U.S. DEPARTMENT OF ENERGY | Office of Science

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FY 2019 Second Quarter Performance Metric: Implement and Evaluate the Effects of Air Temperature Change and Water Management on Stream Temperature

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1.0 Product Definition

Stream temperature is a key water quality measure for water management, thermoelectric power production, and conservation activities. Currently, 85% of electricity generation in the United States comes from power plants that require cooling. Changes in stream temperature and water availability directly affect thermoelectric power generation capacity. High water temperature and low streamflow can increase cooling water requirements and restrict cooling water availability, which constrains the usable capacity of thermoelectric power plants. This constraint may become more acute in the future, as droughts are projected to be more widespread and prolonged in a warmer climate. These motivate the need to model stream temperature and understand the relative impacts of air temperature and water management on stream temperature.

Stream temperature is mainly controlled by the heat exchanges between river water body and air and river banks, and heat transportation along the river networks. Notably, 98% of the rivers and streams in the United States have been dammed, diverted, or developed. Reservoirs regulate flows for various purposes, such as flood control, irrigation, hydropower production, and navigation. This alters the flow regime by storing water during high-flow periods and enhancing the low flows during the dry season. Changes in the flow regime have important impacts on stream temperature, as they alter the heat exchanges between the rivers and air and river banks.

Through an effort supported by the Multisector Dynamics activity within the Earth and Environmental Systems Modeling program, a stream temperature module has been developed as part of the Model for Scale Adaptive River Transport (MOSART) and coupled with a water management model (WM). This metric report describes (1) the implementation of the stream temperature module and its global testing and evaluation within the Department of Energy’s Energy Exascale Earth System Model (E3SM) and (2) analysis of simulations to understand the relative impacts of air temperature and water management on stream temperature in basins around the world. Simulations with and without water management show that water management has large impacts on the seasonal cycle of stream temperature in arid and semi-arid regions (western U.S., central Asia, northeastern China) where water management alters the flow regime to provide irrigation water supply and in India where groundwater pumping for irrigation is prominent.

2.0 Product Documentation

A Brief Description of MOSART-Heat

MOSART-heat is a stream temperature module (Li et al. 2015a) developed on top of MOSART (Li et al. 2013; 2015b), which is the river component of E3SM v1. MOSART-heat has been implemented in E3SM through coupling with the E3SM Land Model (ELM). MOSART-heat mainly represents natural thermodynamic processes that control stream temperature, including the lateral heat fluxes from hillslope and soils (along with surface and subsurface runoff) into tributary channels, heat balance in tributary channels and main channels respectively. The surface runoff temperature is estimated as the average soil temperature of the top three soil layers in ELM, and the subsurface runoff temperature is estimated as the average soil temperature within the saturated soil layers, which vary with time due to changes in the water table level.

For both the tributary and main channels, the same set of heat balance equations are implemented, including the advective heat fluxes into and out of channels and the heat exchanges between atmosphere and channel water, such as solar radiation, latent heat, and sensible heat. The atmosphere-river heat exchanges are estimated as functions of atmospheric forcings (e.g., solar radiation, wind speed, air temperature) and channel water variables (e.g., water storage, surface water area, water temperature). With coupling to E3SM, the atmospheric forcings are provided as inputs to MOSART-heat via the flux coupler. Note that the current version of MOSART-heat does not include channel ice transport and phase changes (between ice and liquid water), leading to apparent biases of stream temperature simulation in frozen areas or seasons.

MOSART has been coupled to a water management model (WM) (Voisin et al. 2013a; b). In the current version of MOSART-heat_wm, the impacts of WM on stream temperature are captured mainly through regulating and changing the water storage in tributary and main channels. Changes in channel water storage lead to changes in both water surface area and heat storage capacity of channel water, affecting the heat exchanges between channel water and atmosphere. WM also affects stream temperature by regulating streamflow, hence modifying the associated advective heat fluxes. The conceptual structure of MOSART-heat coupled to ELM without (MOSART-heat_nat) and with (MOSART-heat_wm) WM is illustrated in Figure 1. Note that the impacts of thermoelectric power plants on stream temperature are not represented in the model, as such effects are generally confined to a relatively short distance downstream of the power plants. This implementation will be released in E3SM v2. Future improvements planned for E3SM v3 include the incorporation of a module to treat the thermal stratification effect (which causes vertical temperature difference in deep water bodies like reservoirs).

