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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Abstract

Over 270 major dams have been constructed in the Southeastern United States (SEUS) during the past century, changing natural flow patterns and affecting stream temperatures. Projected increases in air temperature combined with changes in precipitation may result in water scarcity and affect maximum stream temperatures during the summer for some regions in the SEUS. Currently existing reservoirs mitigate water shortages during drought by releasing more water but reducing residence time, the ratio of reservoir volume to inflow. Regulating stream temperature in the summer can be done by either increasing residence time or releasing more water. In this study, we investigate the extent to which the current reservoir infrastructure can be used to mitigate the impacts of climate change under current reservoir regulations as well as the range of operating rules that could minimize climate change impacts on both streamflow and river temperature. We use the Variable Infiltration Capacity (VIC) hydrological model to simulate runoff, which is then used as input to a large-scale river routing-reservoir model (MOSART-WM) to simulate reservoir operations and produce regulated streamflow. VIC and MOSART-WM outputs are then used as input to a stream temperature model that accounts for thermal stratification in reservoirs (RBM-res). Climate change projections are based on two representative concentration pathways (RCPs) and multiple global climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5). We compare modeled changes with those from a model implementation that does not include any reservoirs and which therefore lacks any flow regulation (VIC->MOSART-RBM) to evaluate the resilience of current reservoir infrastructures. We also evaluate different reservoir operating rules (residence time versus low flow mitigation) to investigate the extent to which the current reservoir system can be used to mitigate the impacts of climate changes on both streamflow and stream temperature.

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Introduction and objective

Man-made reservoirs

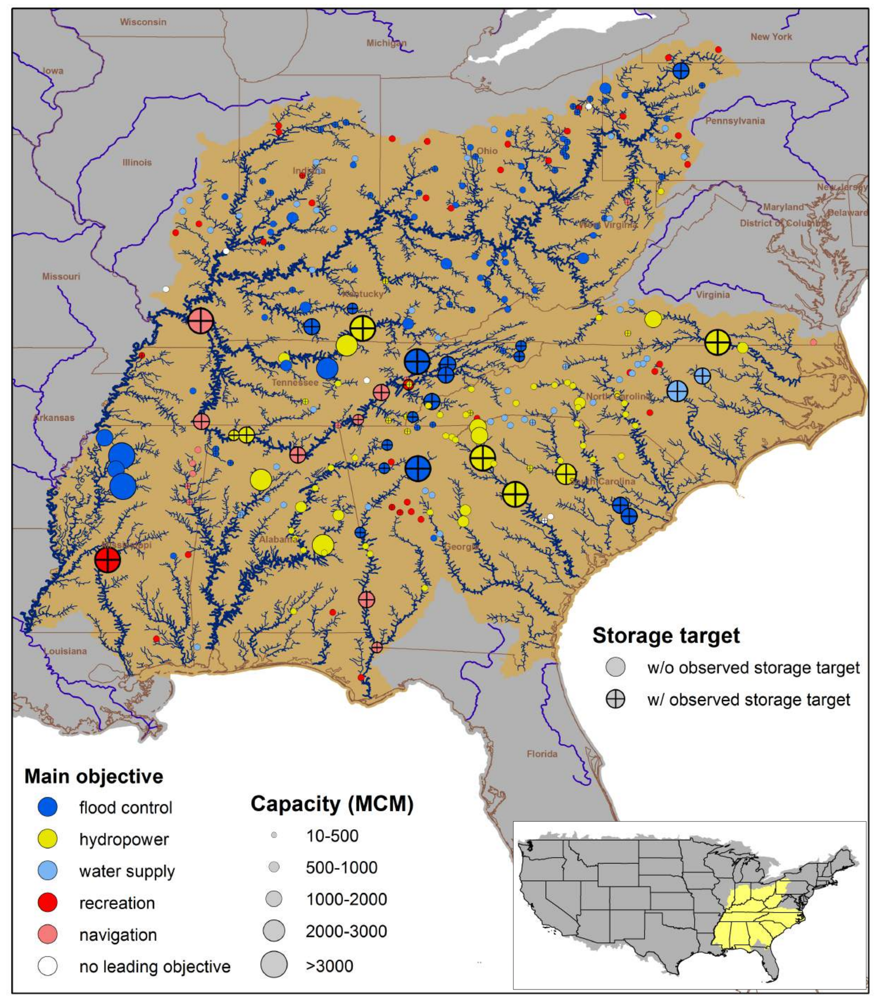
- Regulate and modify streamflow for multiple purposes
- Increase residence time
- Can cause seasonal thermal stratification
- Cool downstream river temperature during summer, which can be used to mitigate the impacts of climate change

