

# MetSim: A Python package for estimation and disaggregation of meteorological data

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## Software

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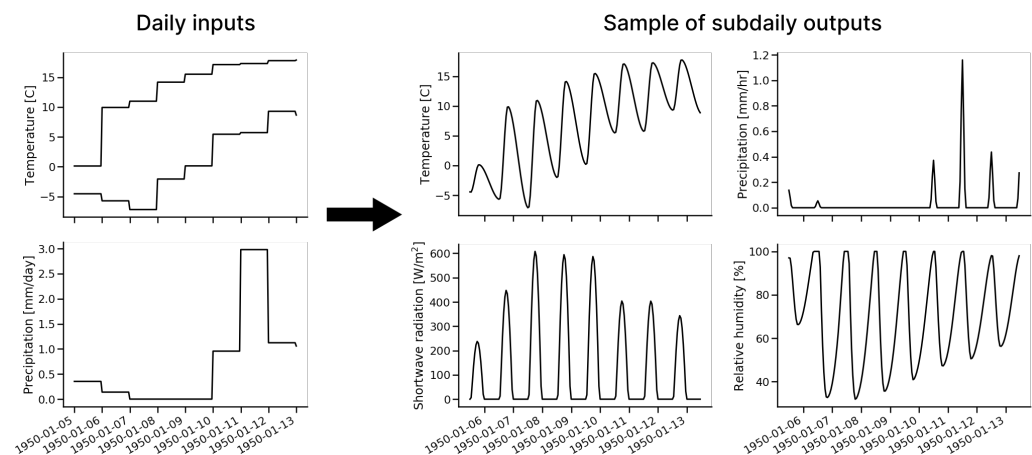
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## Summary

While there has been a boom in the availability of climate, weather, and environmental data thanks to satellite observations, syntheses of in situ observed data sets, and the ubiquity of powerful computers, it is also still often the case that the required data to run complex environmental models is either missing, or at the wrong spatial or temporal resolution. For example, incoming shortwave radiation, longwave radiation, and humidity are often observed with varying record lengths and observation intervals. Further, even when such quantities are measured it is often at a daily timestep, while many environmental models require finer time scales for simulation. To provide the necessary data to solve the model equations in such circumstances we must be able to provide estimates for these quantities at the appropriate temporal resolution. `MetSim` is a Python package and standalone tool for the estimation of meteorological quantities at variable time scales that can address the issues described above. The data that `MetSim` can generate covers most of the variables that sophisticated environmental models may require as input, making it possible to run them in a wider variety of situations than is possible with off-the-shelf datasets. This is especially important in fields such as hydrology and ecology, where there is an increasing push towards finer scale data than is commonly available. `MetSim` can be used to generate spatially distributed sub-daily timeseries of incoming shortwave radiation, outgoing longwave radiation, air pressure, specific humidity, relative humidity, vapor pressure, precipitation, and air temperature given daily timeseries of minimum temperature, maximum temperature, and precipitation. Figure 1 shows an example of `MetSim`'s transformations of these daily values into some of the available subdaily outputs. A summary of the available output variables and tunable parameters are included in the documentation.



**Figure 1:** An example of MetSim input and output. The daily values are shown on the left are used as input along with a number of parameters to produce the hourly output shown on the right. The sample data used to generate this figure is included in the MetSim repository.

We have based MetSim on methods from the Mountain Microclimate Simulator (MTCLIM) and the forcing preprocessor that was built into the Variable Infiltration Capacity (VIC) hydrological model version 4 (Bohn et al., 2013; Liang, Lettenmaier, Wood, & Burges, 1994; Thornton & Running, 1999). The development of MetSim was motivated by gaps in the approaches of both MTCLIM and the VIC forcing preprocessor. The MTCLIM software has not been updated since 2003 and the software does not implement the forcing disaggregation routines which are necessary for models to run at sub-daily timesteps. Recent developments on the VIC model have removed the forcing preprocessor due to algorithmic changes in the model driver. We noticed that processors for forcing estimation and disaggregation usually were implemented as ad hoc solutions based on similar workflows and algorithms, and wanted to formalize the process of generating forcing data by developing MetSim. At the same time, this provides a basis for others to expand a set of commonly available routines.

