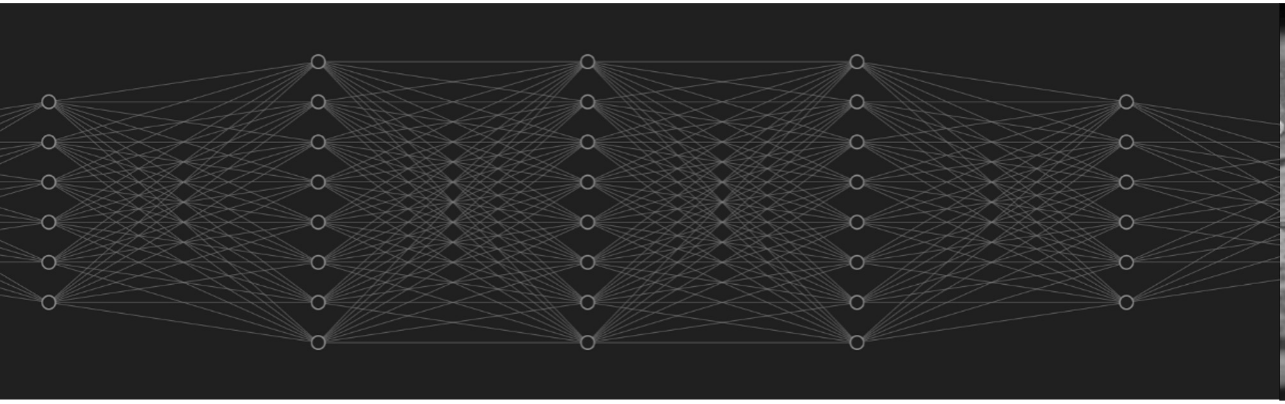
Understanding our Changing Climate with Physics and Machine Learning




Maria J. Molina, Assistant Professor, University of Maryland, College Park, MD

Who am I?

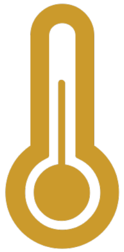
- **Assistant Professor** in Climate and Extremes Data Science.
  - Department of Atmospheric and Oceanic Science.
    - University of Maryland Institute for Advanced Computer Studies (UMIACS).

Who am I?

- **Assistant Professor** in Climate and Extremes Data Science.
    - Department of Atmospheric and Oceanic Science.
        - University of Maryland Institute for Advanced Computer Studies (UMIACS).
- Previously, served as a **Broadcast Meteorologist** on national (USA) news.
    - Worked during the years 2010 through 2016.
        - Covered extreme events like tropical cyclones, wildfires, heat waves, and blizzards.

2011: April Tornadoes

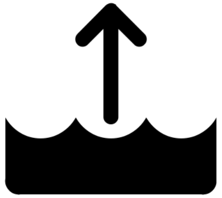
2013: Yarnell Wildfire



2015: Strong El Niño

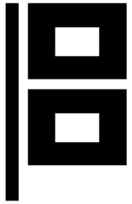
2010: NYC Blizzard

2012: Sandy's Storm Surge



2014: California Drought

2016: Matthew's Floods



As a broadcast meteorologist,

it was **critical** that I put extreme events

into **context** for the public.

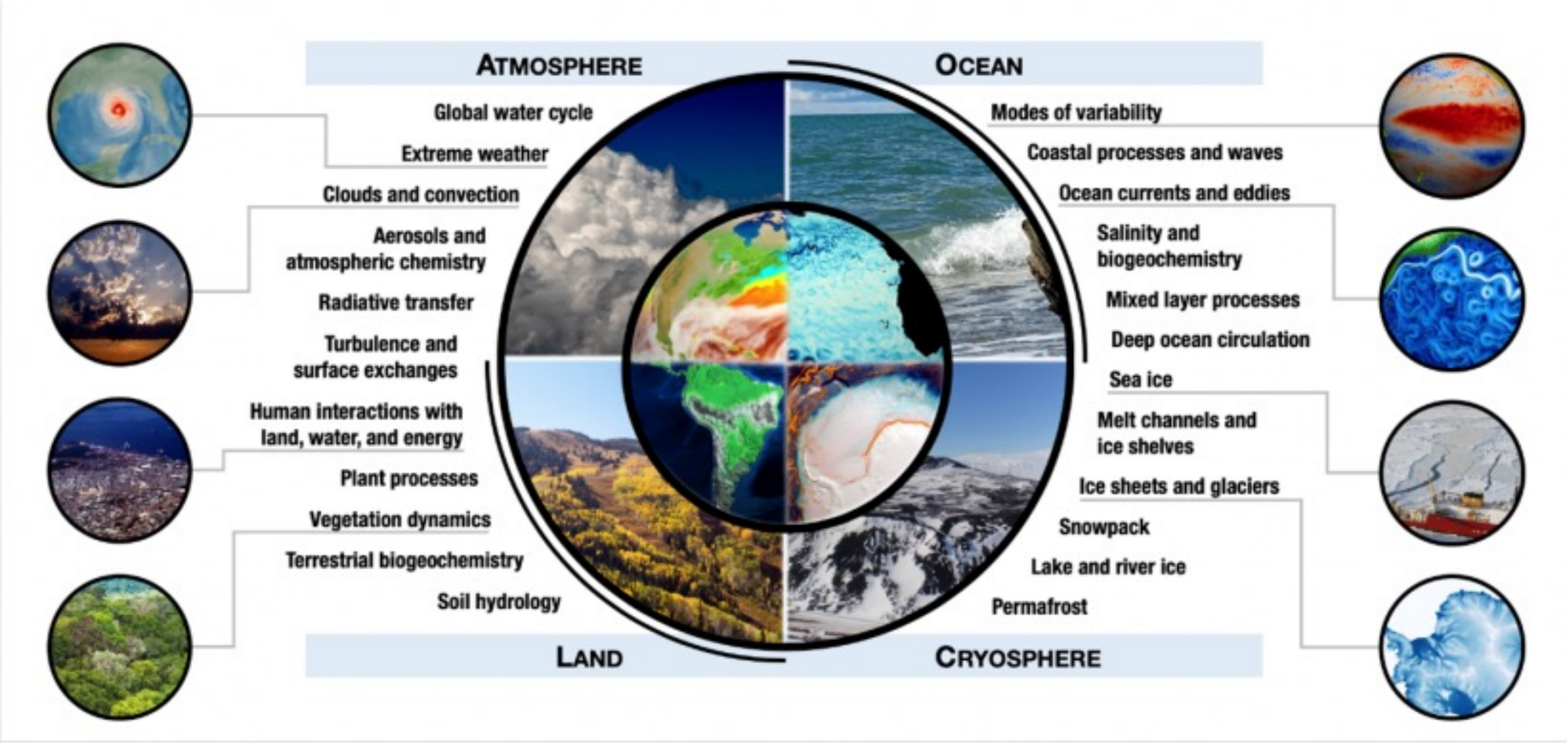
How **unusual** is this?

Can this happen **again**?

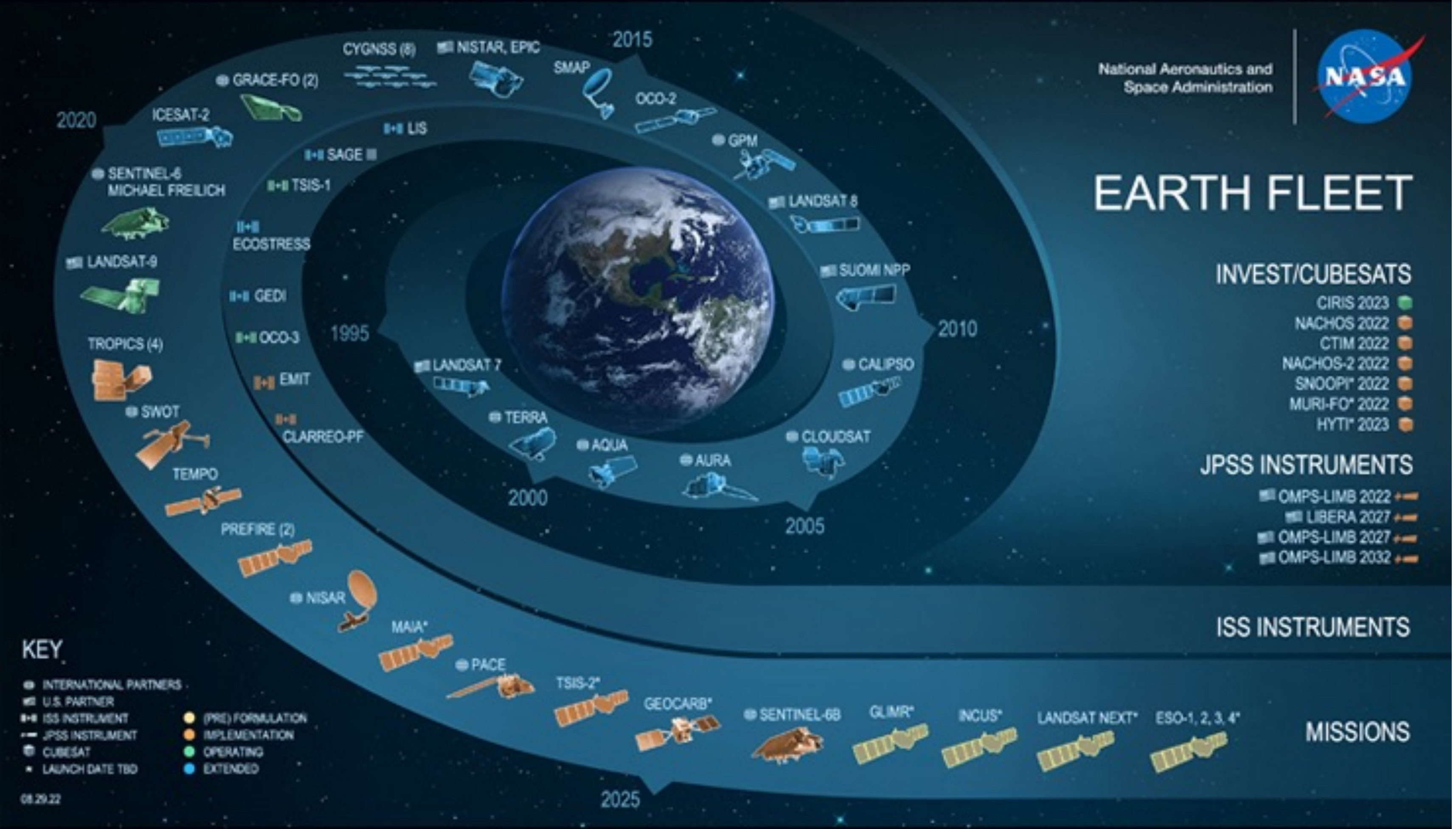
Is this our **new normal**?

Regardless of your career stage or path, you will likely need to be able to discuss climate change and extremes.

Let’s talk about the Earth system and DATA…



Earth system models include many interdependent components and processes to help us understand our planet. Image courtesy of Paul Ullrich, University of California, Davis