Objective

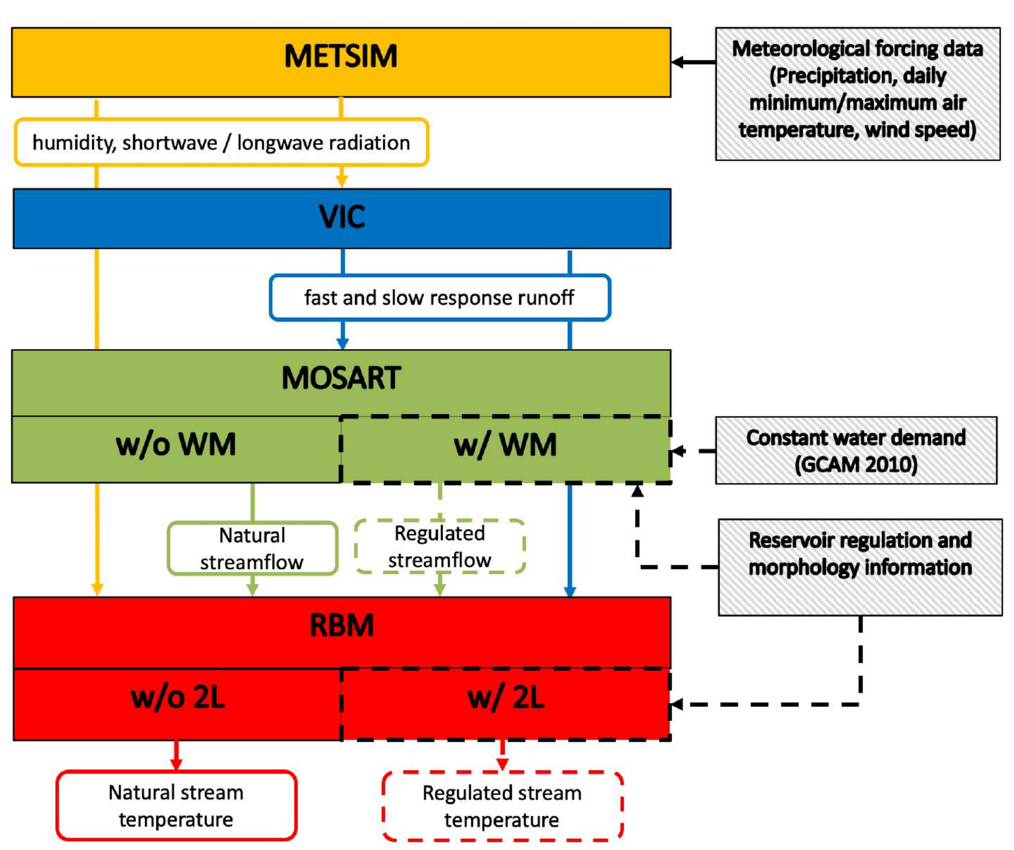
- Investigate how reservoirs can be used to mitigate the compounded impacts on river temperature and streamflow under current reservoir operation rules

