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User manual to operate the script to calculate the Reference Evapotranspiration based on the Penman approach

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Summary

In this report you will find a user manual for an R-package that contains a routine to calculate the Reference EvapoTranspiration (ET_0) following the parameterization of Makkink. This parameterization is a simplification of the one provided by Penman-Monteith, which is generally regarded as the most realistic and physically comprehensive parameterization for ET_0. The motivation to provide a simplified version of the Penman-Monteith parameterization is that the assumption under which this parameterization is valid (a large area of short-clipped well-watered grass) is not always met. In addition, the diversity of meteorological data required for this parameterization is large and not always available. The report is concluded with a comparison of the various parameterizations and recommendations on its use.

1. Introduction

Grass reference evapotranspiration (ET_0) is defined as the evapotranspiration from a clipped-grass surface with a standard height and bulk surface resistance. Recommended by the Food and Agriculture Organisation (FAO) as the preferred parameterization for this reference evapotranspiration is the Penman-Monteith equation. This definition helps in standardizing the estimate for ET_0 for the various climates found in Europe.

The Penman-Monteith equation is a modification of the simpler Penman equation which is based on radiation only. The latter was soon found to frequently overestimate ET_0 (Allen et al, 1994). Nevertheless, simpler parameterizations than the Penman-Monteith one do have their value: they are applicable in more diverse conditions since the application of the Penman-Monteith equation assumes conditions, like a well-watered grass surface, which are often not present. In addition, the complexity of the Penman-Monteith is often an obstacle since it requires a very complete set of observations (including humidity and wind speed, apart from radiation and temperature). This has inspired various simplifications of the Penman-Monteith parameterization. In this report, two of those simplifications are discussed which are principally based on radiation – in the spirit of the basic Penman equation; the Priestley-Taylor and Makkink parameterizations.

The package introduced in this Deliverable calculates the full Penman-Monteith equation for potential evapotranspiration and it provides the possibility to output simplified versions of this parameterization.

In this report, some technical documentation is given on the usage of the scripts to calculate ET_0. In addition, some theoretical considerations behind the Penman and the Penman-Monteith equations are given and a brief analysis is presented on the sensitivity of the results in estimating ET_0 for the temporal resolution of the input data.

2. ‘PETr’ package Introduction

The `PETr` package may be used for computing ET_0 from data in netcdf gridded format or from a time series such as station data. When used for gridded data the `PETr` package is controlled by the package `GridClimInd` which takes care of sending the `PETr` package vectors of data from the netcdf file in the correct format. This controlling software has been optimised to incorporate chunking and multi-processor (cluster computing) usage if required.

Filenames in the following are examples and do not need to be adhered to.

3. ‘PETr’ package user manual for computing ET_0 from gridded data

Where do I find the package?

The package is available from Github at: https://github.com/ECA-D/PETr

How should I install the package?

Installation requires the inclusion of the packages `GridClimInd` and `ClimInd`, which are available from GitHub at: https://github.com/ECA-D/gridclimind and https://github.com/ECA-D/climind.

There are dependencies on system libraries such as `netcdf4` and `udunits`, on Ubuntu these are installed by:

```
sudo apt-get install libnetcdf-dev libudunits2-dev
```

Install additional packages

Depends R (>= 3.6)

install.packages(c(‘ncdf4’,'PCICt','functional','proj4','caTools','SPEI','Runit’,’snow’,’ncdf4.helpers’,‘snow’,’udunits2’))

NB If ‘ncdf4.helpers’ is unavailable from cran please download from here:

https://cran.r-project.org/src/contrib/Archive/ncdf4.helpers/ncdf4.helpers_0.3-3.tar.gz

and install:

- R CMD INSTALL ncdf4.helpers_0.3-3.tar.gz

Take the following steps:

- download package from github

- unzip PETr-master.zip

- R CMD build PETr-master

- R CMD INSTALL PETr_0.1.0.tar.gz

Continue with `climind`:

- download package from github

- unzip climind-master.zip

- R CMD build climind-master

- R CMD INSTALL climind_1.0.0.tar.gz

Continue with `gridclimind`:

- download package from github

- unzip gridclimind-master.zip

- R CMD build gridclimind-master

- R CMD INSTALL gridclimind_1.0.0.tar.gz

Which script should I run to reproduce the example?

