




Heatwave Diagnostics Package: Efficiently Compute Heatwave Metrics Across Parameter Spaces

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Summary

The heatwave diagnostics package (HDP) is a Python package that provides the climate research community with tools to compute heatwave metrics for the large volumes of data produced by earth system model large ensembles, across multiple measures of heat, extreme heat thresholds, and heatwave definitions. The HDP leverages performance-oriented design using xarray, Dask, and Numba to maximize the use of available hardware resources while maintaining accessibility through an intuitive interface and well-documented user guide. This approach empowers the user to generate metrics for a wide and diverse range of heatwave types across the parameter space.

Statement of Need

Accurate quantification of the evolution of heatwave trends in climate model output is critical for evaluating future changes in hazard. The framework for indexing heatwaves by comparing a time-evolving measure of heat against some seasonally-varying percentile threshold is well-established in the literature (Baldwin et al. (2019); Schoetter et al. (2015); Acero et al. (2024); Argüeso et al. (2016)). Metrics such as heatwave frequency and duration are commonly used in hazard assessments, but there are few centralized tools and no universal heatwave criteria for computing them. This has resulted in parameter heterogeneity across the literature and has prompted researchers to adopt multiple definitions to build robustness (Sarah E. Perkins (2015)). Although studies could attempt to report metrics across larger parameter spaces, the excessive data management costs and computational burden of sampling more parameters makes it increasingly complex and expensive (S. E. Perkins & Alexander (2013)). The introduction of large ensembles has further exacerbated this issue. New heatwave packages have been developed to simplify the analysis, but they are often not optimized specifically for evaluating the potential sensitivities of heatwave hazard to the selections of heat measure, extreme heat threshold, and heatwave definition.

Development of the HDP was initially focused on addressing the challenges of handling terabyte-scale ensembles, but then quickly expanded to investigate new scientific questions around how the selection of characteristic heatwave parameters may impact hazard analysis. The HDP can provide insight into how the spatial-temporal response of heatwaves to climate perturbations depends on the choice of heatwave parameters. While other software packages primarily focus on calculating heatwave metrics for individual parameter selections (e.g. `heatwave3` (Schlegel et al., 2024), `xclim` (Bourgault et al., 2023), `ehfheatwaves` (Loughran, 2021)), the HDP builds on these tools to efficiently evaluate metrics across large ranges of the parameter space.

Key Features

Extension of Xarray with Implementations of Dask and Numba

xarray is a popular Python package used for geospatial analysis and for working with the netCDF files produced by climate models. The HDP workflow is based around xarray and seamlessly integrates with the xarray.DataArray data structure. Parallelization of HDP functions is achieved through the integration of dask with automated chunking and task graph construction features built into the xarray library.

Heatwave Metrics for Multiple Measures, Thresholds, and Definitions

The “heatwave parameter space” refers to the span of measures, thresholds, and definitions that define individual heatwave “types” as described in Table 1.

Table 1: Parameters that define the “heatwave parameter space” and can be sampled using the HDP.

Parameter	Description	Example
Measure	The daily variable used to quantify heat.	Average temperature, minimum temperature, maximum temperature, heat index, etc.
Threshold	The minimum value of heat measure that indicates a “hot day.” The threshold can be constant or change relative to the day of year and/or location.	90th percentile temperature for each day of the year derived from observed temperatures from 1961 to 1990.
Definition	“X-Y-Z” where X indicates the minimum number of consecutive hot days, Y indicates the maximum number of non-hot days that can break up a heatwave, and Z indicates the maximum number of breaks.	“3-0-0” (three-day heatwaves), “3-1-1” (three-day heatwaves with possible one-day breaks)

The HDP allows the user to test a range of parameter values: for example, heatwaves that exceed 90th, 91st, ... 99th percentile thresholds for 3-day, 4-day, ... 7-day heatwaves. Four heatwave metrics that evaluate the temporal patterns in each grid cell are calculated for each measure and aggregated into a xarray.Dataset. Detailed descriptions of these metrics are shown in Table 2.

Table 2: Description of the heatwave metrics produced by the HDP.

Metric	Long Name	Units	Description
HWF	heatwave frequency	days	The number of heatwave days per heatwave season.
HWN	heatwave number	events	The number of heatwaves per heatwave season.
HWA	heatwave average	days	The average length of heatwaves per heatwave season.

Metric	Long Name	Units	Description
HWD	heatwave duration	days	The length of the longest heatwave per heatwave season.

Diagnostic Notebooks and Figures

The automatic workflow compiles a “figure deck” containing diagnostic plots for multiple heatwave parameters and input variables. To simplify this process, figure decks are serialized and stored in a single Jupyter Notebook separated into descriptive sections. Basic descriptions are included in markdown cells at the top of each figure. The HDPNotebook class in `hdp.graphics.notebook` is utilized to facilitate the generation of these Notebooks internally, but can be called through the API as well to build custom notebooks. An example figure of HWF from the sample figure deck is shown in Figure 1.

`test_temperature_data.test_temperature_data_threshold.HWF`

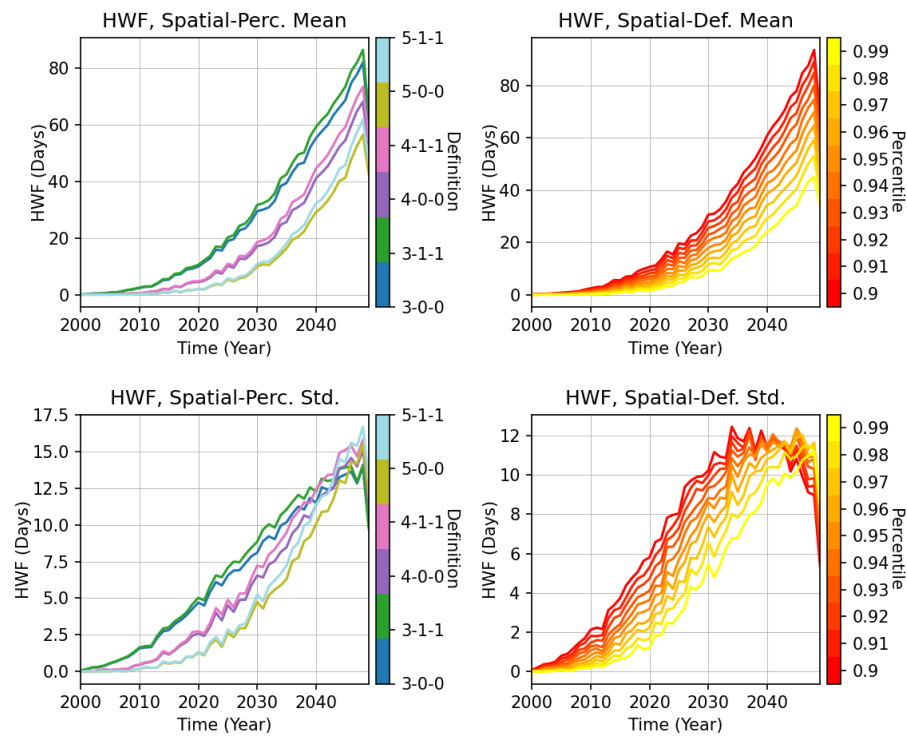


Figure 1: Example of an HDP standard figure deck

Ongoing Work

This package was used to produce the results featured in a research manuscript currently undergoing the peer-review process in a scientific journal. Updates to the HDP are ongoing.

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