NASA Earth Science Division Missions

Updated: September 26, 2022

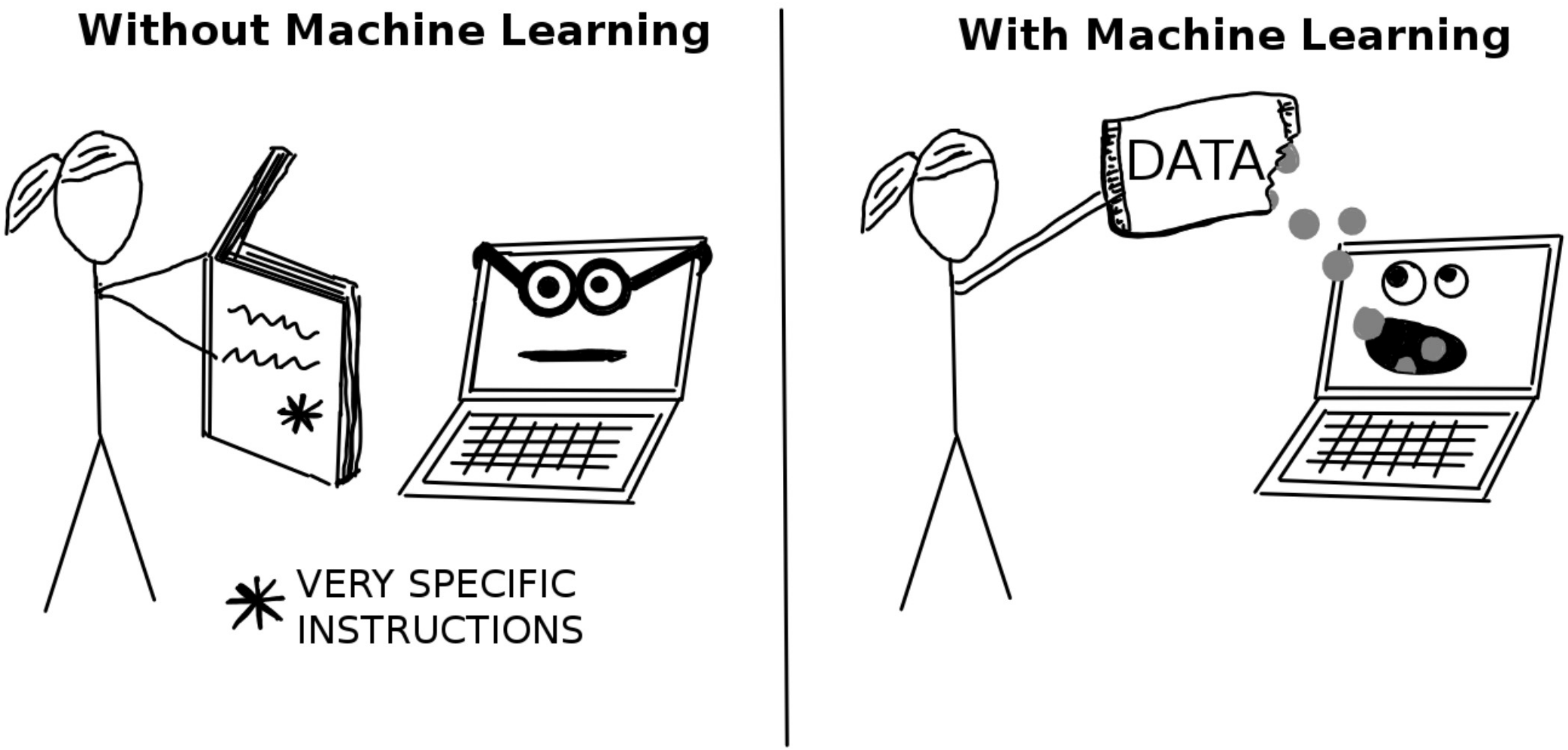
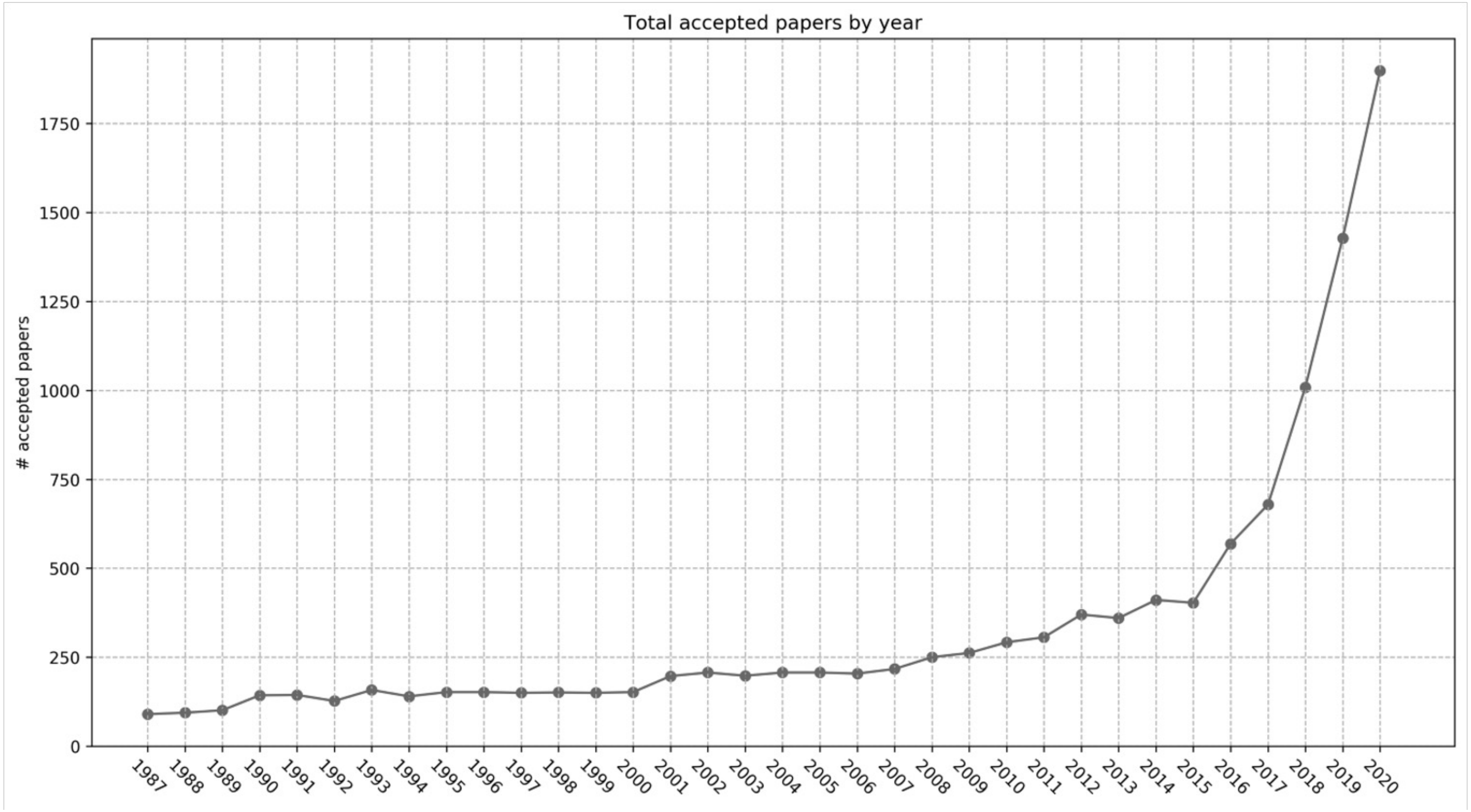


Figure from Interpretable Machine Learning (Molnar, 2019).

Molnar, C. (2019). Interpretable Machine Learning. A Guide for Making Black Box Models Explainable. https://christophm.github.io/interpretable-ml-book/.

NeurIPS Conference Papers, 1987-2020

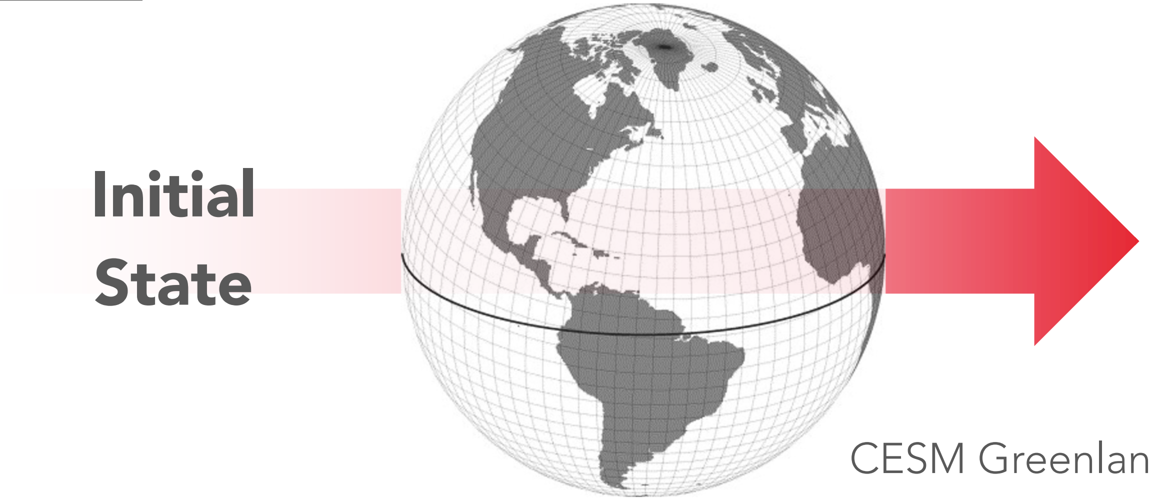


“Traditional” numerical weather prediction / climate modeling

Input
Observations or
Representation of
the Initial State

Run Model
Parameterizations
High Performance
Computing

Output
Predictions with
Certain Lead Time
Future Projections



CESM Greenland Pole Grid.

Molina, M. J., T. A. O'Brien, G. Anderson, M. Ashfaq, K. E. Bennett, W. D. Collins, K. Dagon, J. M. Restrepo, and P. A. Ullrich (2023). A Review of Recent and Emerging Machine Learning Applications for Climate Variability and Weather Phenomena. Artificial Intelligence for the Earth Systems.

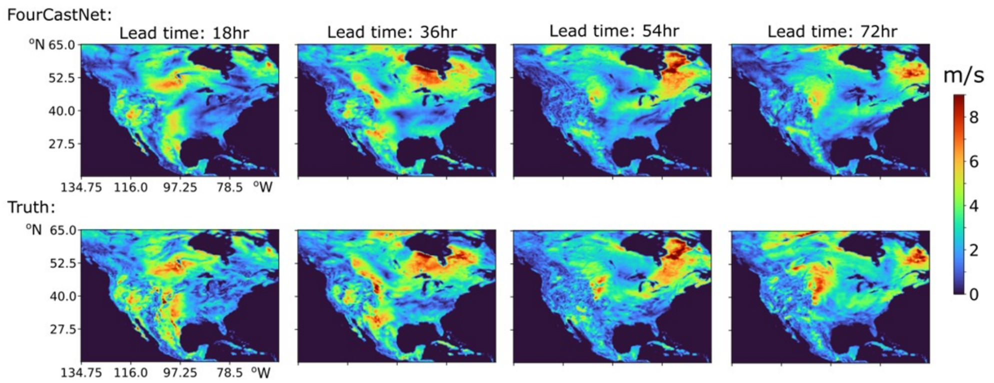
ML-based numerical weather prediction / climate modeling

Input
Observations or Representation of the Initial State

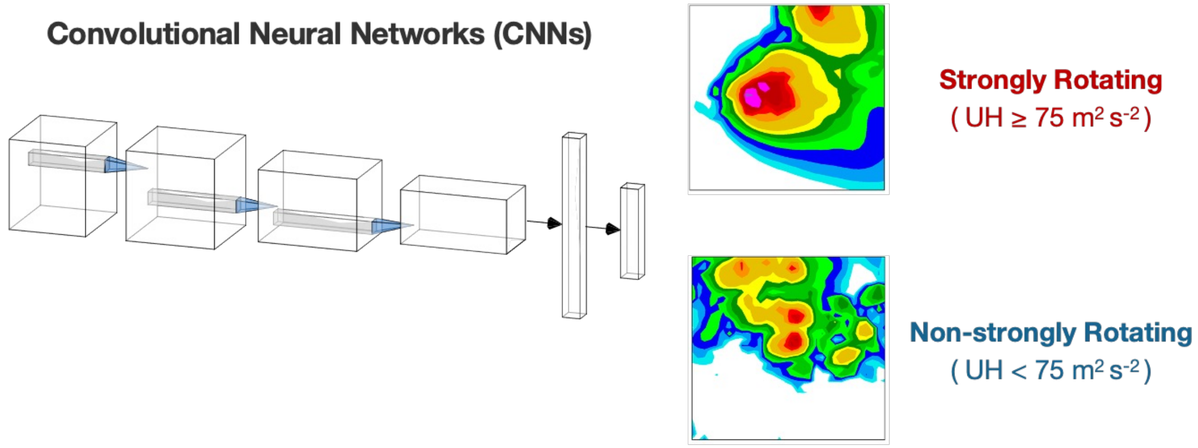
Run Model
Parameterizations
High Performance Computing

Output
Predictions with Certain Lead Time
Future Projections

Pathak, J., et al., 2022. **Fourcastnet: A global data-driven high-resolution weather model using adaptive fourier neural operators.** arXiv:2202.11214.

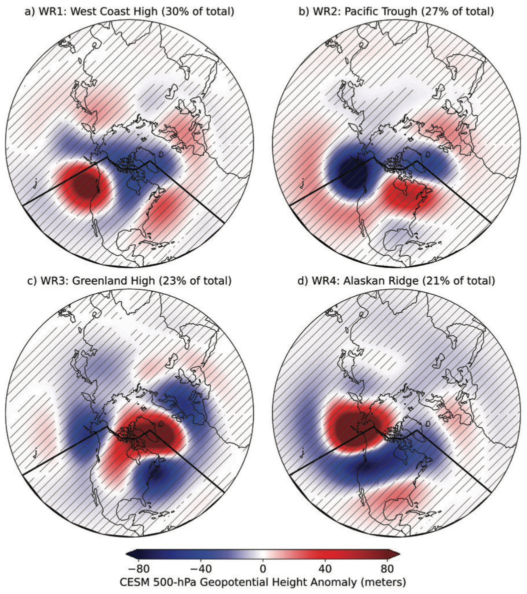


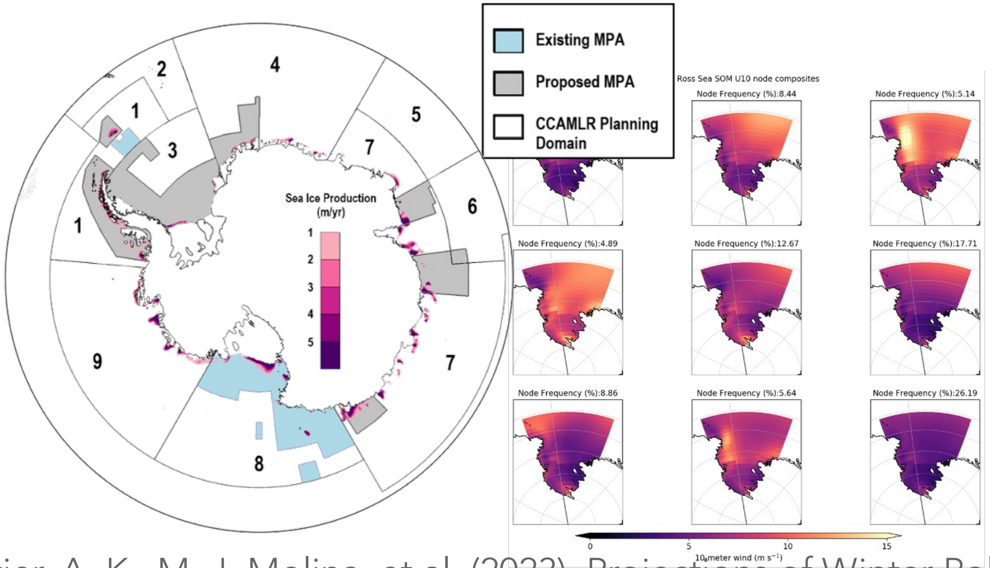
Molina, M. J., T. A. O'Brien, G. Anderson, M. Ashfaq, K. E. Bennett, W. D. Collins, K. Dagon, J. M. Restrepo, and P. A. Ullrich (2023). A Review of Recent and Emerging Machine Learning Applications for Climate Variability and Weather Phenomena. Artificial Intelligence for the Earth Systems.