MetSim provides a modern workflow, building upon previous tools by improving performance by adding scalable parallelism, adding new IO routines, allowing for exact restarts, and providing an extensible architecture which can incorporate new features. We have implemented MetSim in a way that allows for runs on arbitrary spatial configurations and at arbitrary spatial scales, as opposed to the forced latitude-longitude grid that was used in the VIC preprocessor. We have designed MetSim to fit into the broader scientific Python ecosystem, building on popular packages such as xarray (Hoyer & Hamman, 2017), dask (Rocklin, 2015), pandas (McKinney, 2010), and numba (Lam, Pitrou, & Seibert, 2015).

## Architecture and performance

MetSim's architecture follows the common design of a model driver that coordinates high level operations and that delegates computation to several modules to do the bulk of the work. The top level model driver handles all IO routines as well as job scheduling and parallelism. A schematic representation of MetSim's architecture is shown in Figure 2. MetSim provides both a command line tool and API access as a Python module. The command line tool provides an interface to the driver via configuration files and command line options.

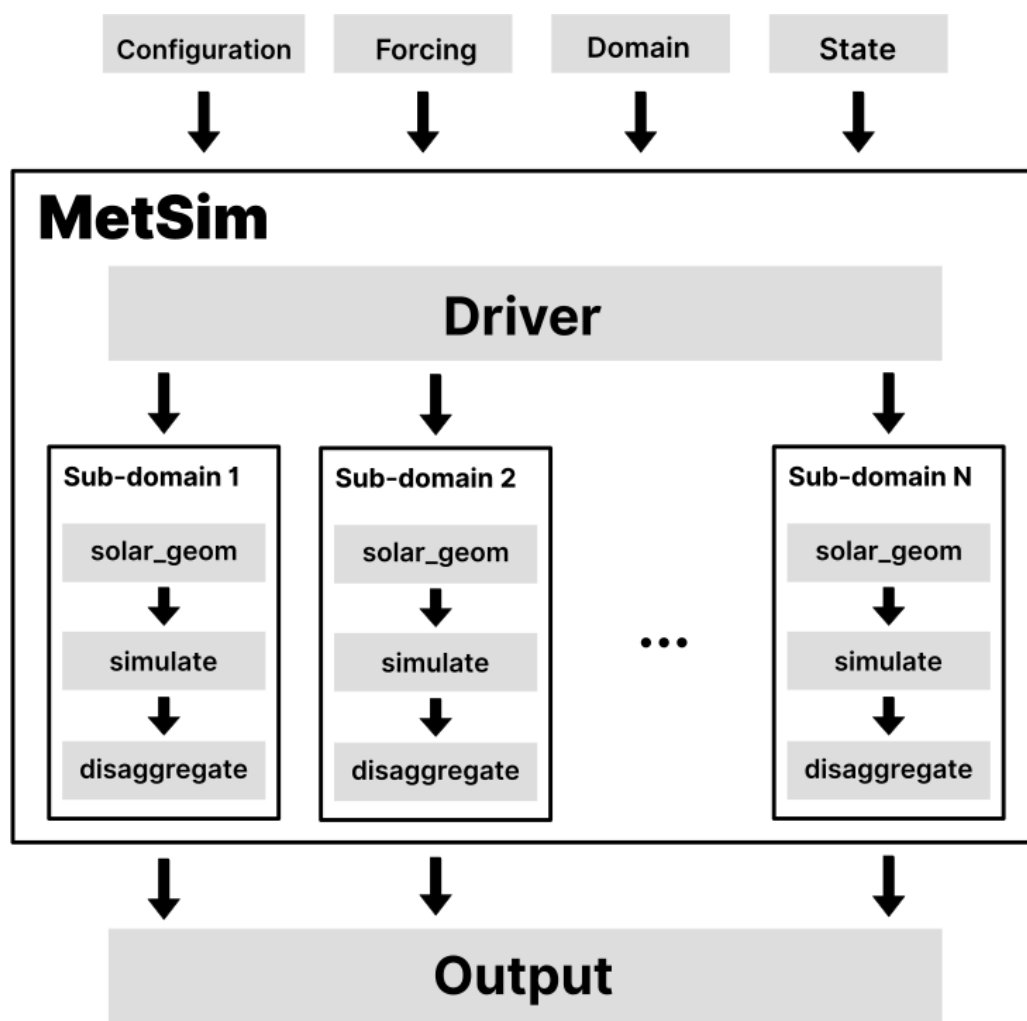


Figure 2: A schematic representation of the MetSim software flow

MetSim has three main computation modules for solar geometry, meteorological simulation, and temporal disaggregation. The solar geometry module computes the daily potential radiation, daylength, transmittance of the atmosphere, and the fraction of daily radiation received at the top of atmosphere during each 30 second interval. Computations are based on the algorithms described in Whiteman & Allwine (1986) as implemented in MTCLIM (Thornton & Running, 1999). The data from the solar geometry module is fed to the meteorology simulation module along with the input forcings. MetSim implements the estimation methods discussed in Bohn et al. (2013) and Thornton & Running (1999) to estimate the daily mean temperature, shortwave radiation, vapor pressure, and potential evapotranspiration. If disaggregation to shorter time steps is configured, the data is passed from the meteorology simulation module to the disaggregation module. Bohn et al. (2013) provides a further description and evaluation of these algorithms. Here we briefly mention the disaggregation procedures for completeness, but no substantial changes were made to the earlier algorithms.