Numerical Experiment

To evaluate MOSART-heat and the relative impacts of air temperature and water management on stream temperature, two simulations were performed using MOSART-heat coupled to ELM in an offline global configuration. The first simulation (nat) did not include coupling with WM, so the streamflow and stream temperature in this simulation correspond to the natural conditions only. In the second simulation (wm), MOSART and MOSART-heat were coupled with WM, so the impacts of flow regulation and water extraction are simulated in addition to changes in natural conditions. Comparison of the two simulations allows us to evaluate the relative impacts of air temperature and water management on streamflow and stream temperature.

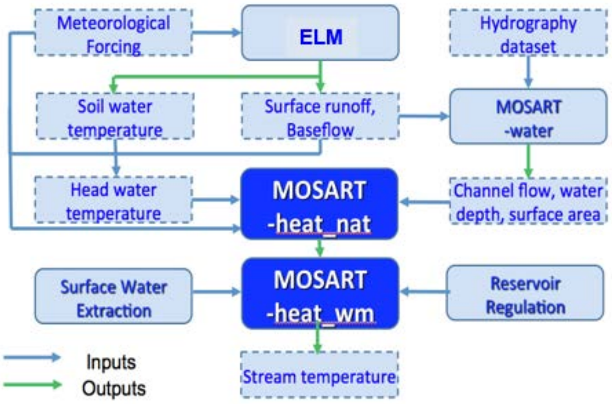


Figure 1. Conceptual diagram of MOSART-heat and coupling to ELM and WM. MOSART-heat_nat and MOSART-heat_wm are the MOSART-heat components without (natural) and with water management (adapted from Li et al. (2015a)).

The simulations were driven by the QIAN meteorological forcing data (Qian et al., 2006) from 1972 to 2000 for a total of 29 years. The QIAN forcing dataset includes 6-hourly air temperature, specific humidity, wind speed, surface pressure, precipitation, and incoming solar radiation. The data were interpolated to the ne30 grid used by ELM, which has a horizontal resolution ~100km. The cropland in ELM was represented by crop plant function types based on MIRCA2000 (Portmann et al., 2010). The model simulates irrigation water demand following Leng et al. (2013; 2014). The surface water and groundwater withdrawal fractions were based on the gridded maps created by Siebert et al. (2010) and re-gridded to the ne30 resolution.

The MOSART-WM model was run on a 0.5° latitude-longitude grid. The model requires topographic parameters including flow direction, channel length, as well as terrain and channel slopes to simulate the river flow. These parameters were derived using the Dominant River Tracing (DRT) algorithm (Wu et al., 2012), which was produced based on the 90m resolution Hydrological Data and Maps Based on Shuttle Elevation Derivatives at Multiple Scales (HydroSHEDS) (Lehner et al., 2006). Dam and reservoir parameters were obtained from the Global Reservoir and Dam (GRanD) database (Lehner et al., 2011), which includes dam location, reservoir capacity, and major functions for more than 4,200 dams worldwide. The location of the dams and the spatial distribution of the cropland equipped for irrigation are presented in Figure 2.

