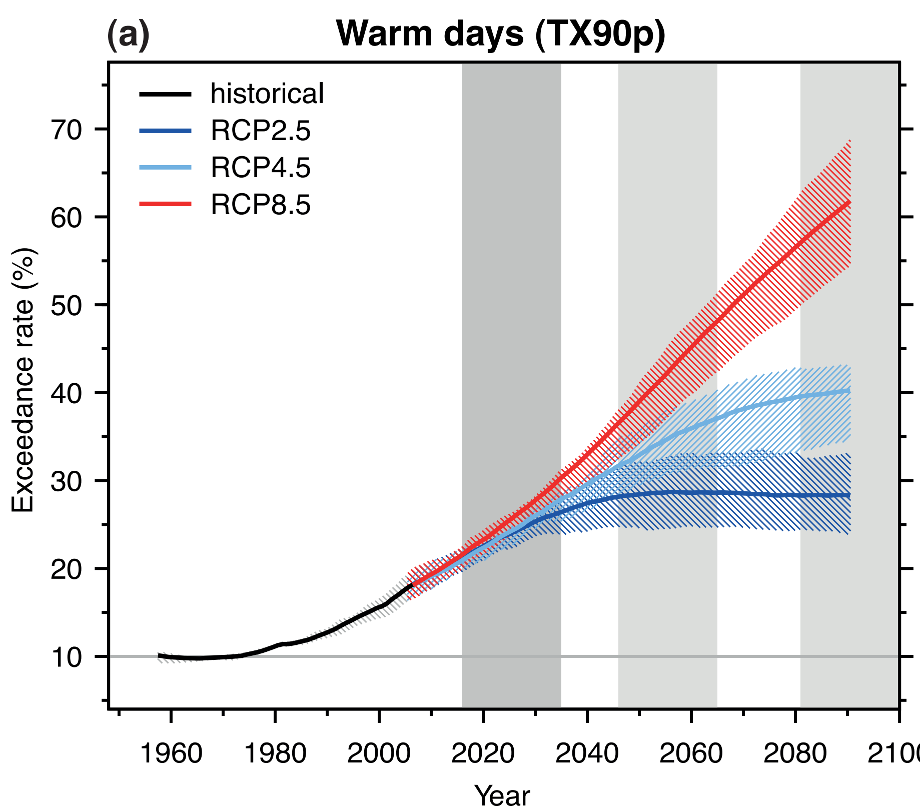

IPCC AR5 2013

Figure 11.17 | Global projections of occurrence of (a) warm days (TX90p), from RCP2.6, RCP4.5, RCP8.5. Solid lines: ensemble median, shading: 25-75th %). shown: % days/yr w/daily max surface air temp (T_{max}) exceeding 90th %tile for 1961–1990

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- **Heat stress and wet bulb temperature:** important role for humidity
- **Heat wave statistics** and how they might change in a future warming scenario: shift of mean vs change of variance.
- More heat waves expected in a warmer future climate, little uncertainty, esp if we believe model projections that statistics mostly change due to shift in mean.

The End