Shortwave is disaggregated by multiplying the total daily shortwave by the fraction of radiation received in a given timestep (provided by the solar geometry module). This calculation is corrected for cloud cover by assuming constant transmissivity throughout the day (which is calculated in the meteorological simulation module). Temperature is disaggregated by estimating the time at which the daily maximum and daily minimum temperatures occur. These are chosen so that the daily minimum temperature occurs at sunrise and the daily

maximum temperature occurs at a fixed time during the day (which is configurable by the user as a parameter in the configuration file if desired). Then a Hermite polynomial interpolation is used to obtain the full temperature timeseries at sub-daily time steps. Vapor pressure is disaggregated by linearly interpolating between the saturation vapor pressure values calculated based on the daily minimum temperature and that are assumed to occur at the time of the daily minimum temperature. An additional correction is made to ensure that the vapor pressure at any given time step does not exceed the saturation vapor pressure, which is calculated directly from the disaggregated temperature timeseries. Air pressure is disaggregated by using the disaggregated temperature as well as the elevation data provided by the domain file. Both specific and relative humidity are then disaggregated using the disaggregated temperature and air pressure time series. If provided, wind speed is disaggregated, but is assumed to be constant throughout the day.

As part of the model configuration, the user can select from a number of different algorithms to estimate longwave radiation. Sub-daily values are calculated with the selected method using the disaggregated values for vapor pressure and temperature.

Precipitation can be disaggregated in one of two ways. The first and simplest way is to evenly spread the daily precipitation across the sub-daily time steps. The second method requires two additional parameters to be specified in the domain file to represent the average precipitation duration and the time of peak precipitation for each cell. The method then disaggregates precipitation by constructing a triangular kernel with total area equal to the daily precipitation centered at the time which is specified as the time of peak precipitation.