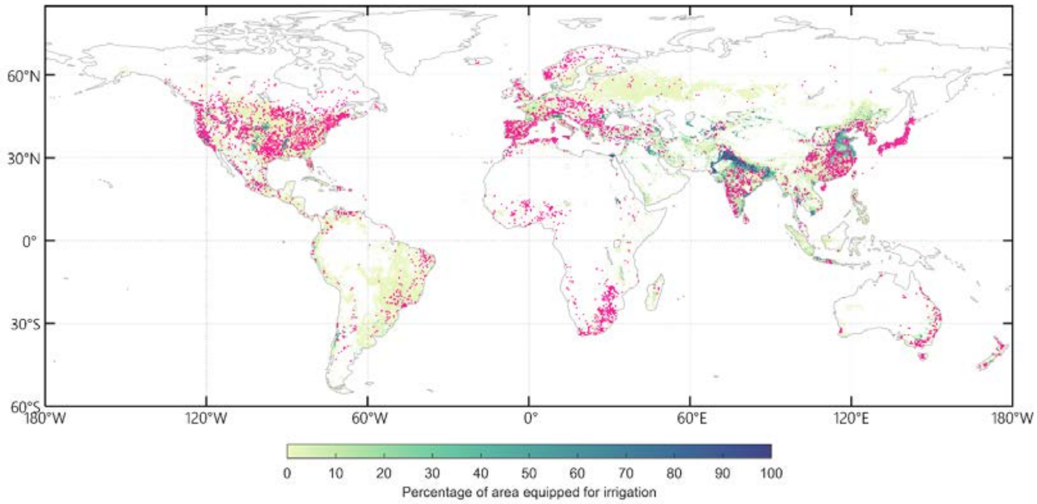


Figure 2. Dams (pink dots) and irrigated land color-coded as inputs in the global simulations (from Zhou et al. 2019).

3.0 General Discussion

The relative impacts of air temperature and water management on stream temperature are analyzed by comparing the "wm" and "nat" simulations. Figure 3 compares the simulated long-term mean streamflow and stream temperature with observations at stream gauges around the world. Observed streamflow data are from the Global Runoff Data Center (GRDC) while observed stream temperature data are from the U.S. Geological Survey and Global Environment Monitoring System (GEMS). Streamflow is generally well simulated and at an annual scale, and the impact of water management is small as the "nat" and "wm" simulations produced similar results. For stream temperature, a general warm bias is found in many locations in the "nat" simulation, with biases as large as 20°C in colder regions.

As discussed earlier, MOSART-heat currently does not represent ice transport and phase changes, so larger biases are expected in cold regions. Noticeably, including water management in the model reduces the warm biases in many locations.

To quantify the impacts of water management on model performance in the simulations, Figure 4 shows the stream gauge locations and the change in the Nash-Sutcliffe (NS) coefficient between the "nat" and "wm" simulations. A red dot is shown in locations where the NS coefficient is higher in "wm" relative to "nat," that is locations where including water management improves the model skill. A blue dot indicates no change or a reduction in the NS coefficient in "wm" relative to "nat." For streamflow, improvements are generally found over the U.S., Europe, eastern Brazil and eastern Australia where water management is used to support multiple water uses. In regions such as the Amazon and Canada where rivers are less impacted by human activities, "nat" and "wm" produced similar skill in capturing the observed streamflow. For stream temperature, including water management noticeably improves the model skill in the western U.S. and India, two regions with intense irrigation use supported by water management.