Molina, M.J., Gagne, D.J., Prein, A.F. (2021). A benchmark to test generalization capabilities of deep learning methods to classify severe convective storms in a changing climate. Earth and Space Science.

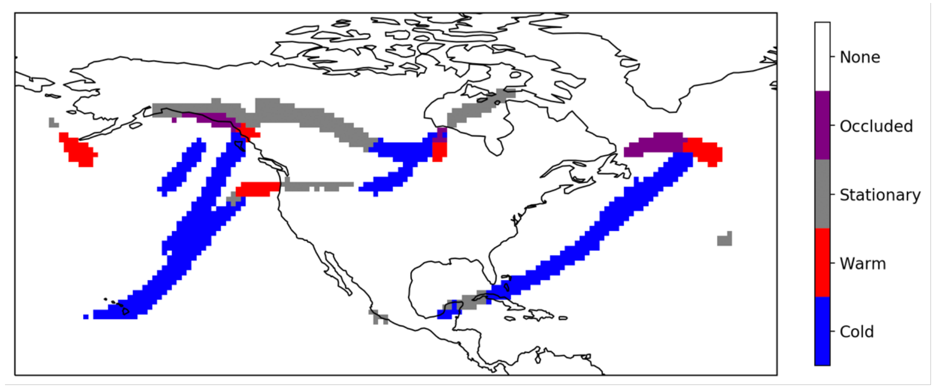
Molina, M. J., et al. (2023). Subseasonal Representation and Predictability of North American Weather Regimes using Cluster Analysis. AI for the Earth Systems.

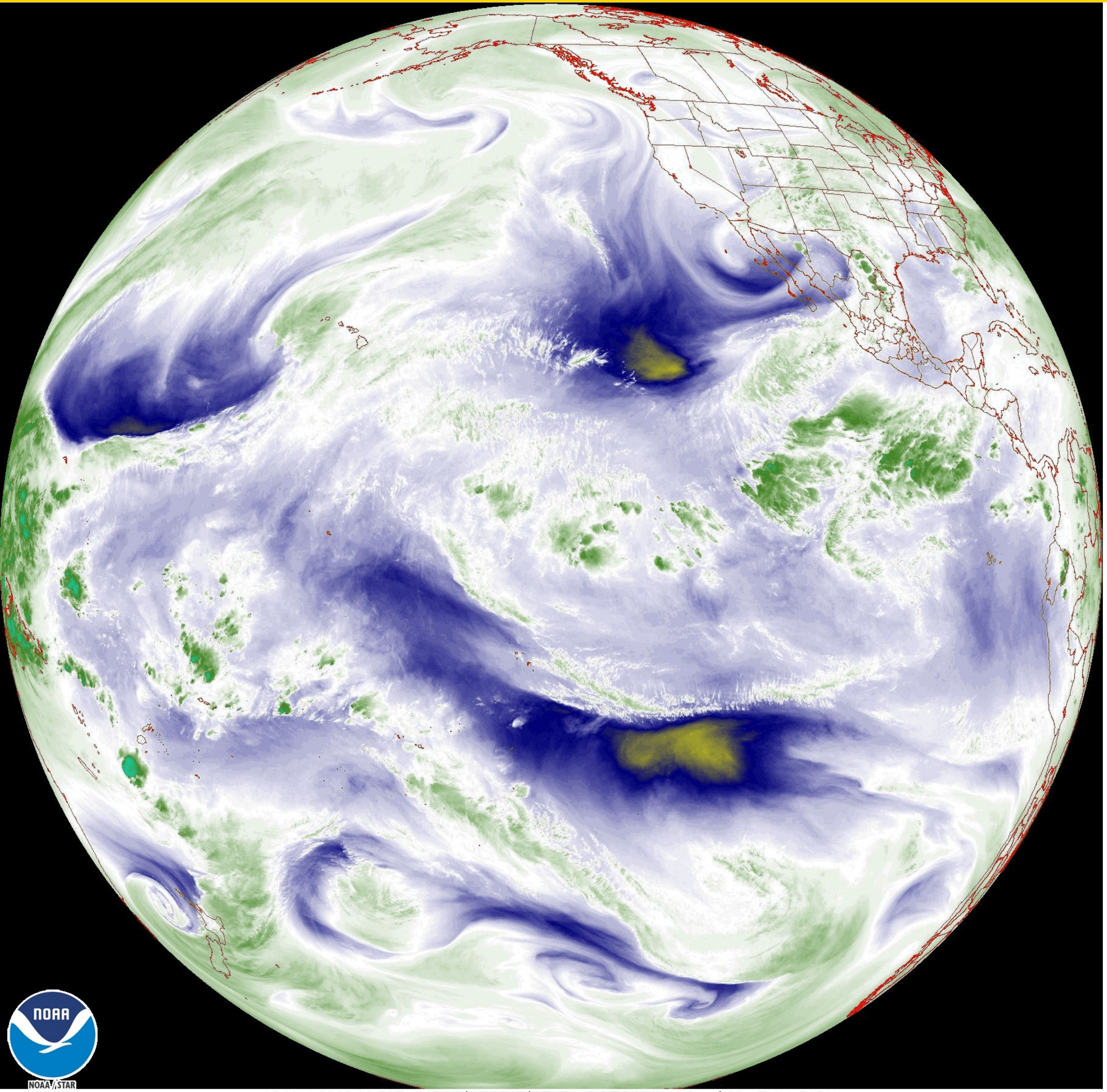




DuVivier, A. K., M. J. Molina, et al. (2023). Projections of Winter Polynyas and Their Biophysical Impacts in the Ross Sea Antarctica. Climate Dynamics.

Dagon, K., Truesdale, J. E., Biard, J. C., Kunkel, K. E., Meehl, G. A. and Molina, M. J. (2022). Machine learning-based detection of weather fronts and associated extreme precipitation. Journal of Geophysical Research: Atmospheres.





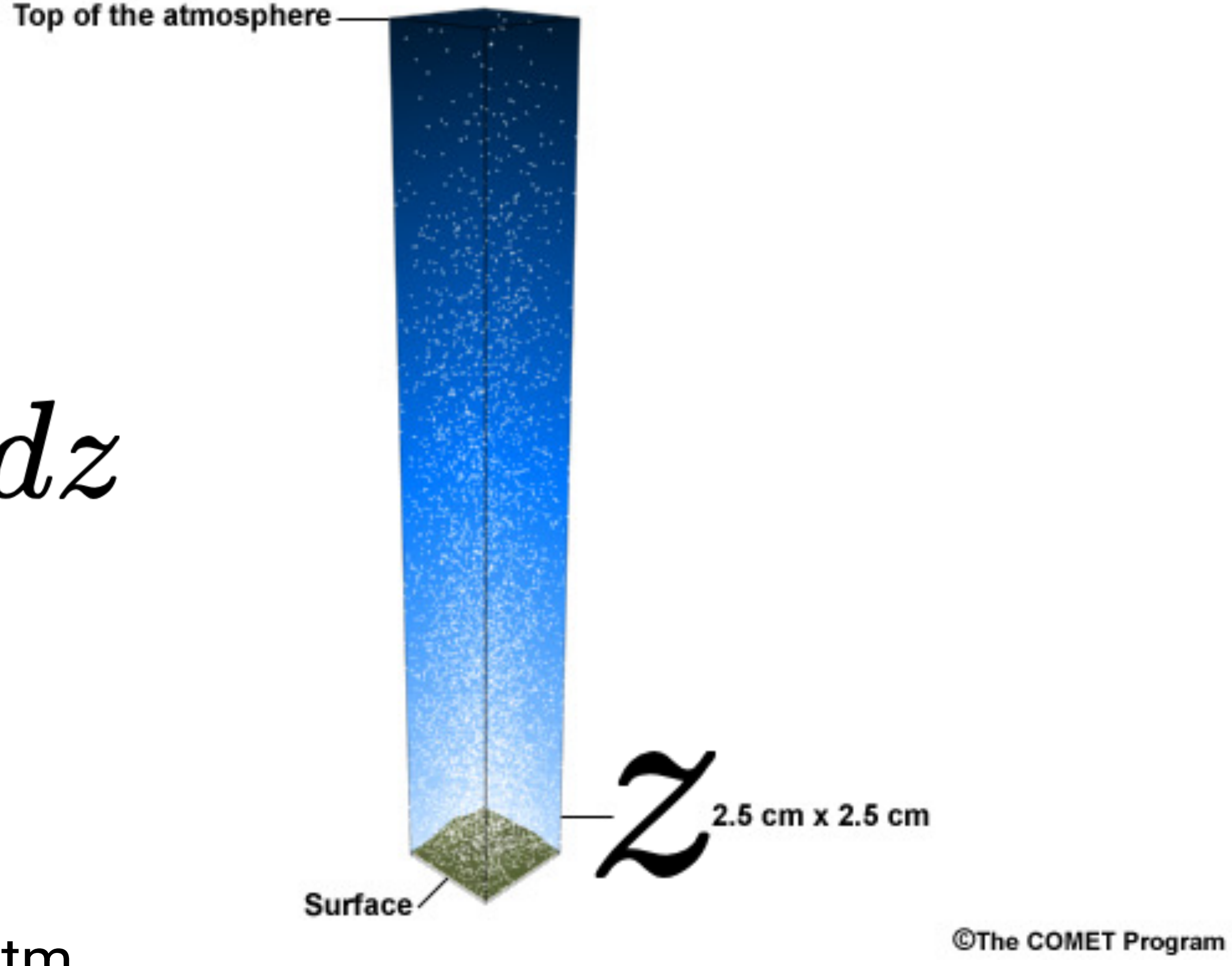
18 May 2023 18:50Z - NOAA/NESDIS/STAR - GOES-West - Band 08 - FULL DISK

The physical basis

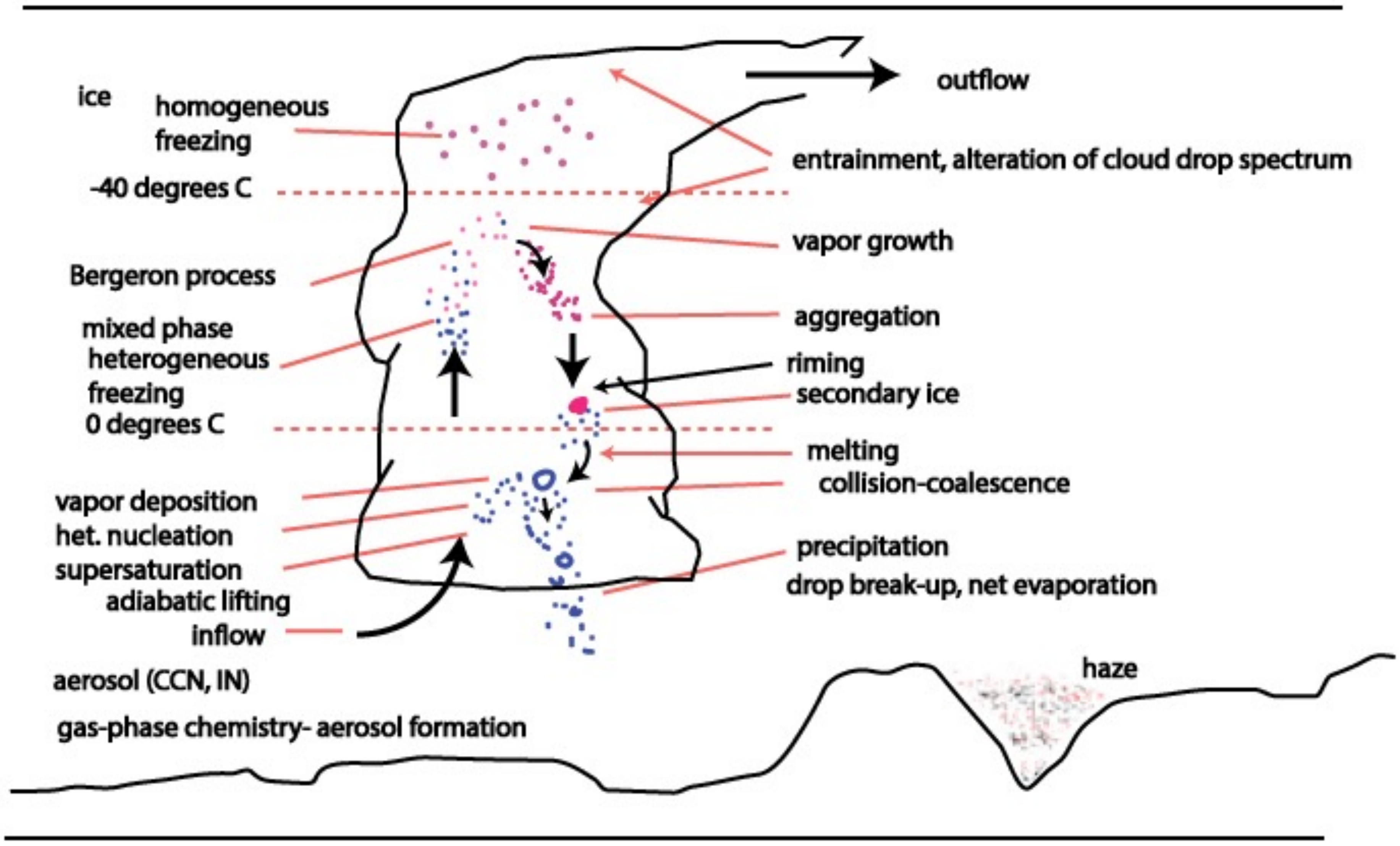
Understanding physics behind the statistics of extremes.