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

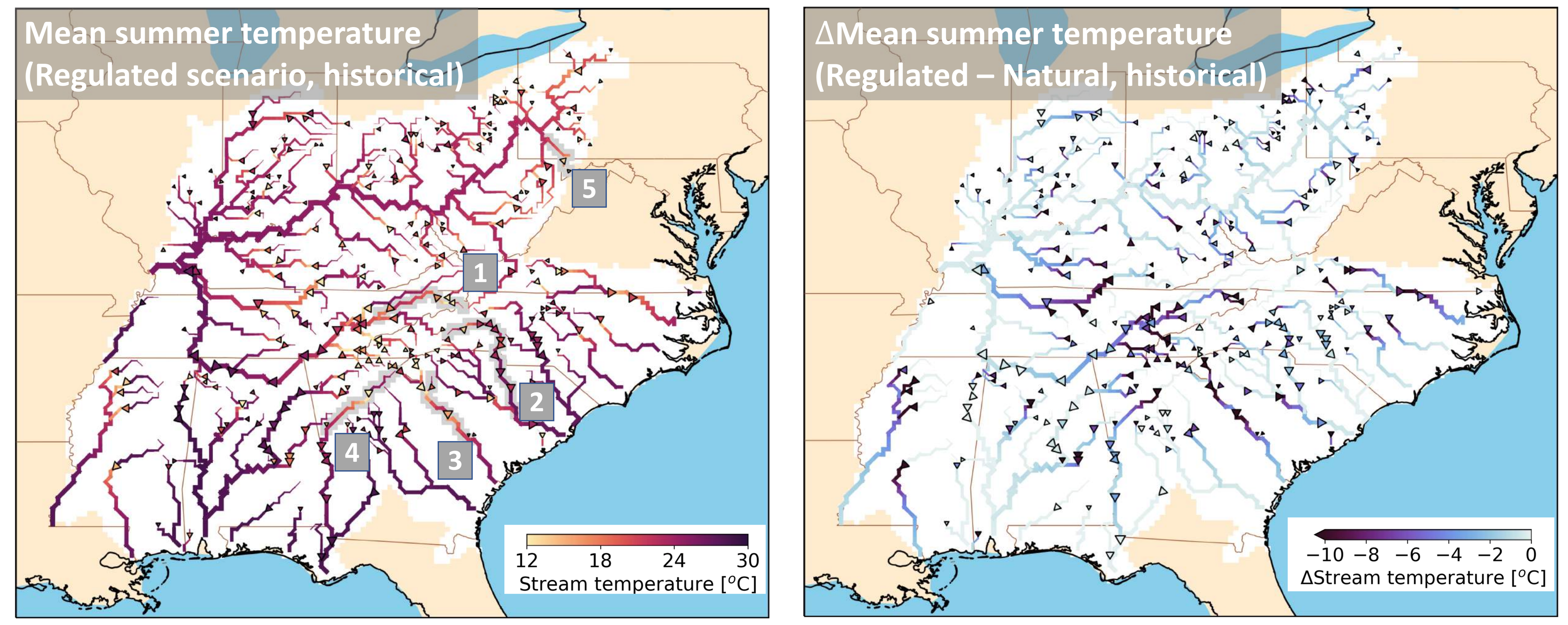
Model set up:

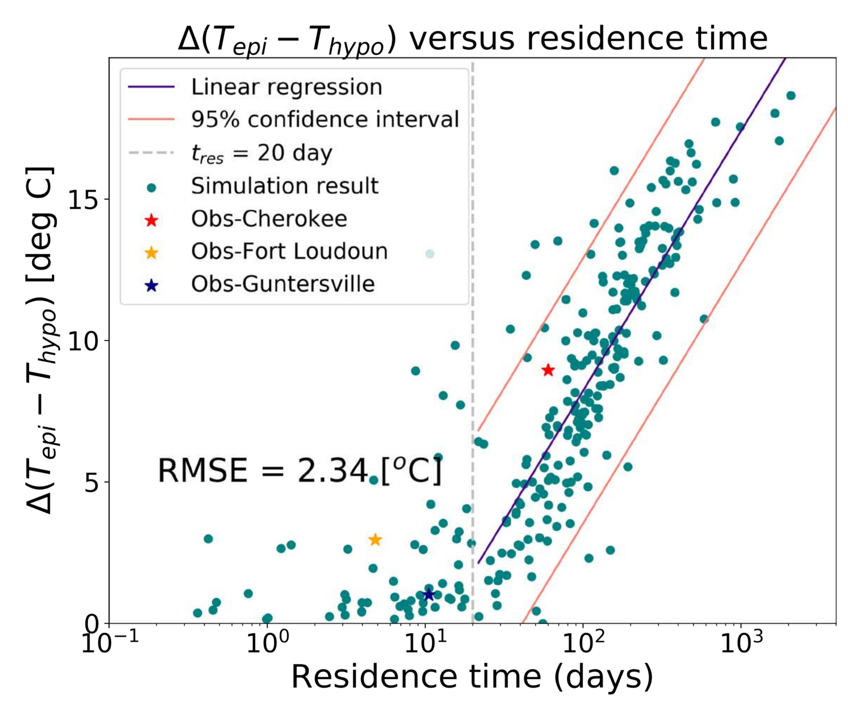
- Grid resolution: 1/8 degree (~12km)
- Timestep: Daily
- **VIC** model parameters [Maurer et al., 2002]
- **MOSART-WM** [Voisin et al., 2013]
  - Water demand (**GCAM**)
  - Fixed storage target for both historical and future period
- **RBM** is fully coupled with a two-layer (2L) thermal stratification 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





