Exploring the Source Regions and Paths of Atmospheric Moisture, and the Associated Atmospheric-Land Interactions that Promote High Humidity During Extreme Heat Events in the Northeast United States

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Abstract

Over the last several decades, heat waves have notably increased in frequency, intensity, and duration in the United States. Studies have credited these trends to a warming climate, and therefore, it is expected that extended periods of consistent and abnormally hot temperatures will continue to occur through the 21st century. Heat waves alone can have harmful impacts on the human body, but when coupled with high humidity, these events can become especially threatening. While other studies have assessed the human health effects of extreme humid heat waves, this study aims to determine the source region and pathway of air parcels during these events, while also understanding the land-surface processes that amplify and dampen the amount of atmospheric moisture present as an air parcel reaches a target region. Through the use of the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model, atmospheric moisture exchanges and concentrations are analyzed for the three days prior to a humid heat wave at Boston, MA, Burlington, VT, Albany, NY, and Philadelphia, PA, between June and August of 1980-2019. Four major source regions are identified as being largely responsible for the atmospheric moisture present during heat waves across these cities: the Atlantic Ocean, Gulf of Mexico, Great Lakes, and terrestrial evapotranspiration from the Midwest and Mid-Atlantic regions of the United States. Geographical location and proximity to water of each city has a notable influence on source region and number of humid heat waves occurring throughout the period of study. At Boston and Philadelphia, the two leading sources of moisture are the Atlantic Ocean and Gulf of Mexico, while at Burlington and Albany, the Great Lakes and terrestrial evapotranspiration are more dominant. Stark differences are also noted between the source regions and trajectories of humid versus dry heat waves at a given location. Examining the sources and paths of air parcels leading up to extreme heat events, as well as analyzing the atmospheric-land interactions that take place during that time, will provide a comprehensive understanding into the importance of a given moisture source region on a particular location, and how a warming climate may ultimately alter the degree to which a source region is responsible for atmospheric moisture in the future.

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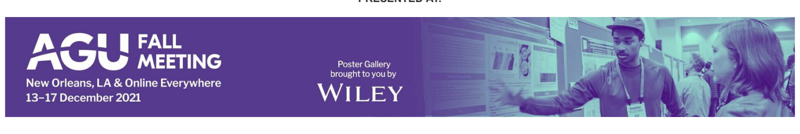


INTRODUCTION & MOTIVATION

Each year, municipalities across the United States are scorched with periods of consistent and abnormally hot temperatures. Dangerously hot temperatures alone can create life threatening conditions for populations, however, when coupled with high humidity, the impacts can become especially threatening.

Goal: Determine the source region and pathway of air parcels during extreme heat events across six locations in the Northeast United States, while also gaining insight into the atmospheric-land processes that amplify and dampen the amount of atmospheric moisture present as an air parcel reaches a target region.

Why is this important?

- Under abnormally hot and humid conditions, the efficiency of evaporative cooling of the human body is greatly reduced, thus, putting the body at risk of heat illness and ultimately hyperthermia.
- According to the National Climate Assessment's 3rd report, the Northeast United States is projected to be highly vulnerable to extreme heat events.
- The Northeast United States is the most densely populated region in the country, leaving millions at risk of serious heat illnesses moving into the future.
- Examining the sources and paths of air parcels, as well as the atmospheric-land interactions that take place in the days prior to an extreme heat event, provides a comprehensive understanding into the importance of a given moisture source region on a particular location.

DATA & METHODS

Heat Wave Definition/Identification:

- Three or more consecutive days where the daily maximum temperature (TMAX) exceeds the daily 95th percentile during the summer months (June - August) of 1980 - 2019.
  - Obtained daily TMAX data from gridMET, a 4-km resolution gridded dataset.
  - After using the 95th percentile criteria to identify the extreme heat days, heat wave days were further separated into "dry" and "humid" categories based on the associated minimum daily relative humidity (RMIN, gridMET).
  - **Humid Heat Waves** = daily RMIN > calendar day 75th percentile
  - **Dry Heat Waves** = daily RMIN < calendar day 25th percentile