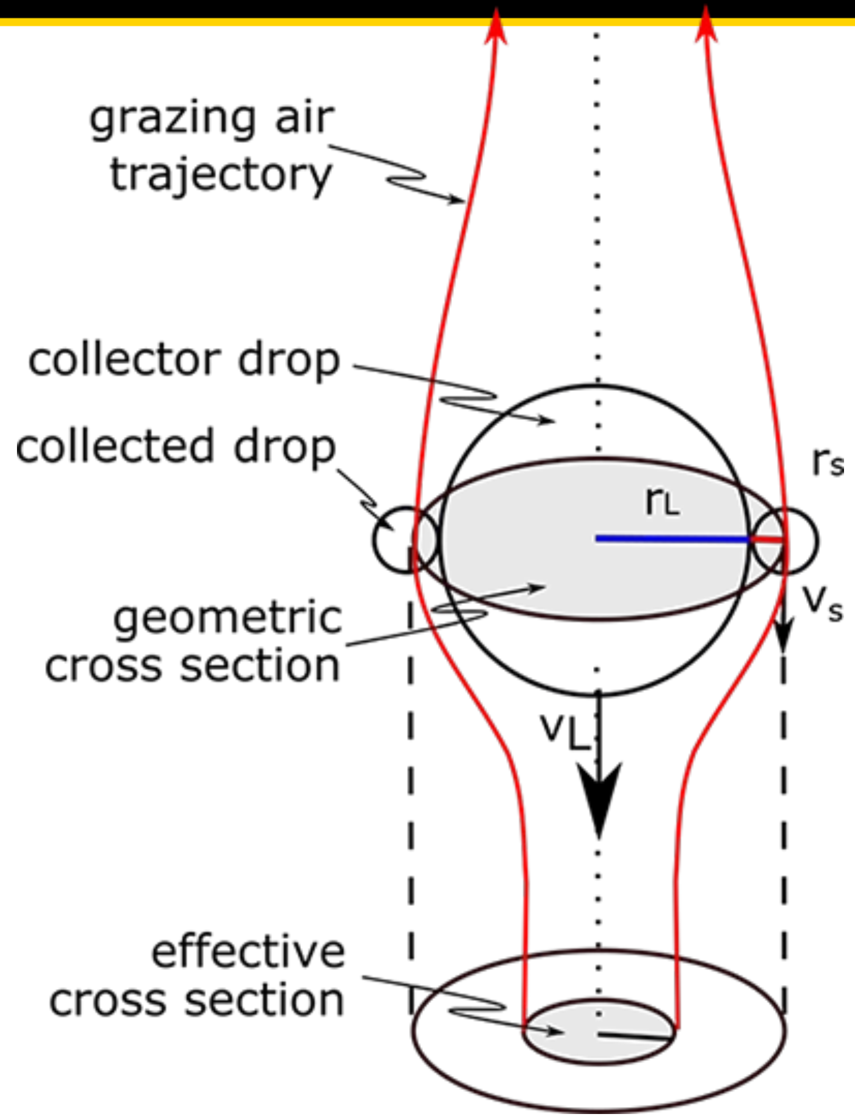
Hydrostatic Equation

$$p(z) = \int_z^\infty g\rho dz$$



Pressure at sea level is 1013 hPa = 1 atm.


outflow
ice
homogeneous
freezing
entrainment, alteration of cloud drop spectrum
-40 degrees C
vapor growth
Bergeron process
aggregation
mixed phase
heterogeneous
freezing
riming
secondary ice
0 degrees C
melting
collision-coalescence
vapor deposition
het. nucleation
supersaturation
adiabatic lifting
inflow
precipitation
drop break-up, net evaporation
haze
aerosol (CCN, IN)
gas-phase chemistry- aerosol formation



$$\frac{dm_L}{dt} = \pi(r_L + r_s)^2 \cdot E_c \cdot (v_L - v_s) \cdot LWC$$

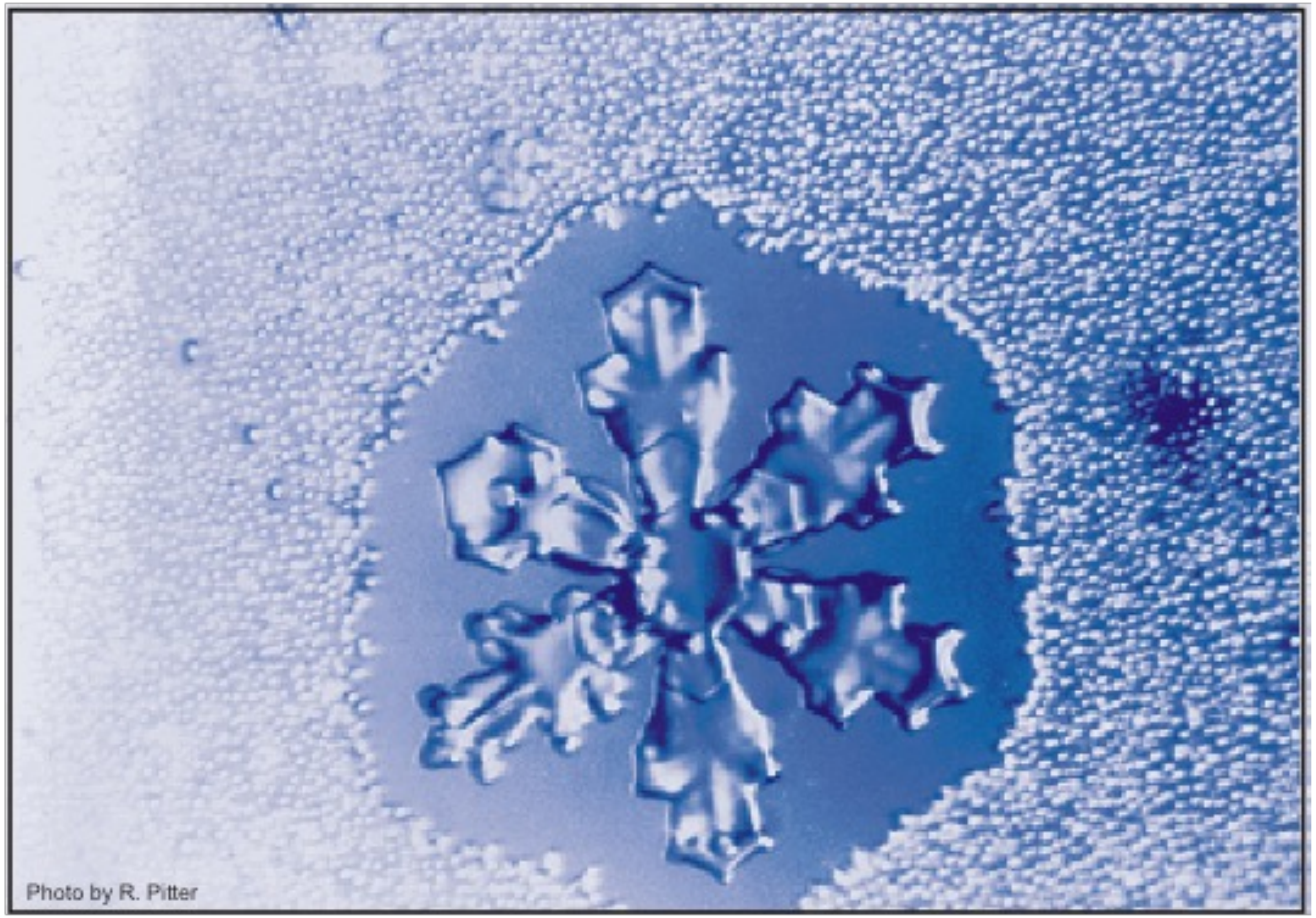


Photo by R. Pitter

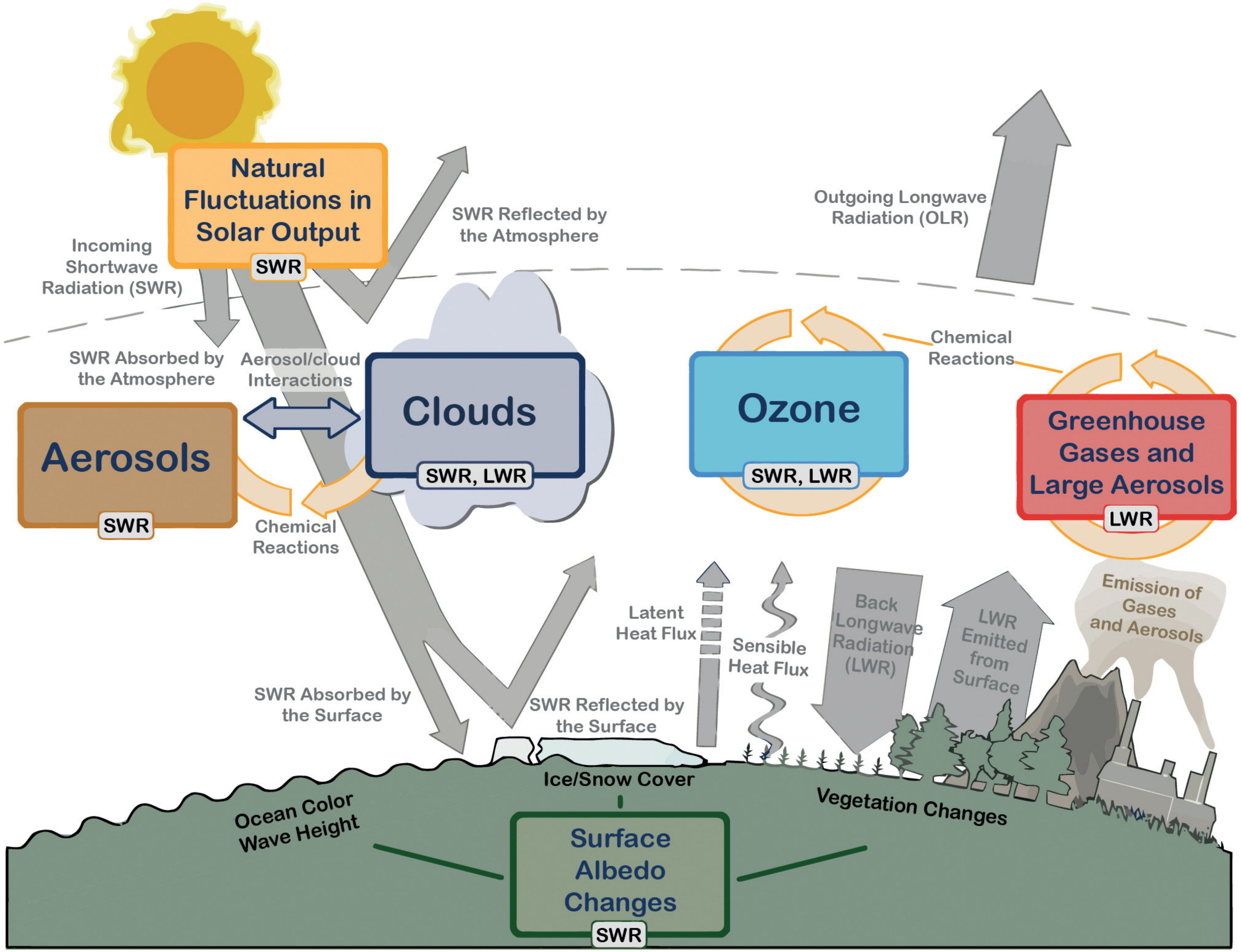


Image from

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G. and Nganga, J., 2007. Changes in atmospheric constituents and in radiative forcing. Climate Change 2007: The Physical Science Basis. *Contribution of Working Group I to the 4th Assessment Report of the Intergovernmental Panel on Climate Change.*