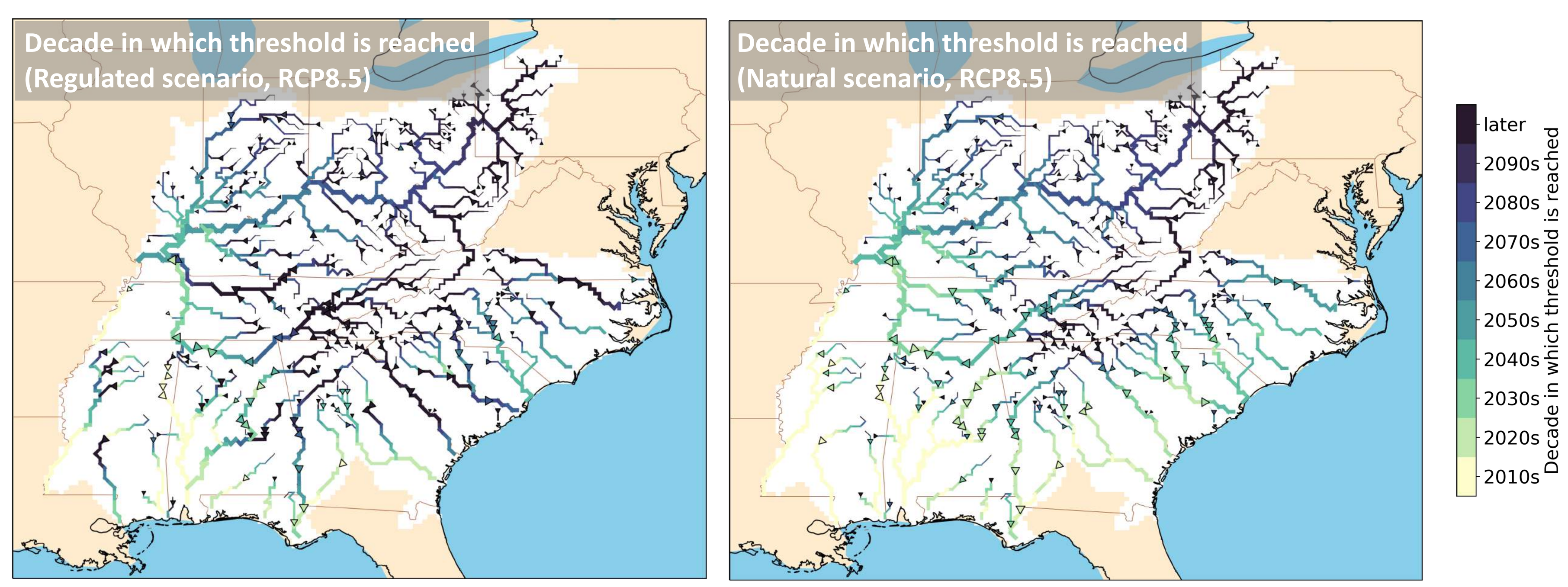
Black triangles denotes reservoir locations
Gray shaded rivers denotes selected rivers, showing streamflow and stream temperature profiles along river in downstream direction (see right for corresponding river name).

