# Exploring the ability of reservoir infrastructure to mitigate climate change compounded impacts on stream temperature and water availability in the Southeastern United States

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## Introduction and objective
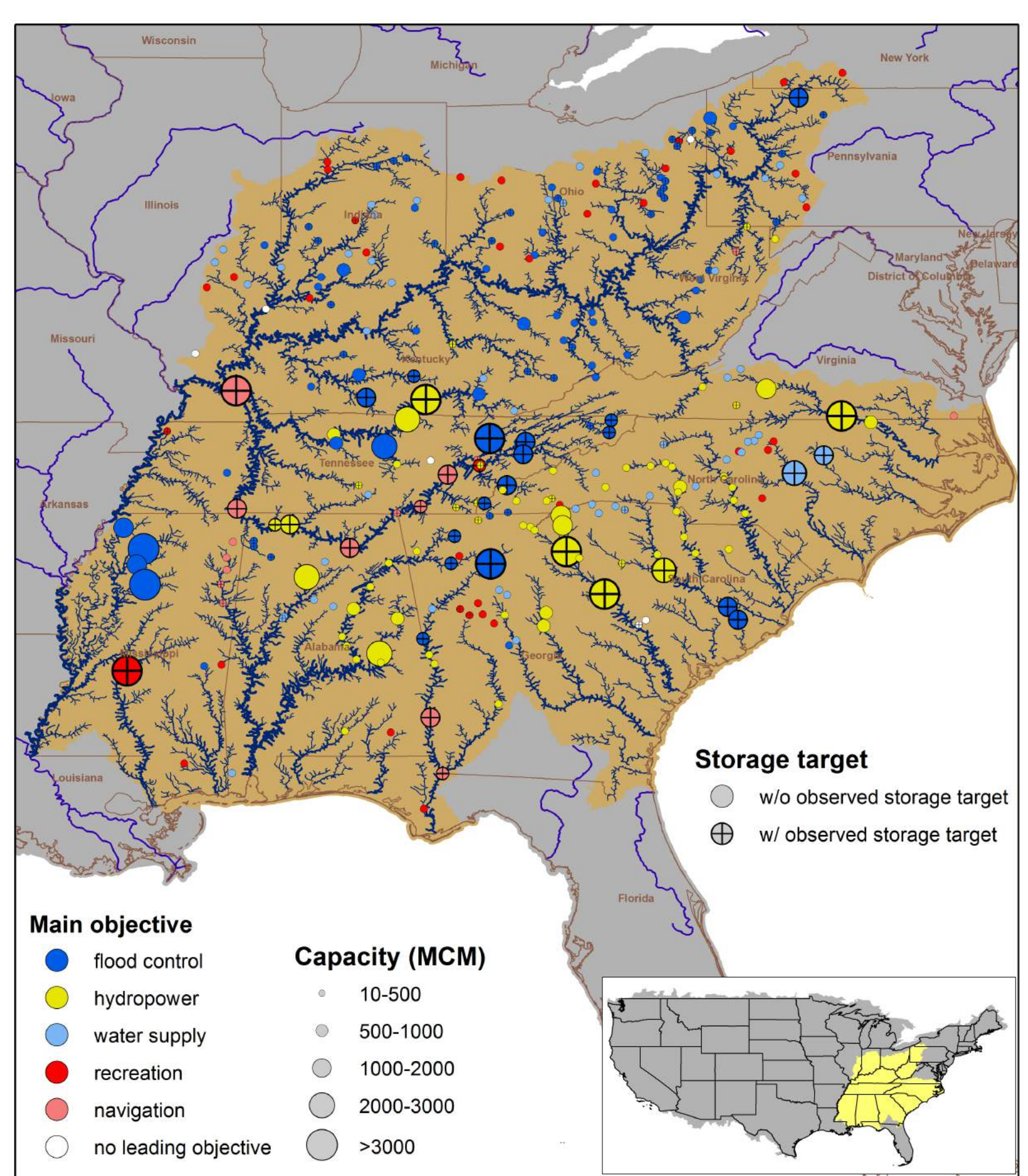
**Man-made reservoirs**
- Regulate and modify streamflow for multiple purposes