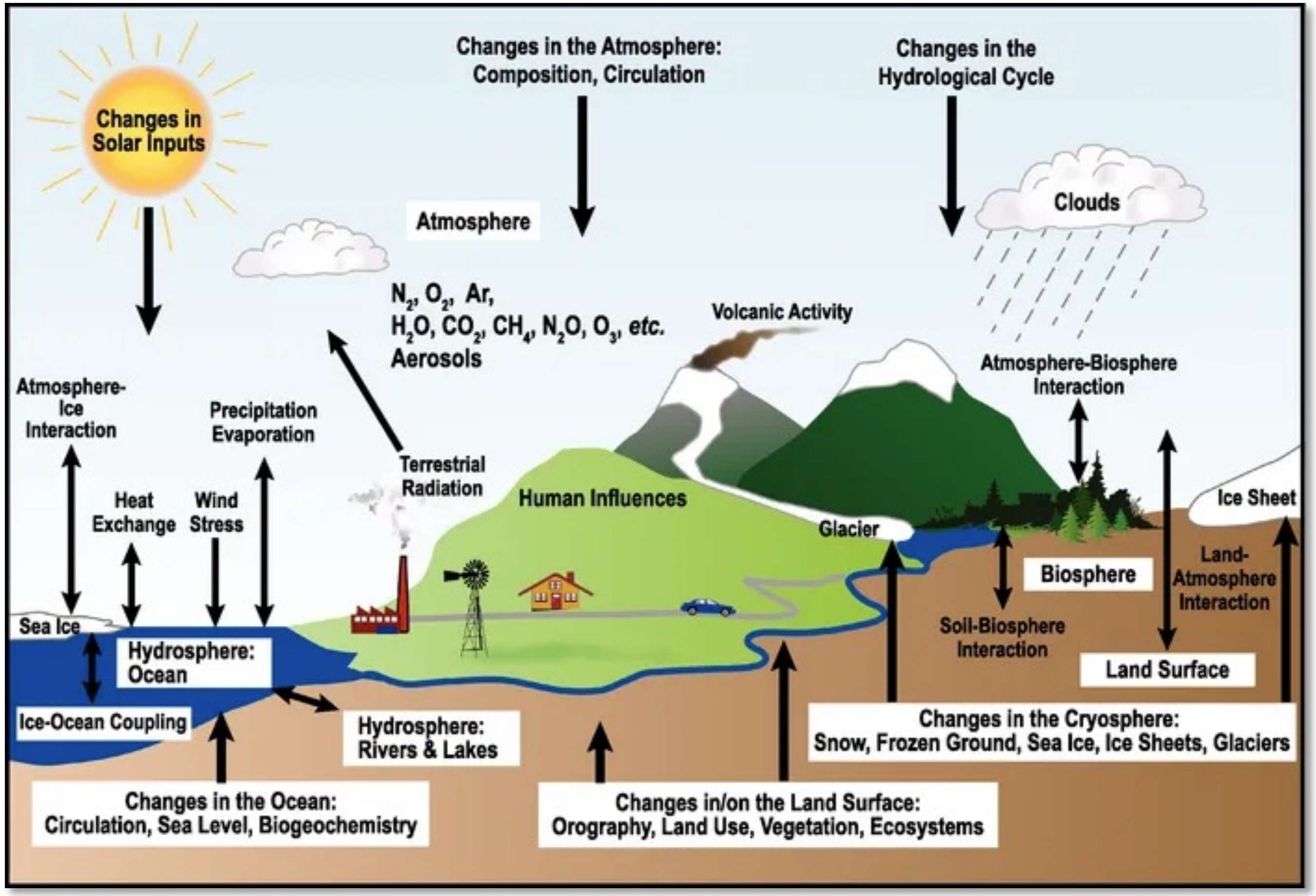


Image from

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M. and Miller, H., 2007. IPCC fourth assessment report (AR4). Climate change, 374.

Changes in one component of the Earth system can drive changes in another.

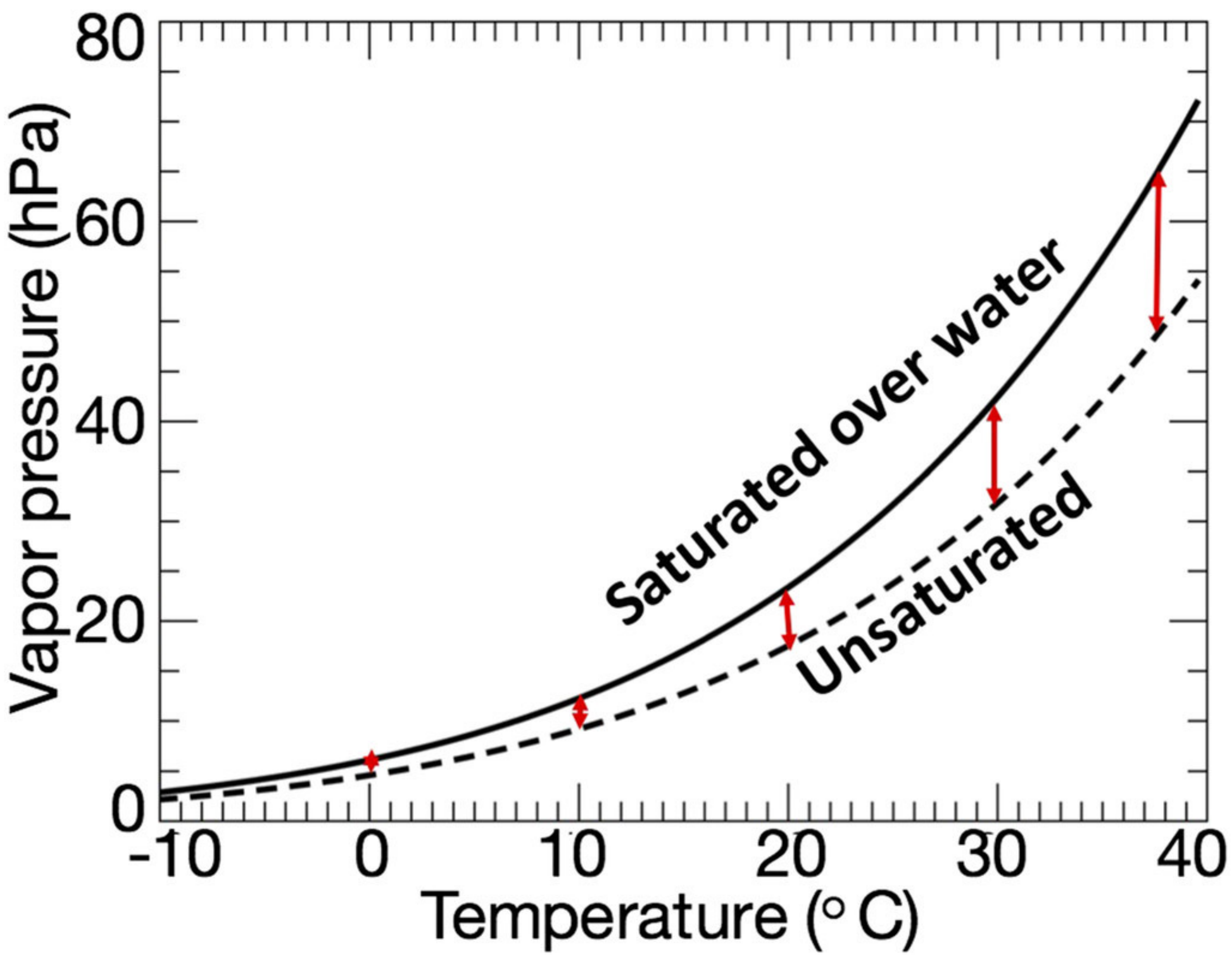


Image from Friedrich, K., et al., 2018. Reservoir evaporation in the Western United States: current science, challenges, and future needs. Bulletin of the American Meteorological Society, 99(1), pp.167-187.

"As air warms, its capacity to hold water increases at the **Clausius-Clapeyron rate** (approximately 7% per °C)" (Skliris et al. 2016).

Skliris, N., et al., 2016. Global water cycle amplifying at less than the Clausius-Clapeyron rate. Scientific reports, 6(1), pp.1-9.

CORE CONCEPTS | EARTH, ATMOSPHERIC, AND PLANETARY SCIENCES |

What a 190-year-old equation says about rainstorms in a changing climate

David Adam Authors Info & Affiliations

March 30, 2023 | 120 (14) e2304077120 | https://doi.org/10.1073/pnas.2304077120

Weather Icons
Erik Flowers
CC BY 3.0

"A lot of people are interpreting the equation incorrectly. Clausius–Clapeyron controls the amount of moisture in the atmosphere, but it doesn't control rainfall directly." – Kevin Reed

Adam, D., 2023. What a 190-year-old equation says about rainstorms in a changing climate. Proceedings of the National Academy of Sciences, 120(14).

Precipitation **also depends on other factors**, such as:

- the atmospheric circulation pattern and rainfall mechanisms (i.e., convergence) and,
- atmospheric moisture availability.

Weather Icons
Erik Flowers
CC BY 3.0

Westra, S., Fowler, H.J., Evans, J.P., Alexander, L.V., Berg, P., Johnson, F., Kendon, E.J., Lenderink, G. and Roberts, N., 2014. Future changes to the intensity and frequency of short-duration extreme rainfall. Reviews of Geophysics, 52(3), pp.522-555.

Challenges with Extremes

Assessing statistical trends of extremes requires caution.

Challenges with extremes:
Severe Thunderstorms

Weather Icons
Erik Flowers
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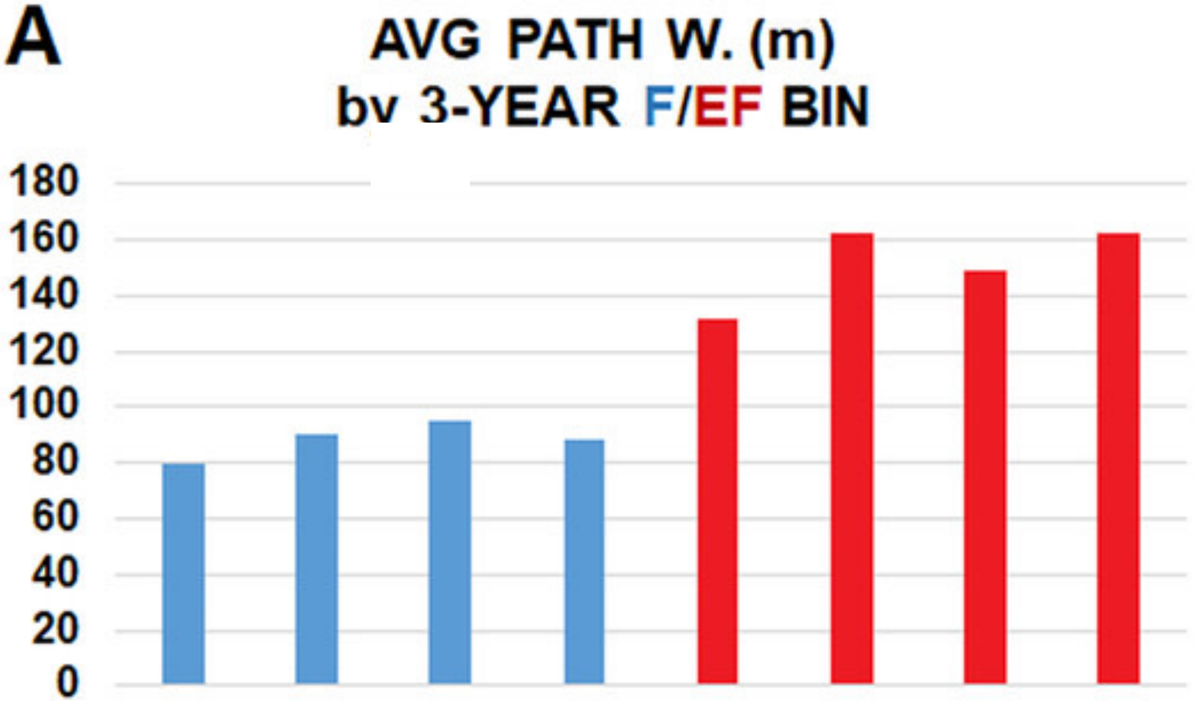


Three-year intervals (from 1995-97 to 2016-18).

Change in tornado rating system contributed to path width increases (Edwards et al. 2021).

Image from Edwards, R., Brooks, H.E. and Cohn, H., 2021. Changes in tornado climatology accompanying the enhanced Fujita scale. J. App. Met. & Clim., 60(10), 1465-1482.

Challenges with extremes: **Severe Thunderstorms**

Large hail is reported more frequently over roads (Allen and Tippett 2015).