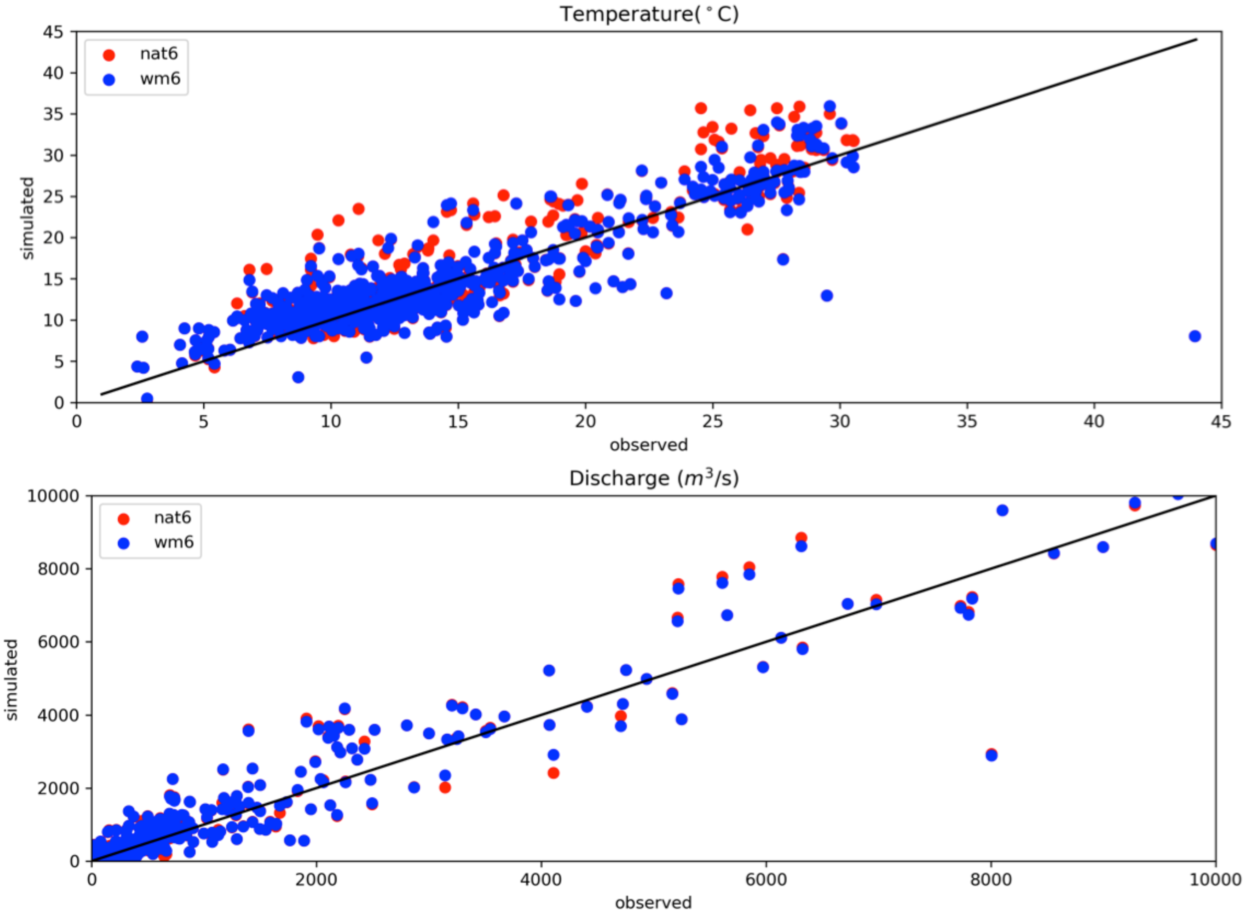
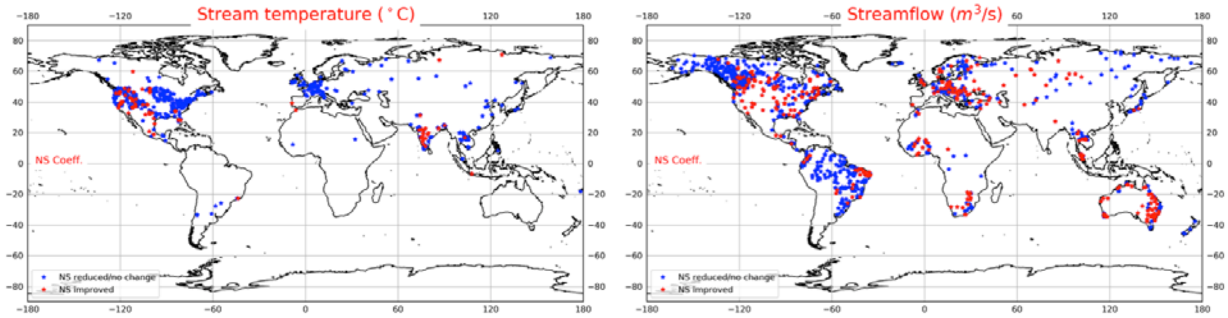


Figure 3. Comparison of simulated and observed stream temperature (upper) and streamflow (bottom) at stream gauge stations around the world for 1972-2000. The "nat" and "wm" simulations are denoted by the red and blue circles, respectively.



Stream temperature ($^\circ$C)

Streamflow (m^3/s)

Figure 4. Comparison of the Nash Sutcliffe (NS) coefficient between the “wm” and “nat” simulations at stream gauge locations for stream temperature (left) and streamflow (right). Red dots represent improved, and blue dots represent no change/reduction in the NS coefficient from “nat” to “wm.”