- Increase residence time
- Can cause seasonal thermal stratification
- Cool downstream river temperature during summer, which can be used to mitigate the impacts of climate change
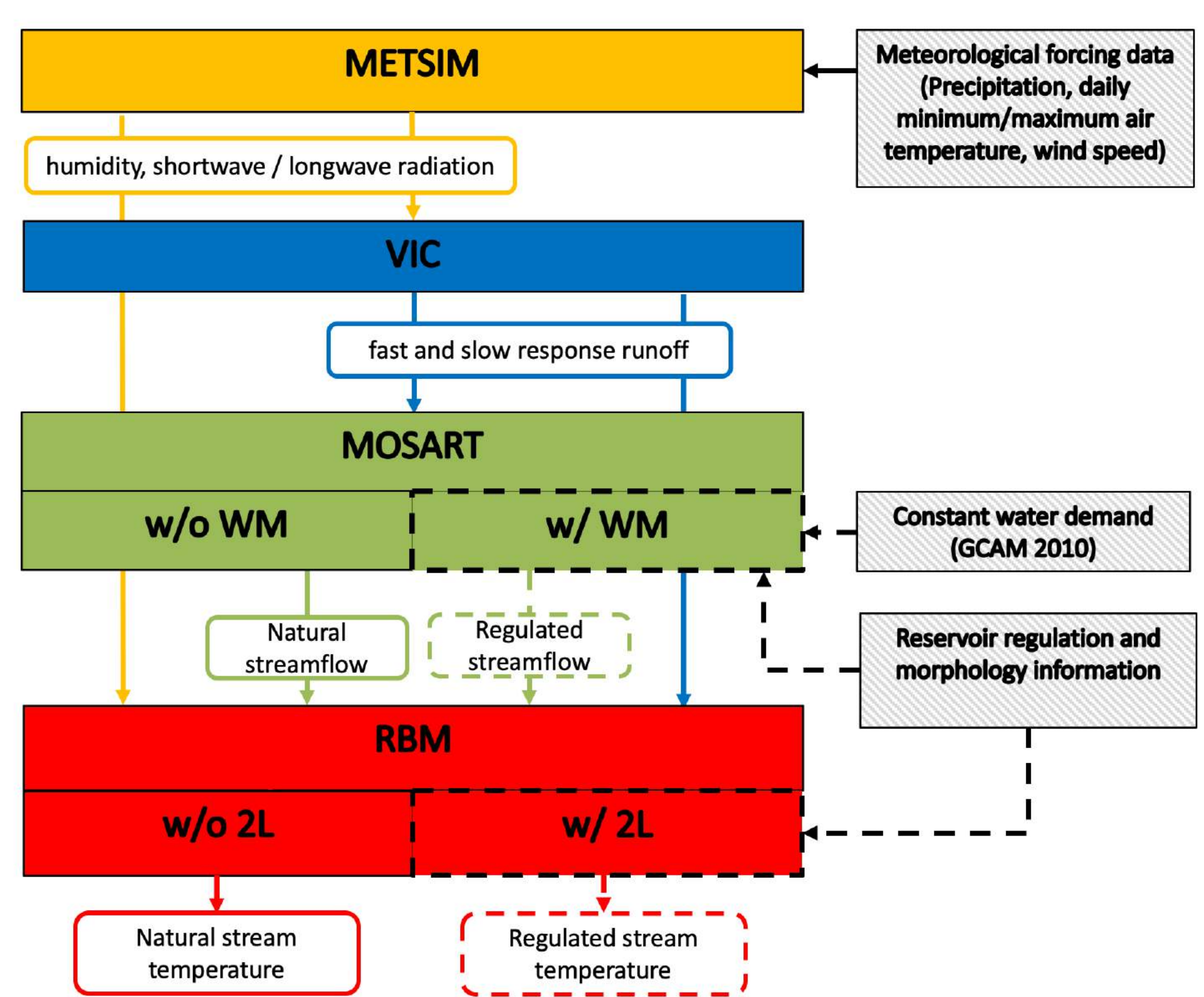
**Objective**
- Investigate how reservoirs can be used to mitigate the compounded impacts on river temperature and streamflow under current reservoir operation rules