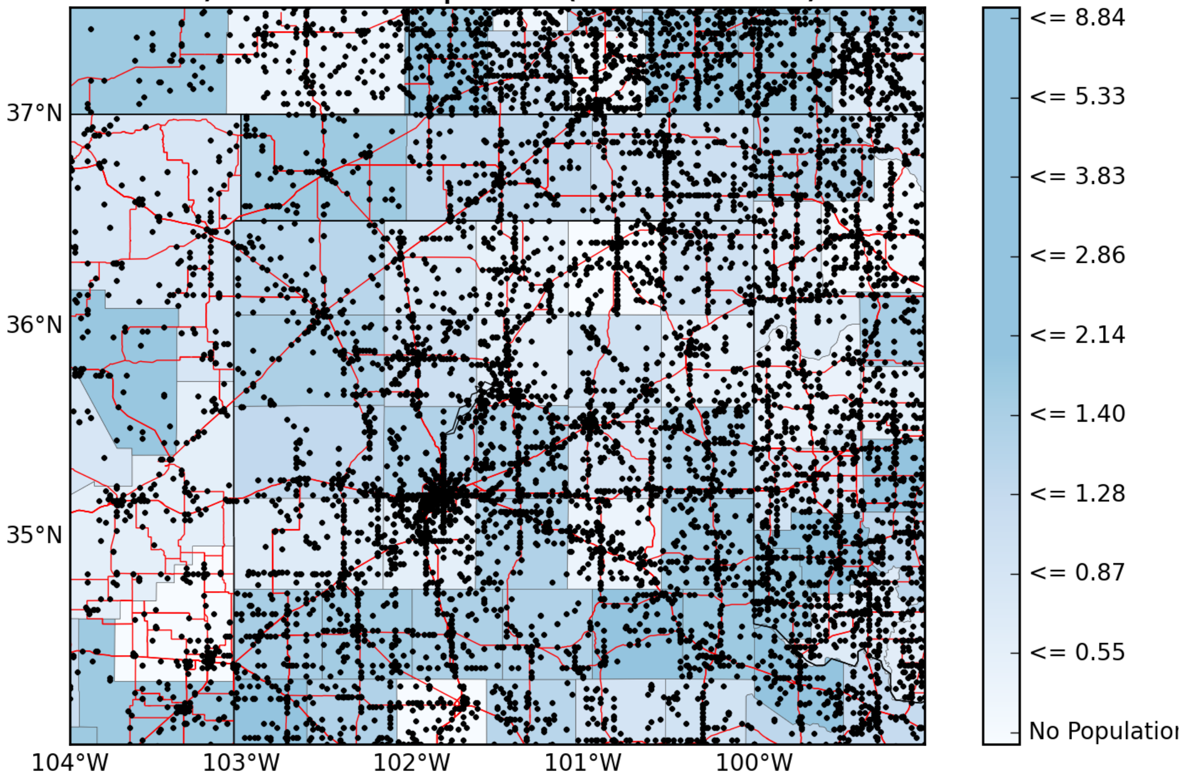
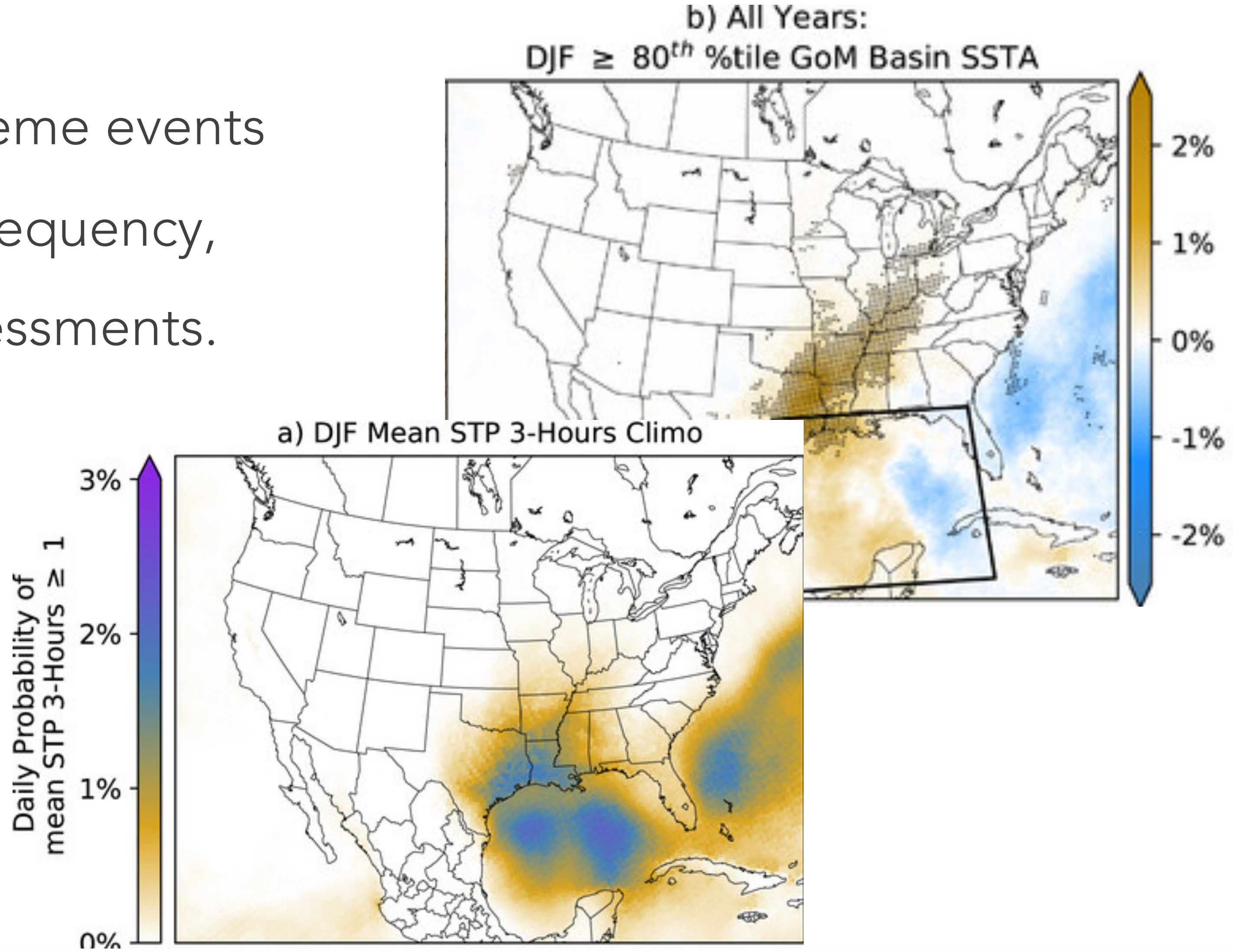


Image from Allen, J.T. and Tippett, M.K., 2015. The characteristics of United States hail reports: 1955-2014. E-Journal Sev. Storms Meteo., 10(3), pp.1-31.

An environmental perspective can help.

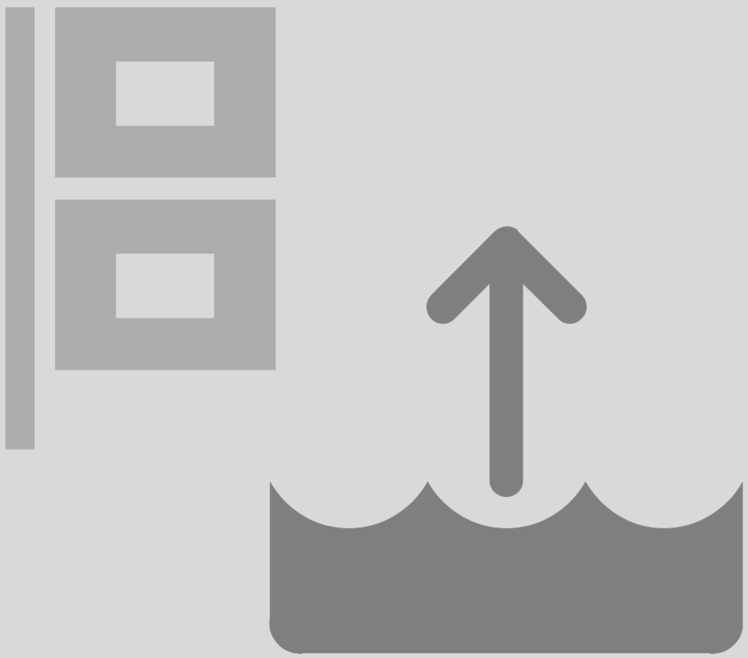
- Environments favorable for extreme events can serve as useful proxies for frequency, intensity, and spatial extent assessments.



Images from
Molina, M. J., J. T. Allen, and V. A. Gensini (2018). The Gulf of Mexico and ENSO influence on subseasonal and seasonal CONUS winter tornado variability. Journal of Applied Meteorology and Climatology, 57(10), 2439-2463.

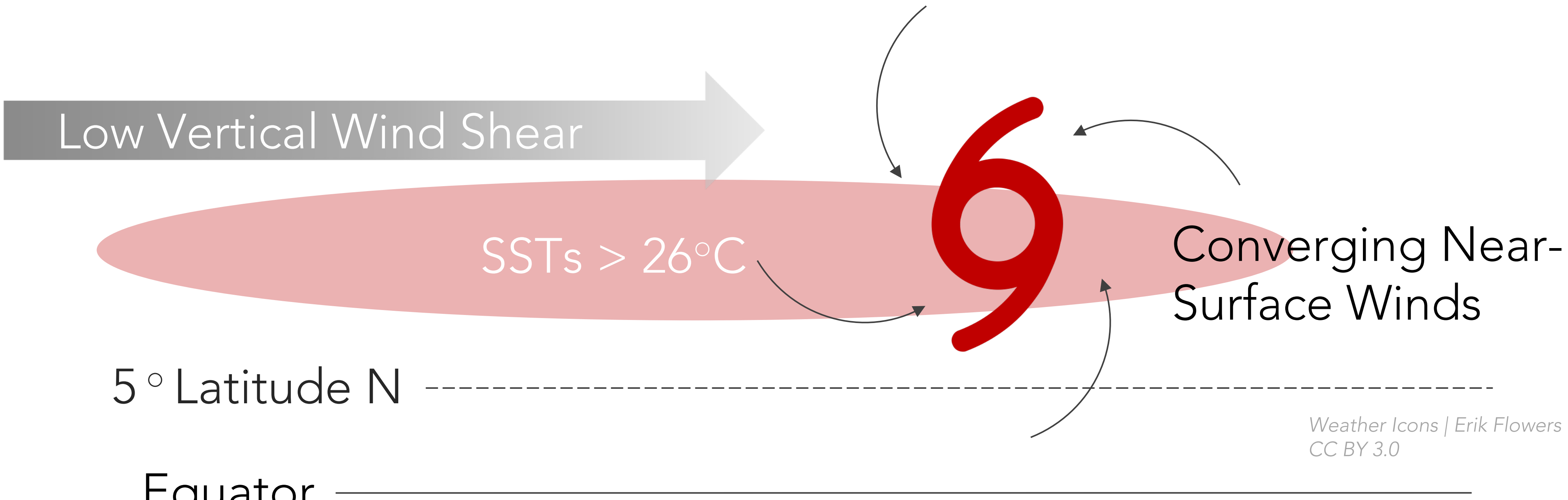
Case Studies

Using tropical cyclones to help our understanding of extremes.



Weather Icons | Erik Flowers
CC BY 3.0

Tropical cyclone drivers



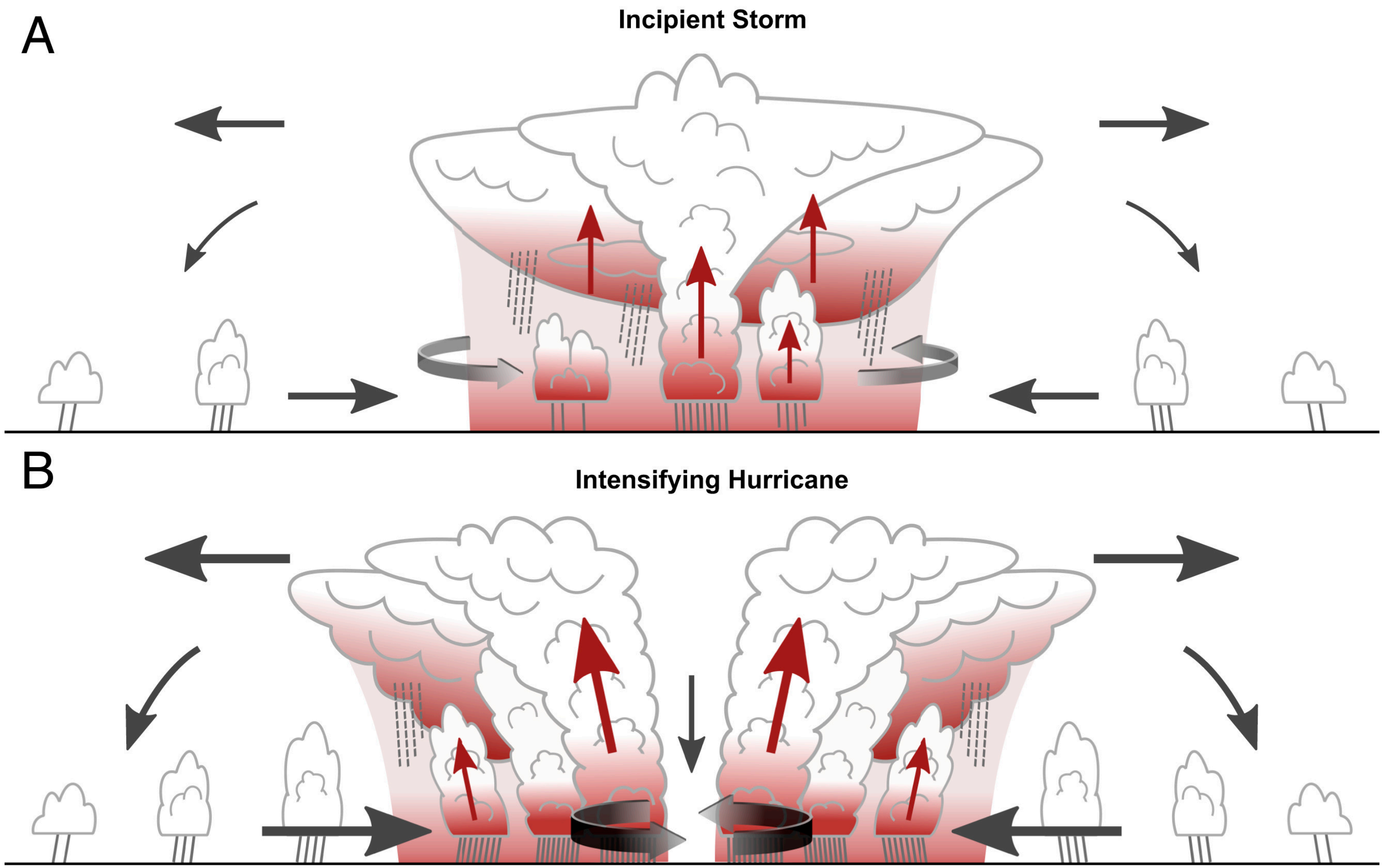


Image from Ruppert et al., 2020.

"…local atmospheric warming caused by this 'cloud greenhouse effect' is a key trigger for promoting and accelerating the evolution of… precursor[s]… into intense TCs."

Ruppert Jr, J.H., Wing, A.A., Tang, X. and Duran, E.L., 2020. The critical role of cloud–infrared radiation feedback in tropical cyclone development. Proceedings of the National Academy of Sciences, 117(45), pp.27884-27892.