Average TMAX, RMIN and HI on Humid Heat Wave Days

	TMAX (°C)	RMIN (%)	HI (°C)
Albany	33.40	51.27	38.06
Boston	33.26	49.33	36.39
Burlington	32.95	51.31	37.51
New York	34.75	43.97	38.42
Philadelphia	35.91	45.34	41.52
Pittsburgh	34.02	49.68	39.10

Average TMAX, RMIN and HI on Dry Heat Wave Days

	TMAX (°C)	RMIN (%)	HI (°C)
Albany	33.92	41.12	36.14
Boston	34.03	36.06	34.82
Burlington	32.95	40.96	34.31
New York	34.75	26.10	36.36
Philadelphia	36.81	27.45	37.34
Pittsburgh	34.71	36.27	36.22

Summary of average daily maximum temperature, minimum relative humidity, and heat index value on dry and humid heat wave days.

Surface Meteorological Data Analyzed:

1. The average **evaporation** (m of water equivalent) on the heat wave day and the three days prior from ERA5, a 0.25x0.25 degree resolution model, was used to observe areas of moisture uptake from the surface.
2. Daily **volumetric soil moisture** (ratio of volume of H_2O to unit volume of soil) data at 40 cm (surface to 40 cm) from NARR, a 32-km resolution model, were used to further assess the role of evaporation and the amount of moisture available from the surface.
3. Daily **sea surface temperature** (K) data from ERA5 was used to anaylze the average ocean and Great Lakes temperature on the heat wave days to better understand the role of evaporation from these bodies of water.
4. Daily **500 hPa geopotential height** data from NARR was obtained and used to assess the dominant atmospheric circulation patterns present on heat wave days.

Anomalies of each of the variables were computed as a way of observing any deviations from normal when heat wave events were taking place (and in the days prior).

Moisture Tracking:

Utilized the NOAA ARL Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) to generate backward trajectories for every heat wave event at the each of the six locations.

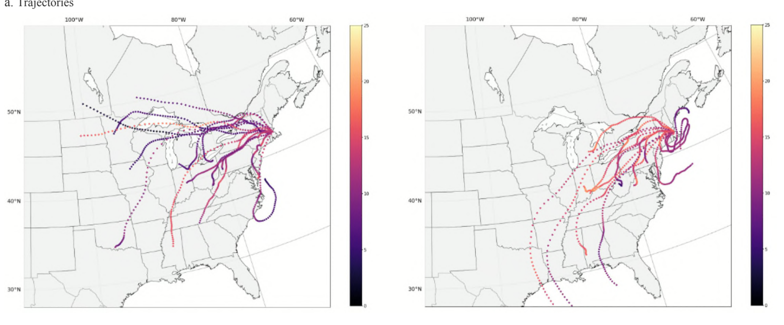
- Used a Lagrangian method (as opposed to Eulerian) to compute backward trajectories for this study, as the former approach allows for specified meteorological variables to be traced as air parcels move along the trajectory.

Generating the Trajectories:

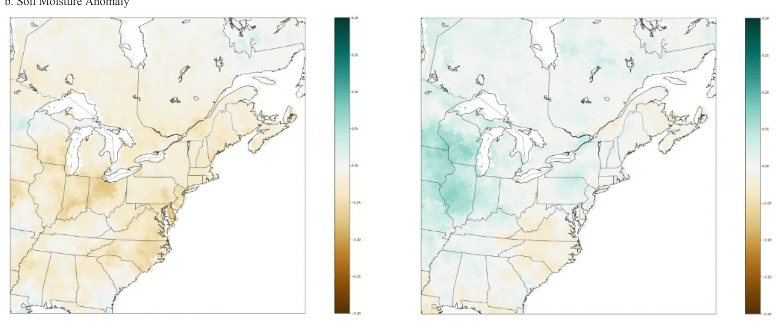
- Data from NARR was used to generate three-day backward trajectories, beginning on heat wave days at each location.
- Trajectories were launched from 200, 600, and 1000 mAGL.
- The pathway, height, specific humidity, precipitation, and moisture uptake were calculated along the trajectories at 1-hour intervals using 3-hourly NARR wind, temperature, humidity, and precipitation data.