**Study region**
- Southeastern United States (SEUS)
- Heavily regulated river systems for flood control, navigation, etc. (271 reservoirs, GRanD database, Lehner et al., 2011)



## Model structure and model experiments



**Meteorological data:**
- Historical data (1979-2010)
  - **METDATA** [Abatzoglou, 2013]
- Future data (2011-2099)
  - Downscaled CMIP5 data
  - Downscaling method: Multivariate Adaptive Constructed Analogs (**MACA**) [Abatzoglou and Brown, 2011]
  - GCM: 20 GCMs
    - BNU-ESM, bcc-csm1-1-m, bcc-csm1-1, CanESM2, CCSM4, CNRM-CM5, CSIRO-Mk3-6-0, GFDL-ESM2M, GFDL-ESM2G, HadGEM2-CC365, HadGEM2-ES365, inmcm4, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MIROC5, MIROC-ESM, MIROC-ESM-CHEM, MRI-CGCM3, NorESM1-M
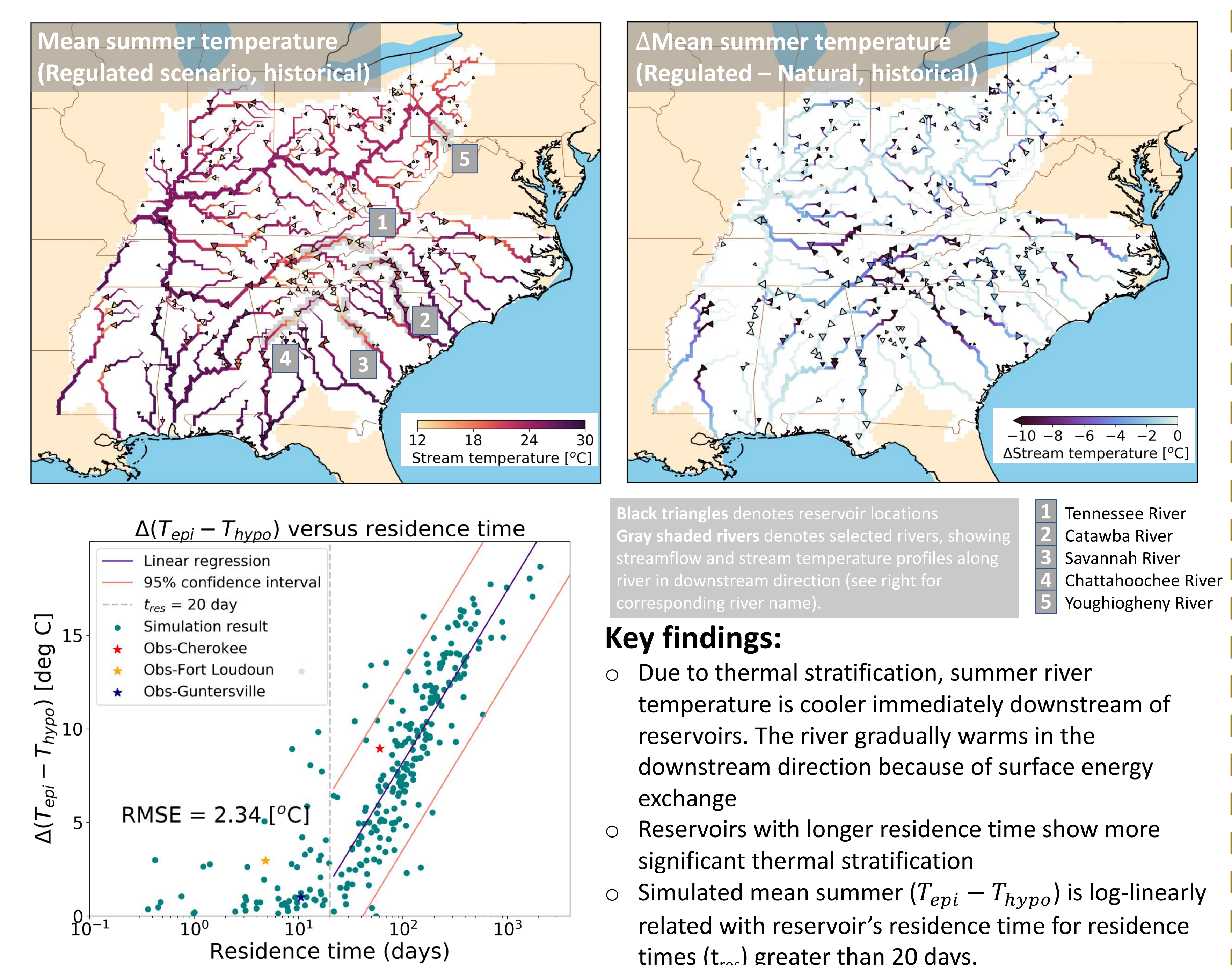  - RCP: RCP4.5 & RCP8.5