Water management is expected to have the largest impacts on the seasonal cycle of streamflow and stream temperature because reservoir operations aim to reduce the seasonal variations of streamflow for flood protection and to provide irrigation water supply. Figure 5 shows the amplitude and phase of the annual cycle of stream temperature in the “nat” simulation and the difference between “wm” and “nat.” In the “nat” simulation, large seasonal amplitude is simulated in inland basins of the mid and high latitudes, such as the northern Rocky Mountains, Eurasia, and southwestern Australia, with the warmest temperature occurring during June or July in the northern hemisphere and during December or January in the southern hemisphere. In the tropics, the seasonal amplitude is generally small, consistent with the small seasonal surface temperature range in the tropics. The spatial patterns of amplitude and phase generally reflect the seasonal cycle of surface air temperature, indicating its dominant influence on stream temperature.

Comparing the “wm” and “nat” simulations, there are large differences in the amplitude, with water management generally reducing the amplitude. The largest impacts are found over the western U.S., central Asia, India, and northeastern China. These regions, except India, are all arid and semi-arid, so large water amount is extracted from the rivers to provide irrigation water supply. Despite the summer monsoon rainfall, India relies on groundwater pumping to provide irrigation water supply to support the agricultural expansion. Hence the impacts of water management on stream temperature are clear. While the phase change in most areas is small, there is a phase delay by 1-2 months in India.

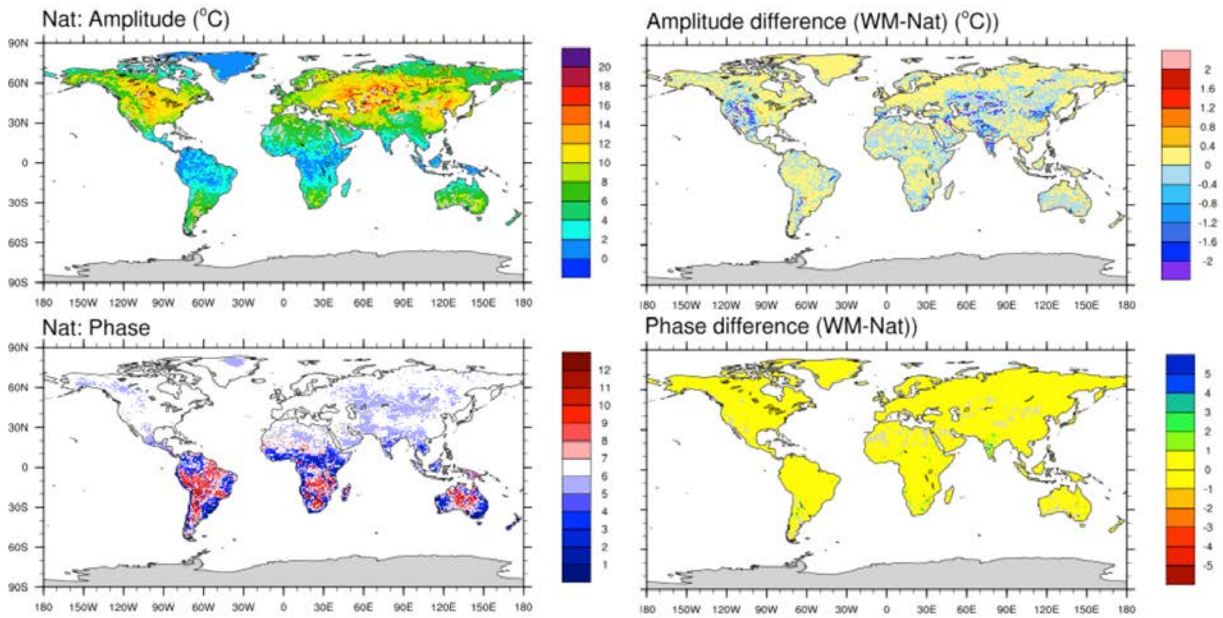


Figure 5. The amplitude and phase of the annual cycle of stream temperature in the "nat" simulation (left) and the difference between "wm" and "nat" (right). The amplitude is shown in °C, and the phase is shown by the timing of the maximum temperature from January (1) to December (12). The phase difference is shown in the unit month.