Run test script `run_PETr_grid_test.r` which is found in directory: PETr/test_data/

This routine produces the following PET output files:

PET_penman_rs_testfile.nc, PET_penman_ss_testfile.nc, PET_priestley_testfile.nc, PET_makkink_testfile.nc which will be written to: PETr/test_data/PET_output

This same directory already contains four static master files with which the new output is compared: PET_penman_ss_testfile_master.nc, PET_penman_rs_testfile_master.nc, PET_priestley_testfile_master.nc, PET_makkink_testfile_master.nc.

If the package installation is OK the following messages will appear:

"penman_ss output matches master file"

"penman_rs output matches master file"

"priestley output matches master file"

"makkink output matches master file"

General comments

The input of the files should have a daily temporal resolution. The output of the scripts is daily as well. The analysis of section 5 shows that there are large differences between the approach of using daily grass reference evapotranspiration ET_0 values aggregated to the monthly level and the approach to use monthly aggregated input data to calculate ET_0. The difference in ET_0 between these two approaches motivated us to recommend the use of daily ET_0 values as the basis for monthly estimates.

The spatial and temporal domain of the output file will reflect that of the input files. However, use of these routines is limited to files on the European domain due to internal use of the elevation file (which is included in the package). Section 6 explains the dependency on elevation in the parameterizations scripted in this package.

Units need to be converted to a specified list.

Variable names

If the users variable names differ from those given they can be modified to suit in the json file which is found in:

```
gridclimind-master/inst/extdata/metadata_config_files
```

so for e.g. to re-map radiation to “qq” go to line 31 in the json file and change to:

```
  "rs": "qq",
```

Note not to modify the left hand side (i.e. “rs” in the example above).

Calculation of Makkink Potential EvapoTranspiration (**create.pet.makkink.from.files)**

The following input variable are required:

variable	description	unit	remark
tn	Minimum temperature	°C	
tx	Maximum temperature	°C	
rs	Radiation	MJ/m2	If ss is unavailable

Other information needed is retrieved from the netcdf file.

All gridded data input must be consistent in dimensions – i.e. latitude, longitude and time.

Example of usage:

```
out.dir <-  "output/"
pet.file <- "<name_of_output_file>.nc"
out.file <- sprintf("%s%s", out.dir, pet.file)

input.files <- c(paste0(in.dir,"tn_0.25deg_regular_1979-2018.nc"),
                 paste0(in.dir,"tx_0.25deg_regular_1979-2018.nc"),
                  paste0(in.dir,"rs_0.25deg_regular_1979-2018.nc"))

create.pet.makink.from.files(input.files, out.file, input.files[1],
author.data,  parallel=FALSE)
```

The first input file (input.files[1]) details such as lat, lon and time are used to generate the output file.

Author.data is a list provided by the user giving additional information to go into the output file, e.g. `author.data <- list(data = "E-OBS")`

`parallel=FALSE` will use a single processor. The user may set this to use more processors if available. For e.g. 5 processors, set: `parallel=5`

4. Some theoretical considerations

The Penman-Monteith parameterization and its simplifications

Evaporation requires relatively large amounts of energy, either in the form of sensible heat or radiant energy. The evaporation (ET) process is therefore governed by energy exchange at the vegetation surface and is limited by the amount of energy available. Because of this limitation, it is possible to predict the rate of ET given a net balance of energy fluxes (Allen et al. 1994).