**Model set up:**
- Grid resolution: 1/8 degree (~12km)
- Timestep: Daily
- **VIC** model parameters [Maurer et al., 2002]
- **MOSART-WM** [Voisin et al., 2013]
  - Water demand (**GCAM**)
  - Fixed storage target for both historical and future period
- **RBM** is fully coupled with a two-layer (2L) thermal stratification model [Yearsley, 2009, 2012]
- Reservoir information
  - Map reservoir locations to grid-based network (match contributing area)
  - Set storage target for **WM** based on historical observations of storage

**Model experiments:**
- Investigate how reservoir regulation can be used to mitigate the impacts of climate change on streamflow and stream temperature
- Two experiments are designed:
  - **Natural:** No reservoirs (w/o WM & w/o 2L)
  - **Regulation:** Regulated river system (w/ WM & w/ 2L)
    - water management model (**WM**) is fully-coupled with routing model (MOSART) to simulate regulated streamflow.
    - A two-layer thermal stratification module (**2L**) is fully-coupled with the river temperature model (RBM) to simulate water temperature (reservoir and river) in regulated systems.

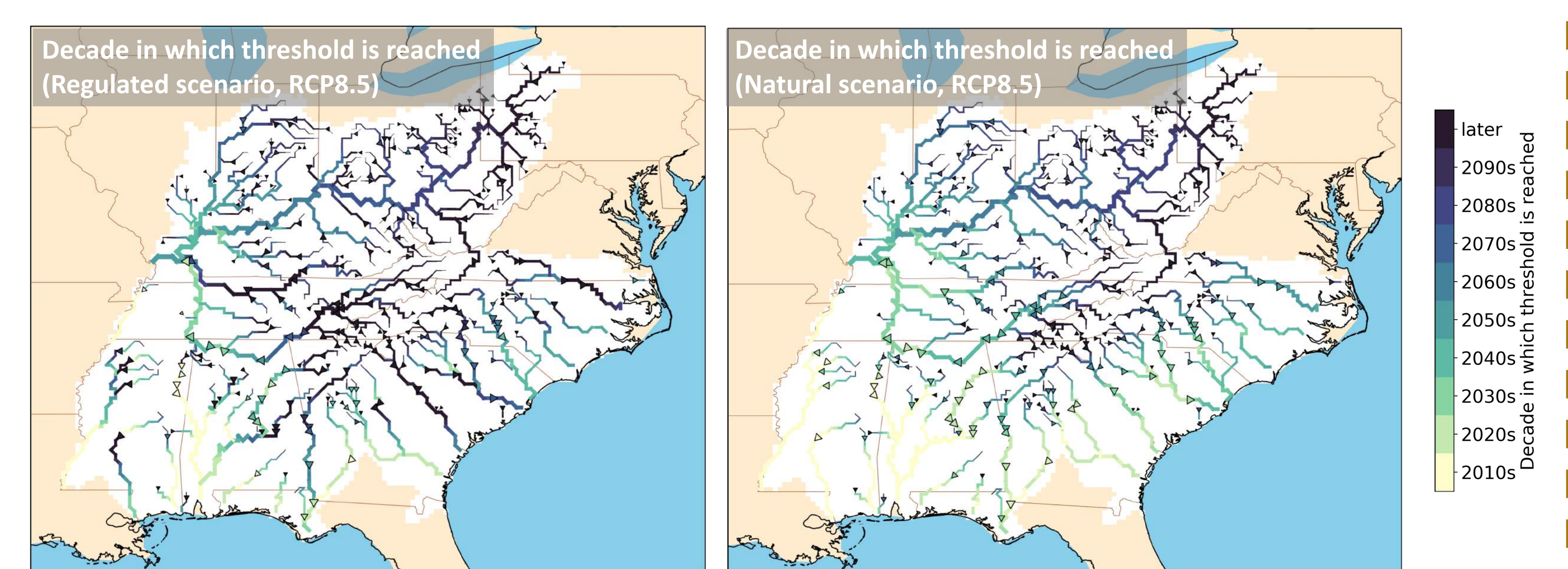## Residence time impacts on thermal stratification