To highlight the impacts of water management on stream temperature, we zoom into two regions for more analysis. In the western U.S., water management reduces the amplitude of the stream temperature seasonal cycle by 2°C or more in some areas such as the Central Valley of California (Figure 6). Changes in phase are generally small. The seasonal variations of stream temperature and streamflow are shown at three stream gauge locations in the bottom panel of Figure 6. Water management changes the flow regime significantly at the stream gauge shown on the left and middle panels, reducing the flow during winter and spring and enhancing the flow in the summer for irrigation water supply. These changes in the flow regime have important effects on the stream temperature, reducing the maximum monthly stream temperature by up to 10°C. For the stream gauge shown on the right, water management also reduces flow slightly in both winter and summer. Although the flow regime change is relatively small compared to that of the other stream gauges, the impacts on stream temperature are significant during summer and fall. Water management shifts the timing of the maximum stream temperature by about two months earlier.

Over India, water management also has significant effects on the stream temperature seasonal cycle amplitude, reducing it by 2°C or more in some areas, particularly in western India where groundwater pumping for irrigation is widely practiced. Water management also has significant effects on the phase by delaying it by at least two months over western India. At two stream gauge locations, water management reduces the streamflow but does not change the timing in general. Hence water management has small effects on stream temperature, reducing it by 1–2°C during some months.

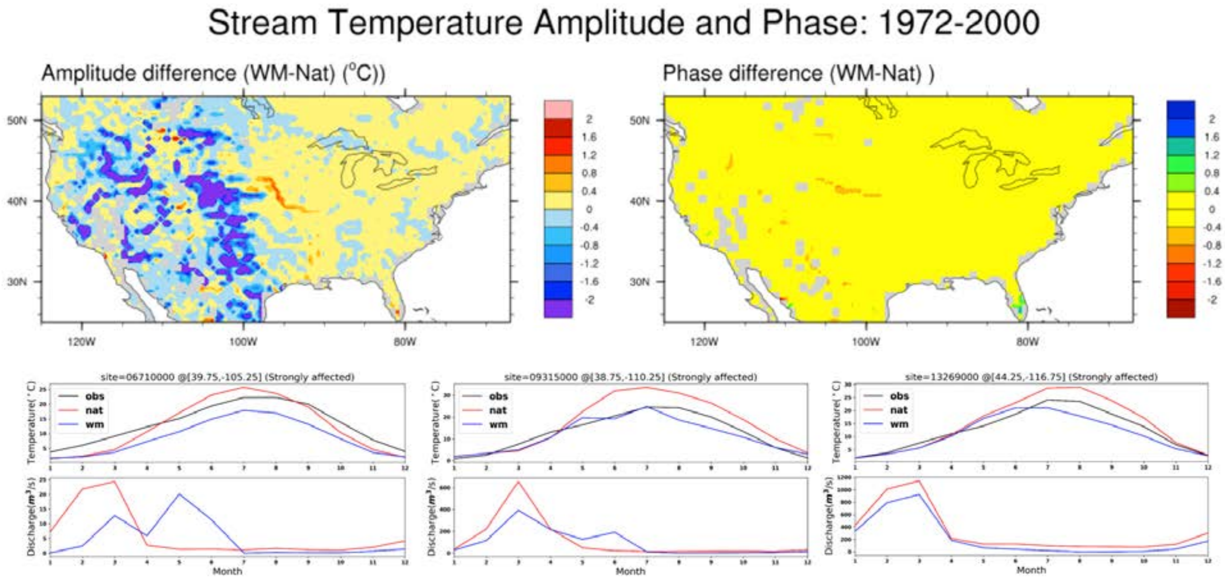


Figure 6. Top: Seasonal amplitude (left) and phase (right) difference between the “wm” and “nat” simulations over the U.S. Bottom: Mean monthly stream temperature (top) and streamflow (bottom) at three stream gauge locations comparing observations (black), “nat” (red) and “wm” (blue).

4.0 Summary

In summary, MOSART-heat has been coupled in the E3SM framework as an additional module to MOSART to simulate stream temperature. Coupled with a water management model, the impacts of reservoir operations and water extractions can be simulated to understand the relative impacts of air temperature and water management. Offline simulations of ELM-MOSART-heat-WM with and without water management show that water management has large impacts on the seasonal cycle of stream temperature in arid and semi-arid regions (western U.S., central Asia, northeastern China) where water management alters the flow regime to provide irrigation water supply and in India where groundwater pumping for irrigation is prominent. Without water management, the spatial pattern of seasonal amplitude and phase of stream temperature generally follows that of surface air temperature. However, water management can significantly reduce the seasonal amplitude by altering the flow regime through reservoir operations. Including water management generally brings the simulation of annual mean as well as seasonal cycle of stream temperature closer to observations.