Challenges with extremes: **Tropical Cyclones**

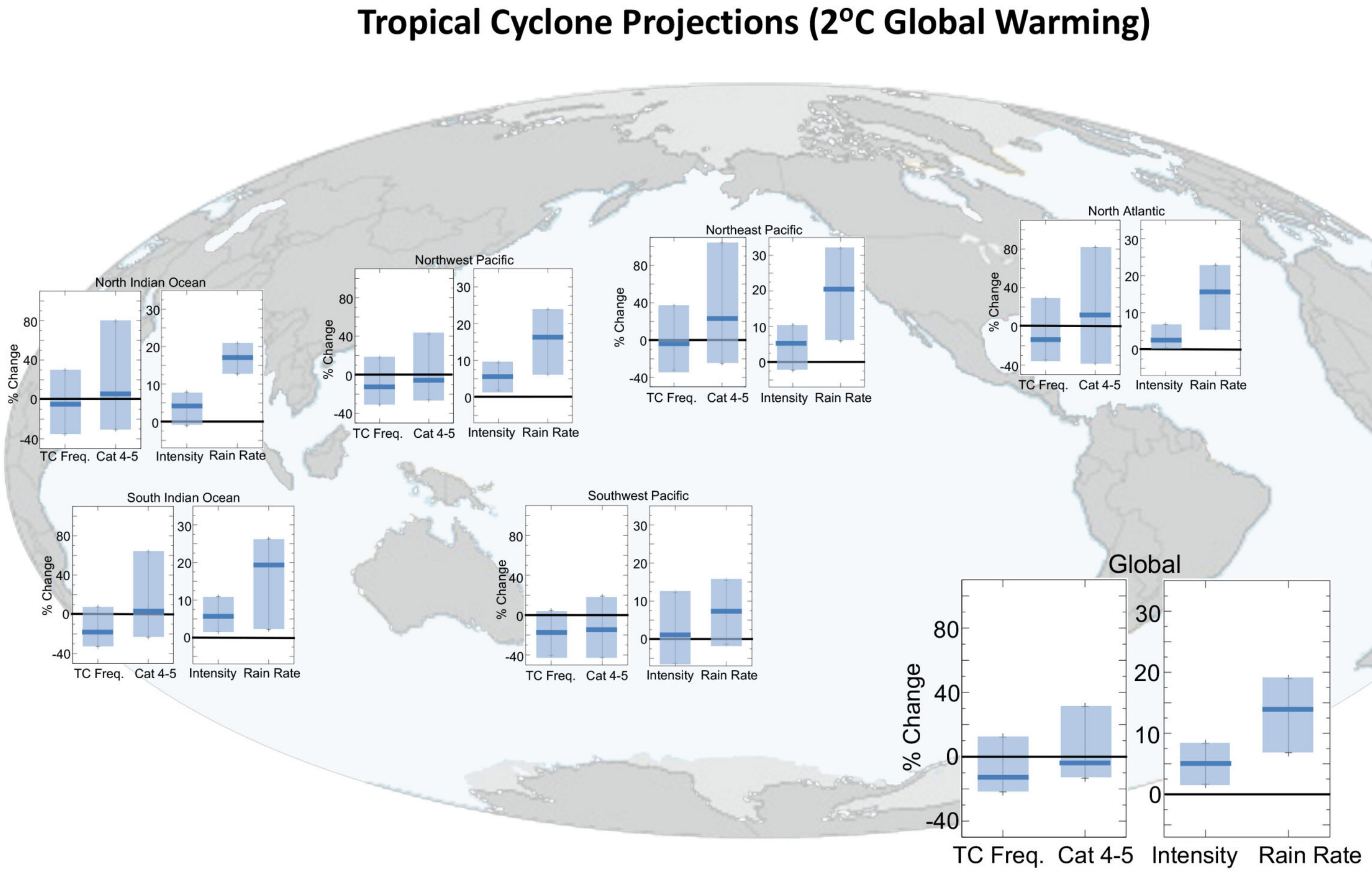


Image from
Knutson, T. et al., 2020: Tropical Cyclones and Climate Change Assessment. Part II: Projected Response to Anthropogenic Warming. Bull. Amer. Meteorol. Soc., https://doi.org/10.1175/BAMS-D-18-0194.1.

An impacts perspective can help.

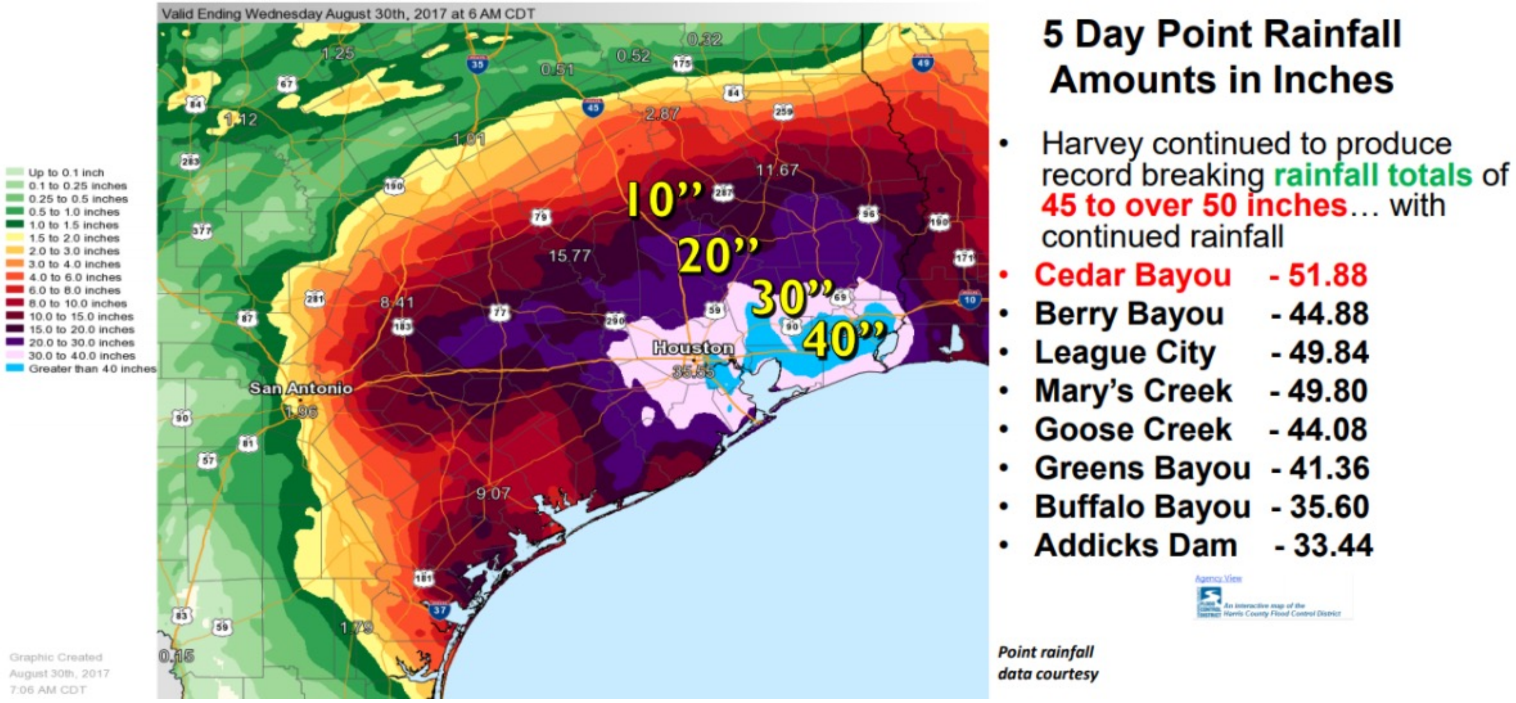
From IPCC AR6:

- Increases in total precipitation and/or precipitation rates are likely.
- Sea level rise projected to increase coastal vulnerability to tropical cyclones.
- Global proportion of tropical cyclones reaching very high intensity is projected to increase.

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I. and Huang, M., 2021. Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change, 2.

Hurricane (Tropical Cyclone) Harvey (2017)

- Estimated cost of $125 billion.
- 30,000 high-water rescues.
- Water from rivers left the entire watersheds in southeast Texas.
- 216 Tornado Warnings were issued.



Source: NOAA NWS West Gulf River Forecast Center

Image: NOAA NWS West Gulf River Forecast Center

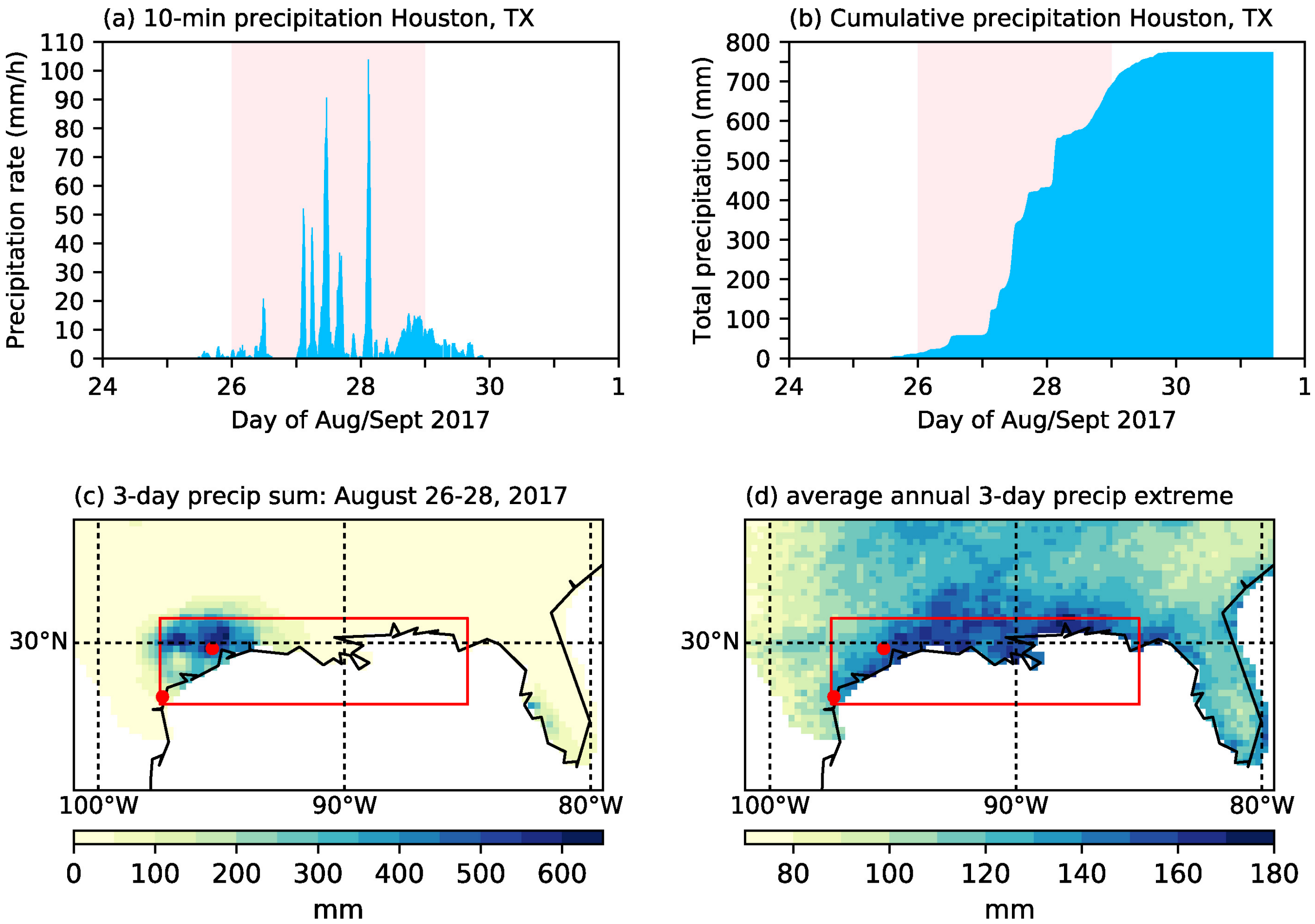


Image from Van Oldenborgh, et al., 2017.

"We conclude that global warming made the precipitation about 15% (8%–19%) **more intense**…"

Van Oldenborgh, et al., 2017. Attribution of extreme rainfall from Hurricane Harvey. Environmental Research Letters, 12(12), p.124009.

Hurricane (Tropical Cyclone) Sandy (2012)

- 147 deaths and left 200,000 without shelter.
- A storm surge measuring nearly 4.3 meters in New York City.
- An estimate of >$50 billion in damages.