MetSim implements several options for parallelism, which are primarily managed by the Dask (Rocklin, 2015) and xarray (Hoyer & Hamman, 2017) libraries. We explore MetSim's computational performance by conducting two scaling experiments. Strong scaling experiments test how the total runtime is affected by adding processors for a fixed overall problem size. Weak scaling experiments test how the total runtime is affected by adding processors proportional to the overall problem size. In ideal cases the runtime halves when doubling the number of processors for strong scaling experiments and remains constant for weak scaling experiments. These ideal cases are represented by the "perfect" cases shown in Figure 3. All of the times reported for the scaling experiments were for a single year run at an hourly time step with default parameter and output settings. For the strong scaling experiment we ran MetSim for one year at an hourly timestep over a domain of 6333 cells and ran using 2, 4, 8, 16, 32, 64, and 128 processors. The time to complete each run is shown in Figure 3 (left). The results show that scaling is nearly linear with the number of processors.

In the weak scaling experiment we ran MetSim using 2, 4, 8, 16, 32, 64, and 128 processors while varying the number of cells in the run to maintain a constant workload per processor. We ran 125 cells per 2 processors, resulting in runs of 125, 250, 500, 1000, 2000, 4000, and 8000 cells, respectively. The results of the weak scaling experiment are shown in Figure 3 (right). Similarly to the strong scaling experiment, we see increasing penalties for adding additional processors.

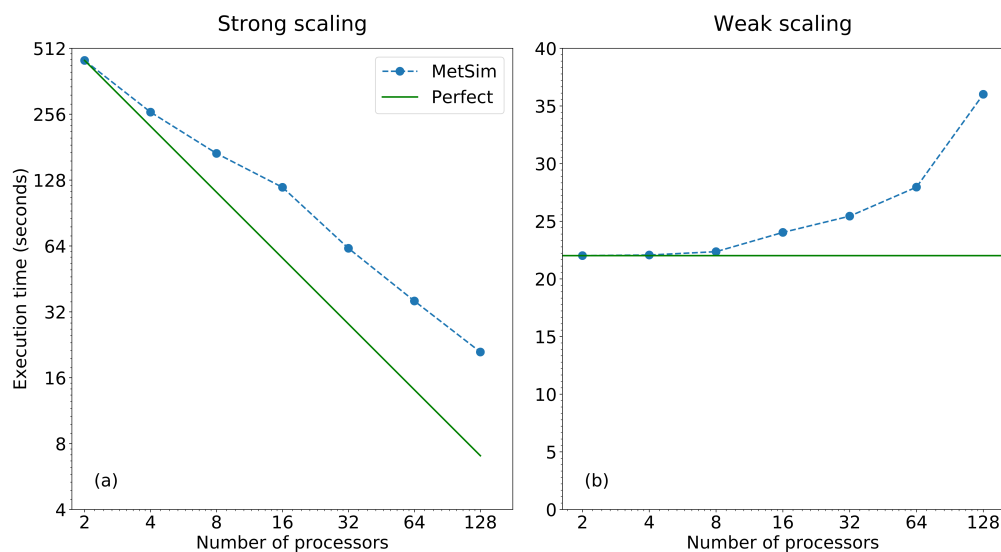


Figure 3: MetSim scaling performance

## Applications & Related work

MetSim has been used in several research applications predominantly for generating input to hydrologic models, though other applications are possible. Bohn, Whitney, Mascaro, & Vivoni (2019) extended the precipitation disaggregation component to include a new option which was shown to result in better streamflow predictions than the default method. Cheng, Voisin, Yearsley, & Nijssen (2020) used MetSim as a component of their modeling framework to explore how reservoirs affect stream temperatures, and how reservoir operations may be able to help mitigate the effects of climate change on warming stream temperatures. The Climate Toolbox (Hegewisch, Abatzoglou, Chegwidden, & Nijssen, 2020) uses MetSim to generate meteorological data as an intermediate step for developing hydrologic predictions. MetSim has many other possible uses and is developer-friendly enough for it to be extended to provide additional functionality.

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