BOSTON, MA

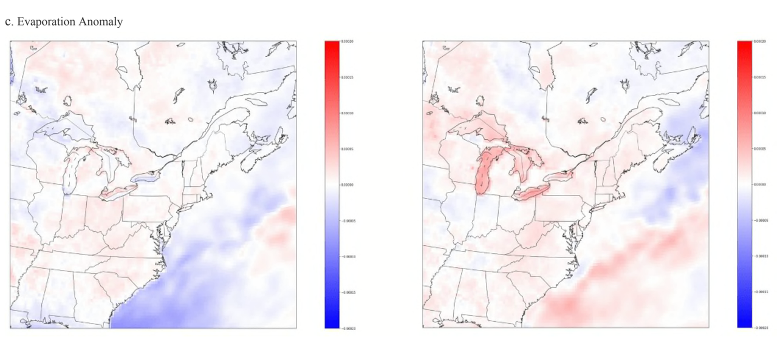
a. Trajectories



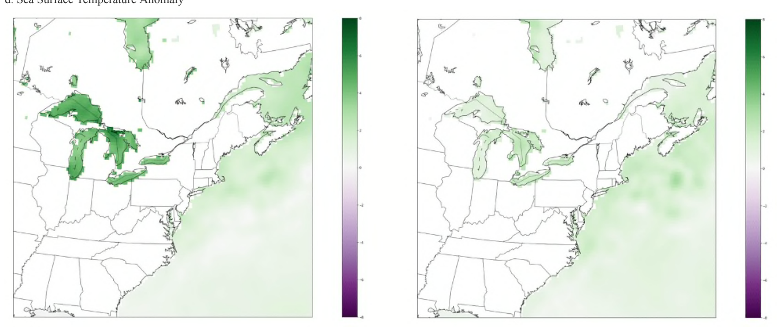
b. Soil Moisture Anomaly



c. Evaporation Anomaly



d. Sea Surface Temperature Anomaly

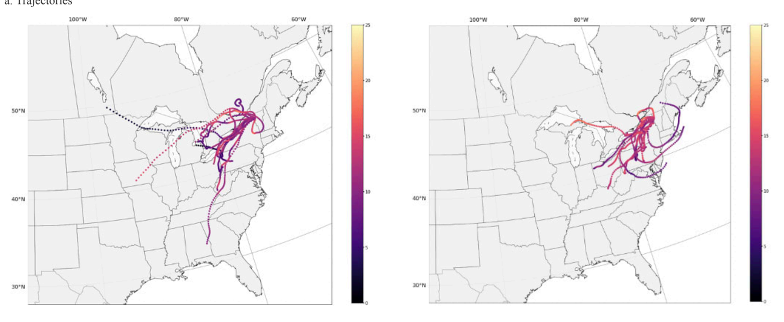


Key Takeaways:

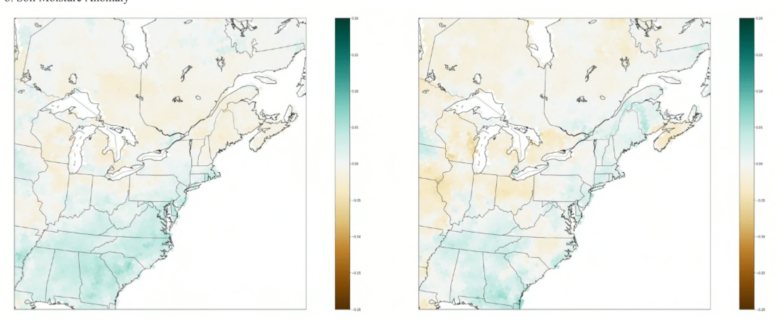
1. Dry (L) and humid (R) heat waves at Boston have notable differennce in trajectory path/source region.
2. During dry events, winds predominately flow from the west and southwest US (a), moving over drier than average soil (b). As a result, evaporation rates are weaker on these days than on humid heat wave days (c).
3. During humid heat events, wind flows primarily from the south and southeast US (a), moving over wetter than average soil (b), and thus, coinciding with stronger evaporation rates (c).