**Black triangles** denotes reservoir locations
**Gray shaded rivers** denotes selected rivers, showing streamflow and stream temperature profiles along river in downstream direction (see right for corresponding river name).

| | |
|---|---|
| 1 | Tennessee River |
| 2 | Catawba River |
| 3 | Savannah River |
| 4 | Chattahoochee River |
| 5 | Youghiogheny River |



**Key findings:**
- Due to thermal stratification, summer river temperature is cooler immediately downstream of reservoirs. The river gradually warms in the downstream direction because of surface energy exchange
- Reservoirs with longer residence time show more significant thermal stratification
- Simulated mean summer $(T_{epi} - T_{hypo})$ is log-linearly related with reservoir's residence time for residence times ($t_{res}$) greater than 20 days

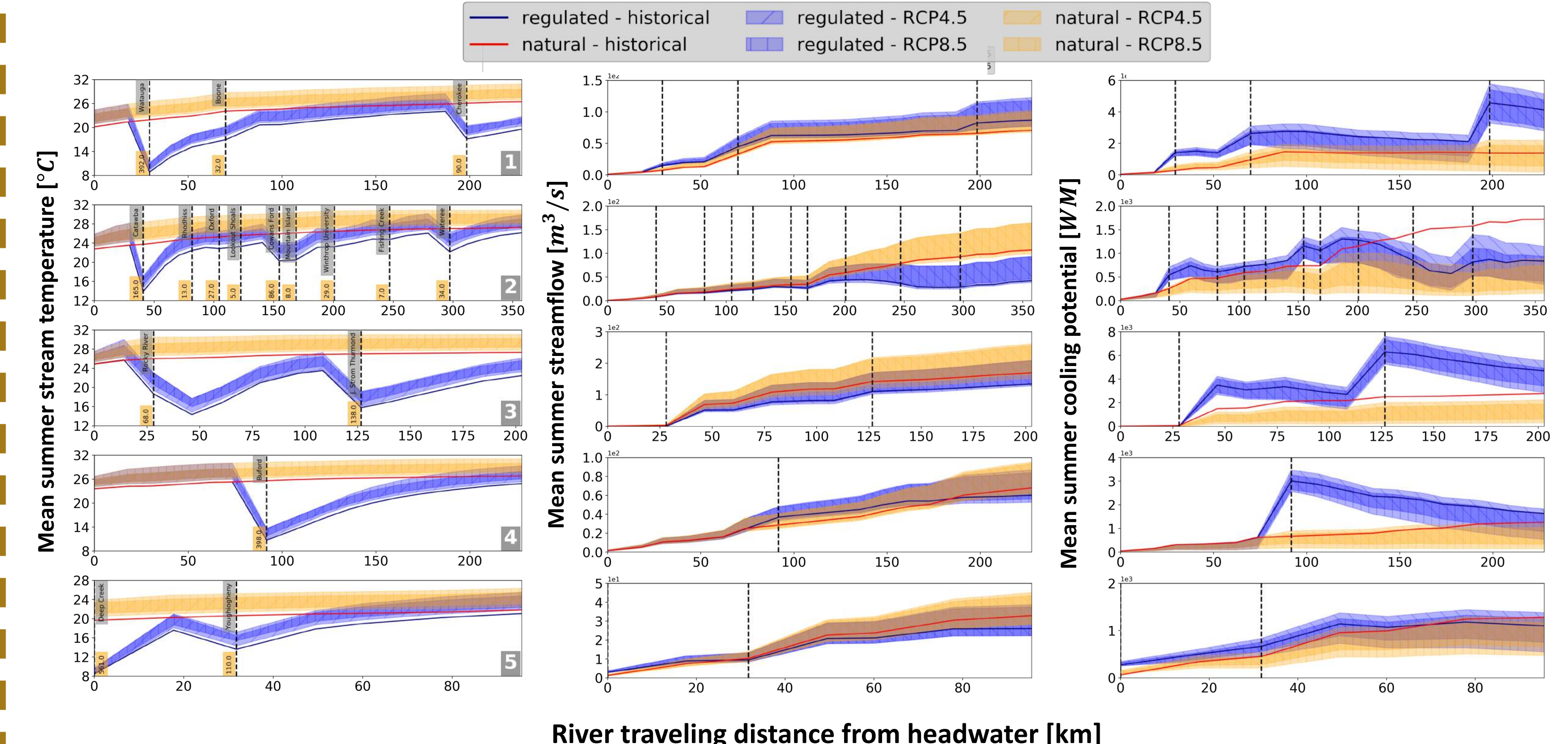## When does river temperature reach "threshold"?