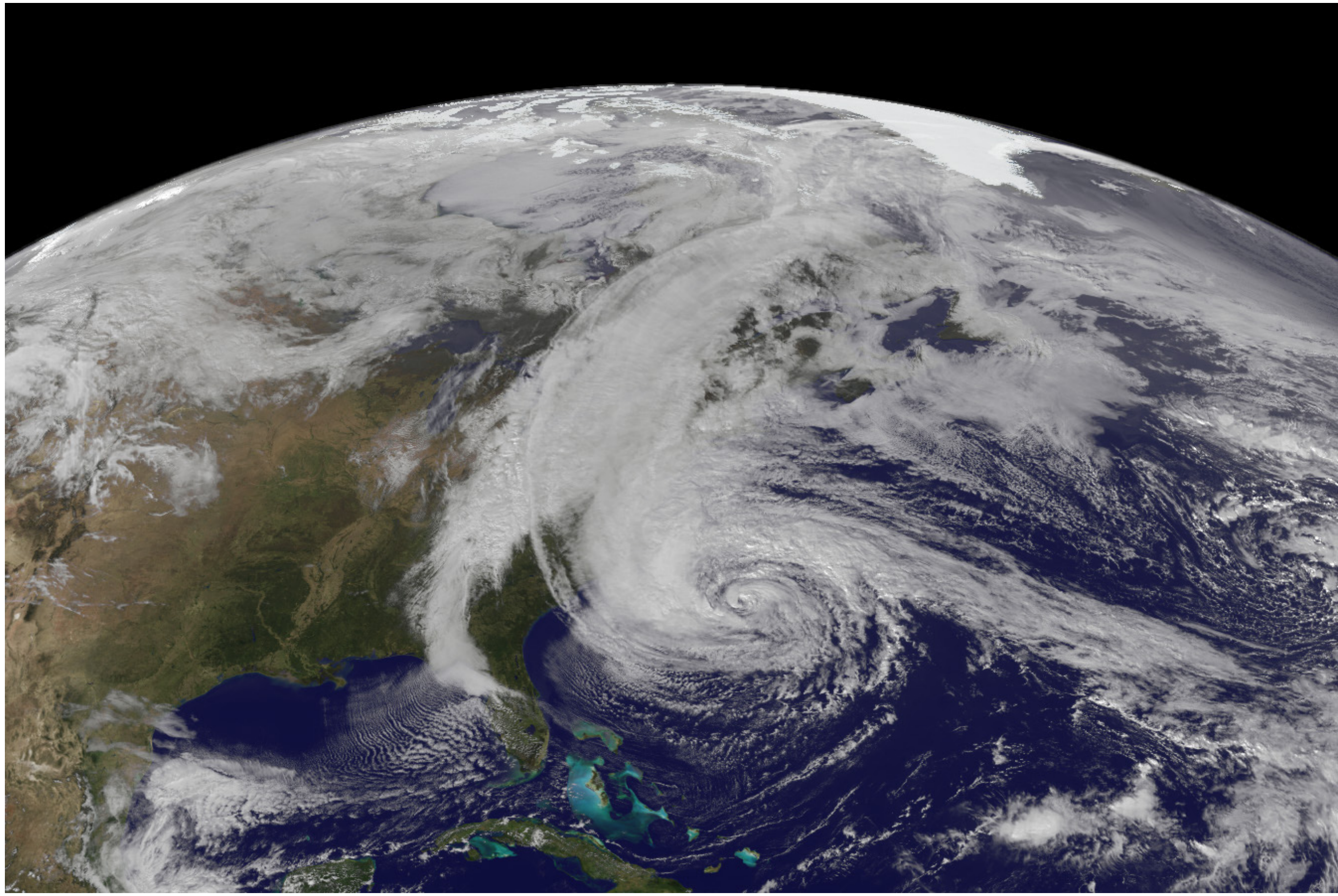


Image: NASA GOES-13, October 28, 2012

Blake, E.S., et al., 2013. Tropical cyclone report: Hurricane Sandy. NOAA National Hurricane Center, 12, pp.1-10.

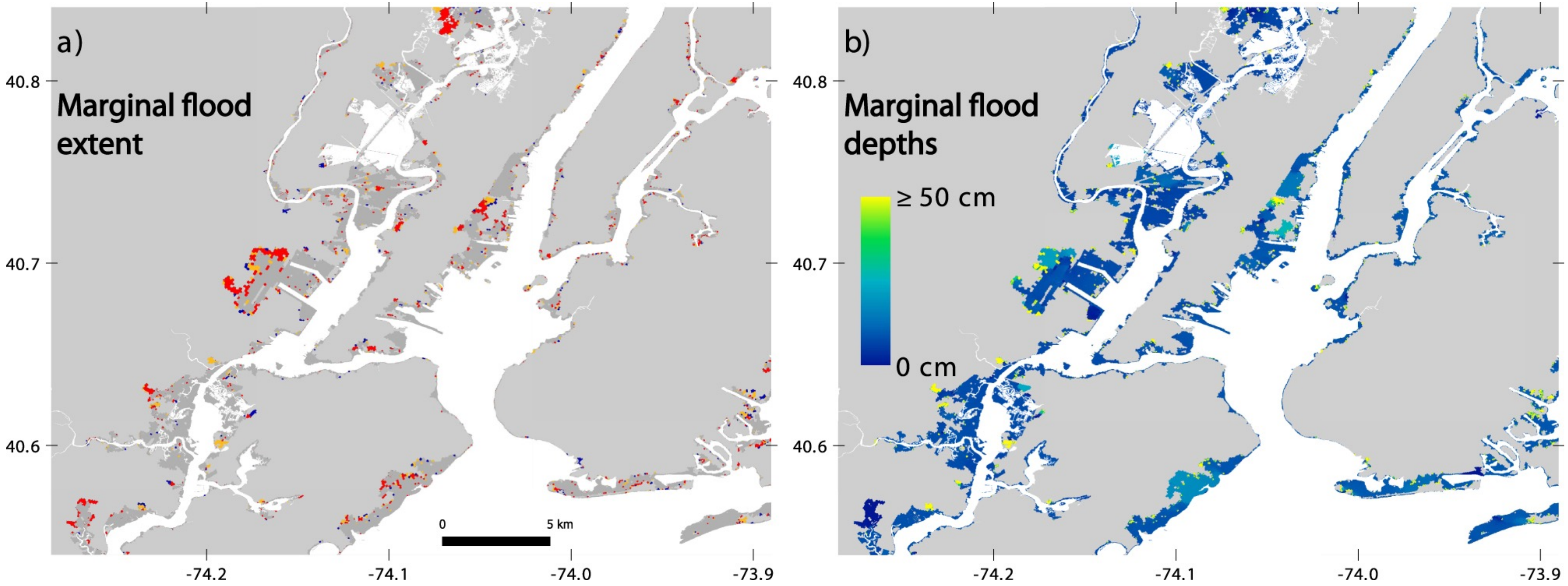


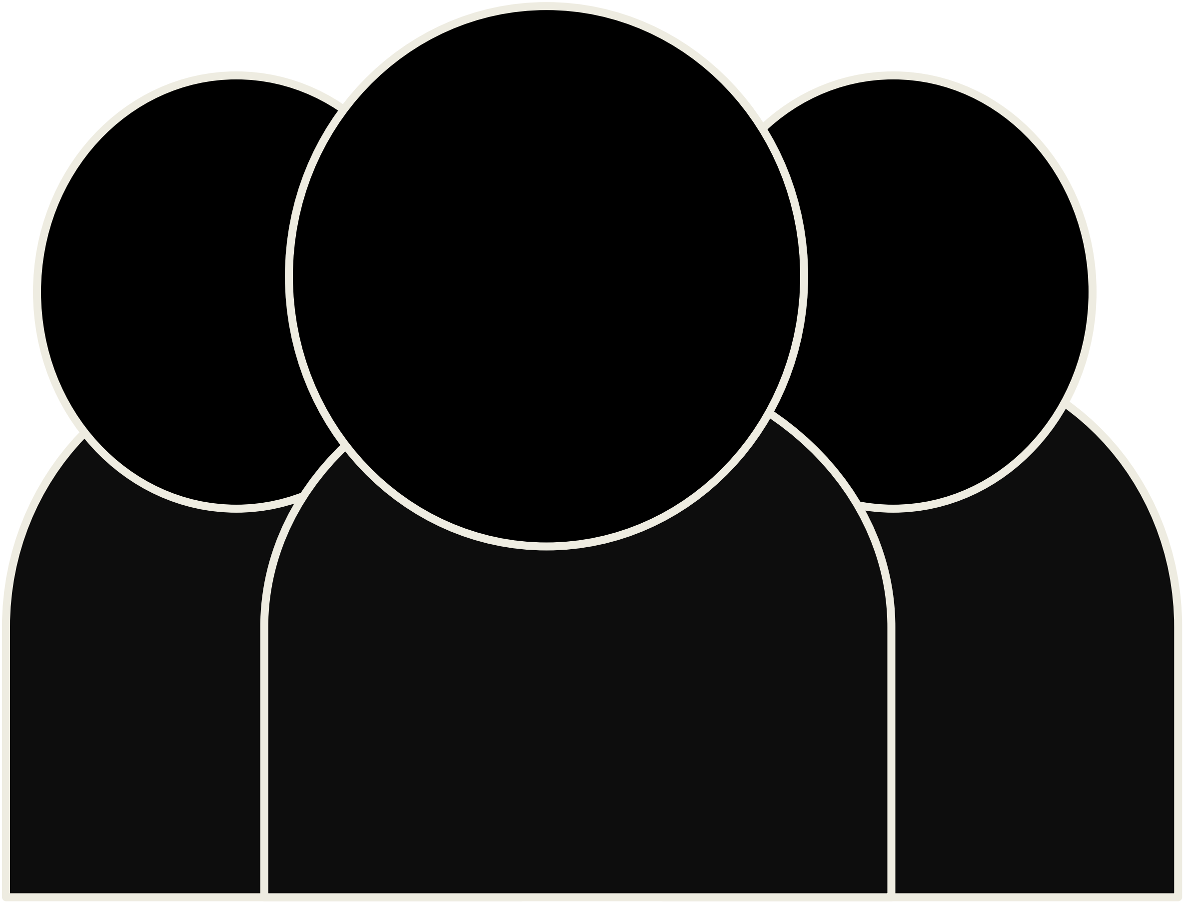
Image from Strauss, B.H., et al., 2021.

> "We find that approximately $8.1B… of Sandy's damages are attributable to climate-mediated anthropogenic sea level rise, as is extension of the flood area…"

Strauss, et al., 2021. Economic damages from Hurricane Sandy attributable to sea level rise caused by anthropogenic climate change. Nature comms.

SOCIETAL IMPACTS

Extremes can have devastating human impacts.



Impact of Extremes on Vulnerable Populations

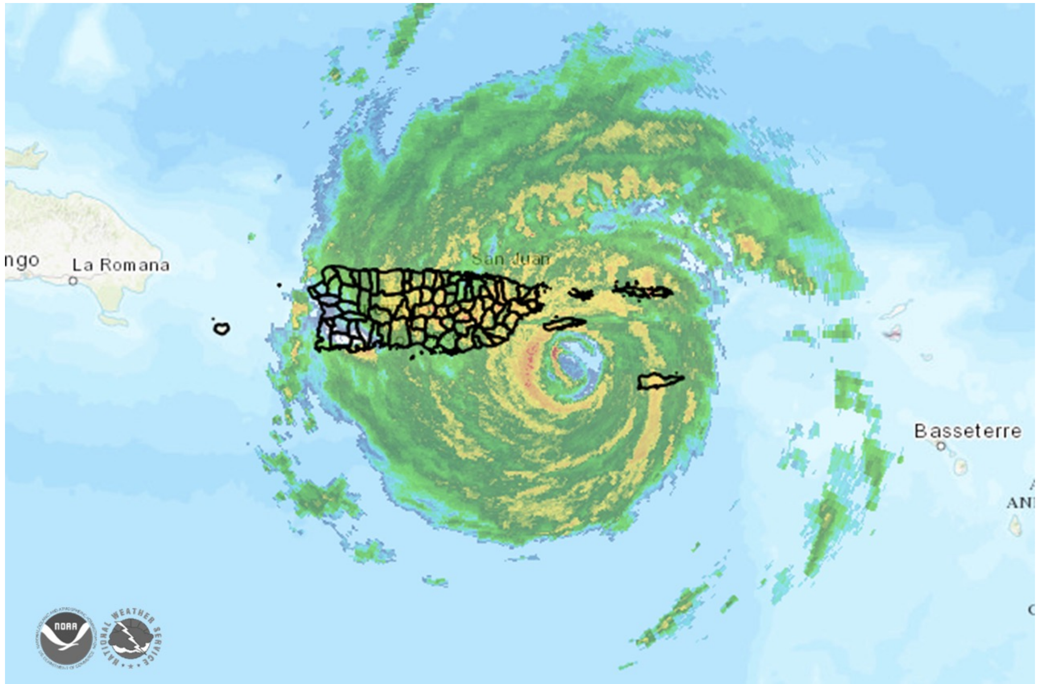
Historically marginalized communities experience **disproportionate vulnerability** to extreme weather events and climate change (Thomas et al. 2019).

Thomas, K., Hardy, R.D., Lazrus, H., Mendez, M., Orlove, B., Rivera-Collazo, I., Roberts, J.T., Rockman, M., Warner, B.P. and Winthrop, R., 2019. Explaining differential vulnerability to climate change: A social science review. Wiley Interdisciplinary Reviews: Climate Change, 10(2), p.e565.

IPCC, 2022: Summary for Policymakers [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3–33, doi:10.1017/9781009325844.001.

Hurricane (Tropical Cyclone) Maria (2017)

- Tied for the sixth-fastest intensifying hurricane in the Atlantic basin record.
- The rains caused serious flooding and mud slides across Puerto Rico (max ~38 inches/~97 cm).



TJUA NEXRAD Radar at 354 AM AST showing the center of Hurricane Maria just south of Vieques (NOAA NWS).

Pasch, R.J., Penny, A.B. and Berg, R., 2023. Hurricane Maria (AL152017), NOAA National Hurricane Center Tropical Cyclone Report.

Hurricane (Tropical Cyclone) Maria (2017)

- Based on a study from George Washington University's Milken Institute School of Public Health (2018), the government of Puerto Rico estimated there were 2,975 fatalities.
- Cell phone service was lost and municipal water supplies were knocked out.
- At of the end of 2017, nearly half of Puerto Rico’s residents were still without power.

Pasch, R.J., Penny, A.B. and Berg, R., 2023. Hurricane Maria (AL152017), National Hurricane Center Tropical Cyclone Report.

Climate change: a threat to human wellbeing and health of the planet. Taking action now can secure our future