BURLINGTON, VT

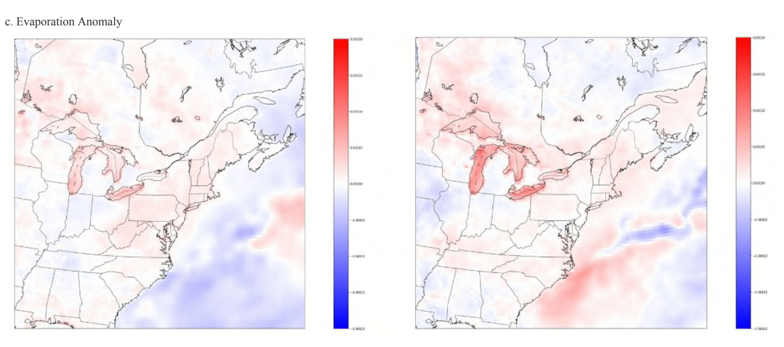
a. Trajectories



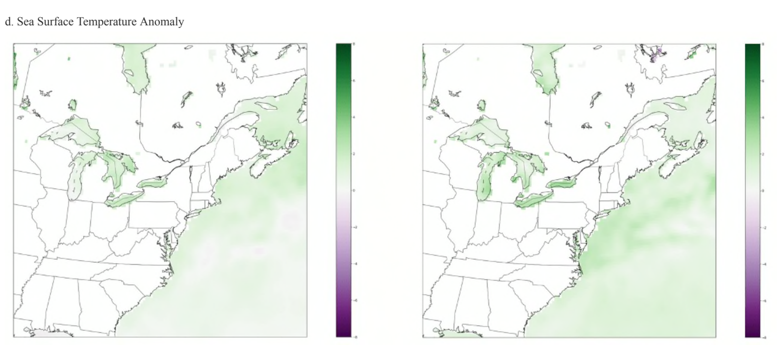
b. Soil Moisture Anomaly



c. Evaporation Anomaly



d. Sea Surface Temperature Anomaly



Key Takeaways:

1. Dry (L) and humid (R) heat waves at Burlington have fewer differences in trajectory path/source region. During both types of events, the winds generally flow from the southwest US, moving over the Great Lakes region (a).
2. During dry heat events, the soil moisture is near average in many parts of the region (specifically the NY/Canadian border) (b). Between near average soil moisture and weaker SST anomalies (d) in the Great Lakes region, evaporation rates are also found to be weaker during these events (c).
3. During humid heat events, the soil moisture is roughly the same in the northeast US as it is during dry events (b), however, evaporation rates are stronger (specifcally over water)(c), with stronger SST anomalies (d).

CONCLUSIONS

In the days leading up to a heat wave event, air parcels undergo atmospheric-land processes that result in the amplification or dampening of atmospheric moisture, thus, leading to the distinction between a dry and humid heat wave at a target location. For some locations, there are clear differences in the trajectory path/source region. These scenarios provide direct insight into the role that a source region plays in supplying moisture (or not) during a heat wave. On the contrary, other locations have similiar trajectory paths/source regions during both types of events, indicating that local surface processes (i.e. evaporation) play a greater role in differentiating between the atmospheric moisture content during both humid and dry heat events.

Understanding the source region and paths of atmospheric moisture, as well as the associated atmospheric-land process that take place along the way, offer useful insights and contributions that can aid in the preparation and warning of extreme heat events in the future.

FUTURE WORK

1. Access the daily minimum temperature that occurs during the nighttime. Higher nighttime temperatures will further prevent the body from getting any relief, and as a result, will be responsible for more heat related illness and death.

2. Generate trajectories and analyze the surface meteorological variables for the heat wave events that fall between the 25th and 75th percentile.

3. Generate 7-8 day backward trajectories to account for longer residence time of moisture in the atmosphere.

4. Perform analysis testing to determine if the differences between dry and humid heat wave events are statistically significant.

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