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"?



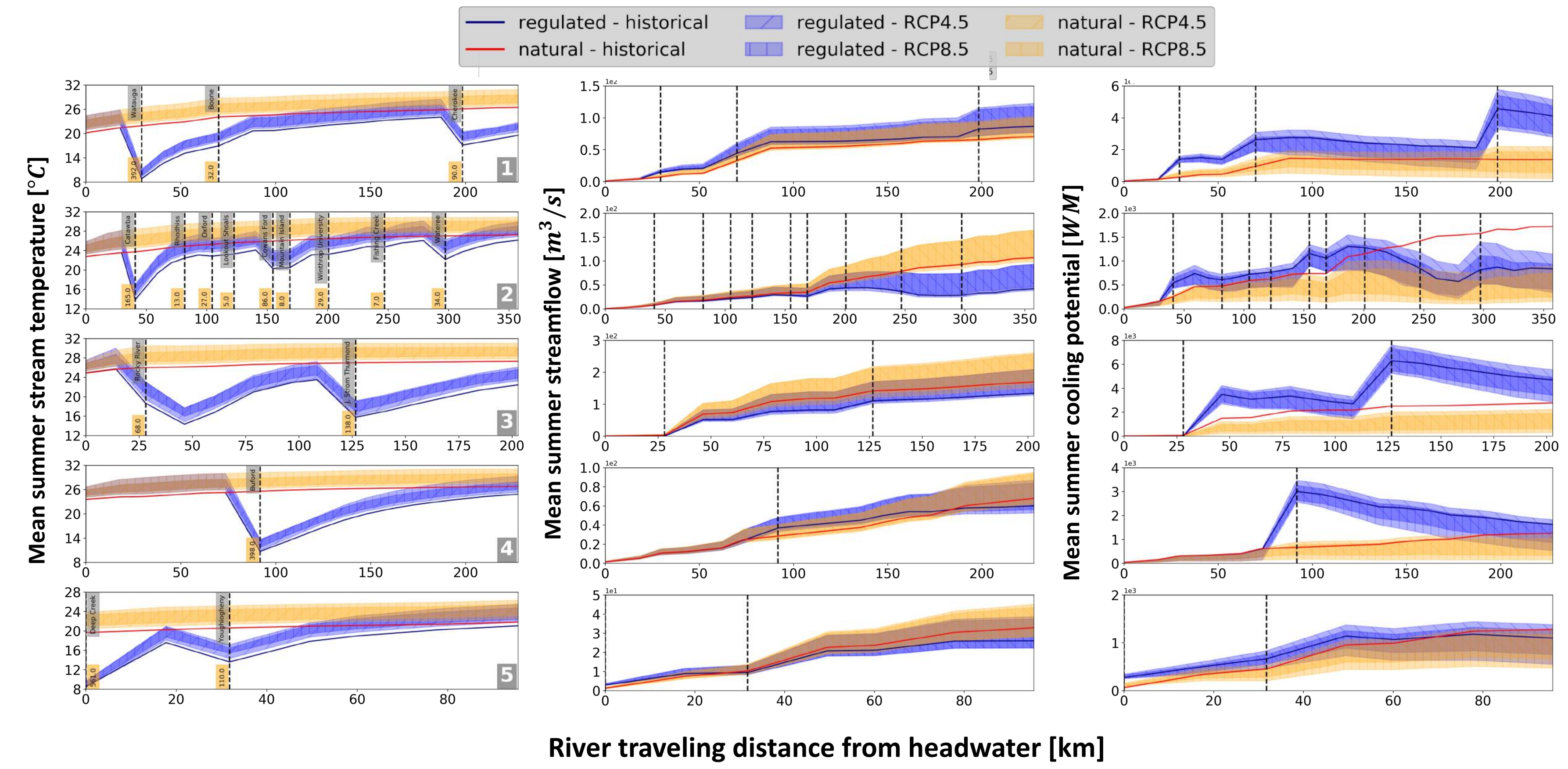
"Threshold" definition:

- *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

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