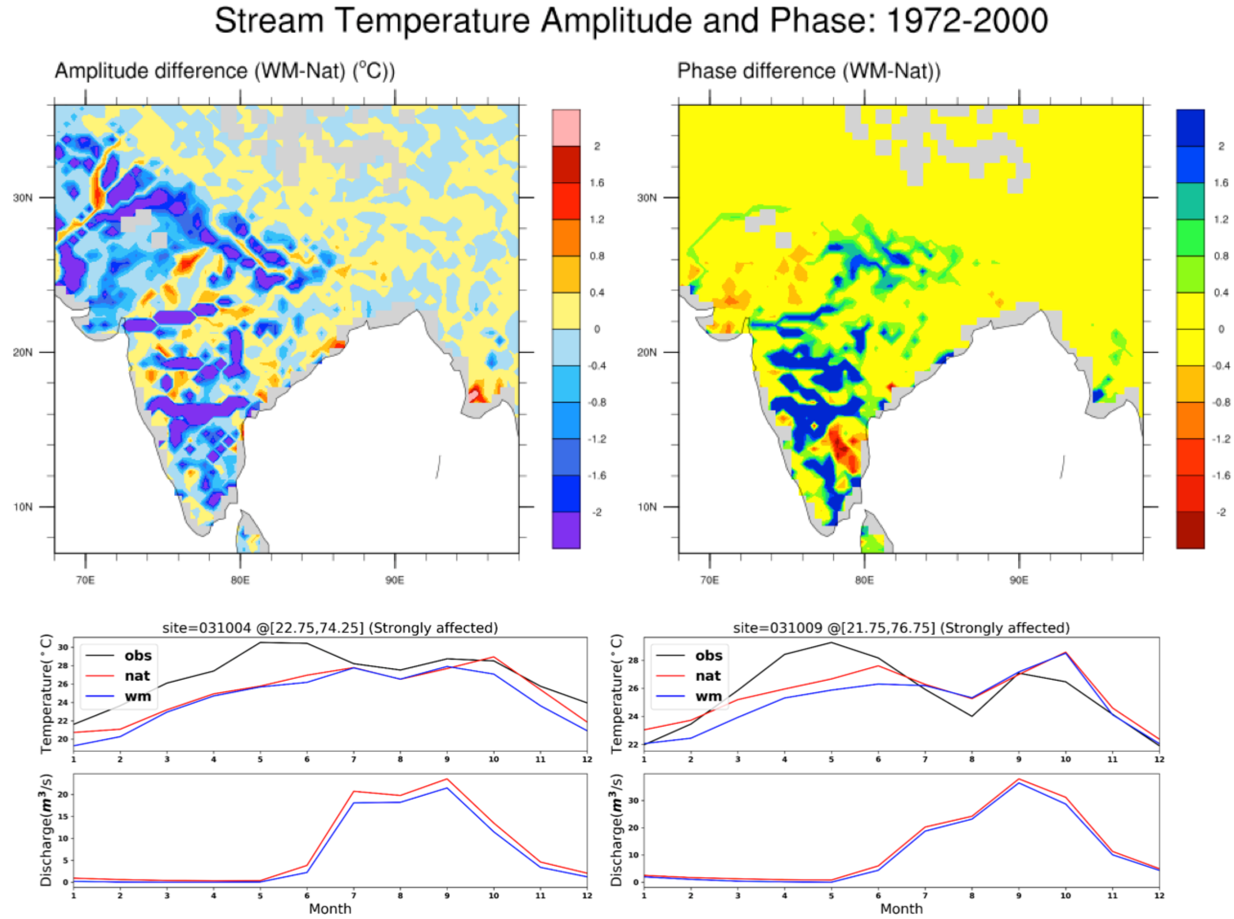


Figure 7. Same as Figure 6 but for India.

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