**"Threshold" definition:**
- *Threshold metric*: Mean annual number of days during which the stream temperature exceeds a given value. Average calculated for each 10-year period (e.g., 2010s: 2010-2019)
- *Threshold value*: 7 days
- *Temperature standard:* Use 31°C ($T_{EPA}$) for entire region for consistency (median value EPA temperature standards of all Southeastern states)

**Key findings:**
- When there is no regulation, the time to reach the threshold is spatially related to air temperature.
- The Tennessee and Ohio rivers reach the threshold in the 2040s and 2060s, respectively
- In the regulated scenario, the time to reach the threshold is delayed compared to the natural scenario, especially downstream of reservoirs with longer residence times

## What is the summer "cooling potential"?



| Vertical black dashed line | Reservoir locations |
|---|---|
| Yellow shaded box | Reservoir residence time (days) |
| Gray shaded box with black text | Reservoir names |
| Gray shaded box with white text | River numbers (left for corresponding names) |

**"Cooling potential" definition:**
- *Definition:* Energy required to warm the river to the temperature standard (31°C)
- *Calculation:*
$$E_{cooling} = \rho C_p (T_{EPA} - T_{sim}) Q_{sim}$$
- *Why this metric:* combined evaluation of regulated streamflow and stream temperature
- *Period:* 2070-2099 (Late 21st century)

**Key findings:**
- Reservoir seasonal thermal stratification persists under climate change.
- In general, there will be more water available for Southeastern United States during summer.
- There is a decreasing trend in the available cooling potential under both regulated and natural scenarios because of the increase in stream temperature. However, the impacts are greater under the natural scenario, especially when temperature reaches 31°C standard.

## Discussion and conclusion

- Reservoirs with longer residence time tend to have stronger thermal stratification during summer
- Thermal stratification is projected to persist under future climate change
- Due to thermal stratification, the time to reach the threshold is delayed in regulated rivers compared to the natural scenario. The length of the delay depends on the reservoir's degree of stratification, with greater reservoir stratification resulting in a longer delay.
- There will be more summer streamflow in late 21st century.
- The cooling potential decreases for all rivers and scenarios because the increase in stream temperature dominates the signal compared to the increase in streamflow.

## Acknowledgements

## References

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Voisin et al., 2013, doi: 10.5194/hess-17-4555-2013
Yearsley, 2009, doi: 10.1029/2008WR007629
Yearsley, 2012, doi: 10.1029/2011WR011515