The primary energy components which are energy sources or sinks at the vegetation surface are net radiation from the atmosphere (R_n), sensible heat from the equilibrium boundary layer (H) and sensible heat from the soils (G). The sum of these three terms equals the energy converted to latent heat energy (λET) during the ET process:

$$\lambda ET = R_n - H - G$$

The energy balance equation can be arranged in terms of parameters R_n and G and parameters within the H and λET components. When this arrangement is made using assumptions for extrapolating temperature and vapour pressure from the weather measurement height to the evaporating surface (the plant leaves), the combination equation of Penman (1948) is obtained (Allen, 1987)

$$\lambda ET = \frac{\Delta}{\Delta + \gamma}(R_n - G) + \frac{\Delta}{\Delta + \gamma}E_a,$$

where Δ represents the slope of the saturation vapour pressure-temperature relationship, γ is the psychrometric constant and $E_a$is an atmospheric vapour transport term. This latter term has the form

$$E_a = f(u)(e_a - e_d)$$

where$f(u)$ is either an empirally or theoretically derived aerodynamic wind function, and $e_a - e_d$ represents the vapour pressure deficit of air at the reference height.

If one further assumes that eddy diffusion transfer factors for latent heat and sensible heat are the same and that differences between transfer factors for momentum and those for heat can be quantified through a simple ration, then the Penman-Monteith form of the combination equation (Monteith, 1965) results:

$$\lambda ET = \frac{\Delta(R_n - G) + \rho C_p\,(e_a - e_d)/r_a}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)}$$

where ρ represents the mean air density, C_p is the specific heat of air t constant pressure, and r_s and r_a are the bulk surface and aerodynamic resistances.

The Penman-Monteith equation as formulated above includes all parameters which govern energy exchange and corresponding latent heat flux (evapotranspiration) from uniform a standard vegetation surface. Most of the parameters of this equation are measured or can be readily calculated from weather measurements on a daily basis.
While the Penman-Monteith formula is considered to be the most comprehensive description of potential evapotranspiration, simplified versions have their benefits as well. Priestley and Taylor (1972) presented a shortened variation of the Penman equation for use in humid regions where advective transport of heat is low. Their form of the Penman equation is

$$\lambda ET = \alpha_1 \frac{\Delta}{\Delta + \gamma}(R_n - G)$$

where α_1 was suggested to have a value of 1.26 for large land areas with a nearly saturated surface.

For grasslands, the term G is generally small (De Bruin and Holtslag, 1982), which brought Makkink (1957) to a further simplification, applicable to grassland, where the evapotranspiration is determined primarily by the radiation and the ambient air temperature. This latter parameter is seen to influence $\lambda, \Delta$and γ. This simplification involved not only the neglect of the ground heat flux G but also the use of the global radiation Q rather than the net radiation R_n. The motivation for this latter simplification was that global radiation was more widely available whereas net radiation is not. This gives:

$$\lambda ET = C \frac{\Delta}{\Delta + \gamma} Q$$

with C = 0.65[1].

The package introduced in this Deliverable calculates the full Penman-Monteith equation for potential evapotranspiration, but it provides the possibility to output the simplified versions of Priestley-Taylor and Makkink.

Elevation dependency of the psychrometric coefficient

Despite the suggestion of its name, the psychrometric constant γ is not really a constant, there is a air pressure dependency in it. Although this dependency is often ignored (for computational ease apparently), we choose to include this dependency as the changes are substantial for the higher elevations found in Europe.

The formula for the psychrometric constant is

$$\gamma = 0.00163 \frac{p}{\lambda}$$

where λ is the latent heat of vaporization (2.45 MJ/kg, at 20°) and p is atmospheric pressure (kPa). The atmospheric pressure has the following relation with elevation z (m above sea level):

$$p = 101.3 \left(\frac{293 - 0.0065\, z}{293}\right)^{5.26}$$

(McMahon et al. 2013).

If the air pressure is at 1013 hPa, then the psychrometric constant γ becomes 0.6739, which is close to the value of 0.67 used (as constant) in the literature (e.g. De Bruin and Holtslag, 1982). However, for the high-elevation sites in Europe's Alpine region (Santis, Sonnblick), the elevation is close to 3000m and γ reduces to 0.466. While this change is arguable of not much interest to the agricultural community, the hydrological community might be interested.

Comparisons between the parameterizations

Figures 1 and 2 show for selected stations, the differences between the parameterizations of Penman-Monteith, Priestley-Taylor and Makkink. In addition, the Penman-Monteith-based estimate has been computed using radiation based on direct measurements and derived from cloud cover. The latter is often used as a proxy when radiation data are not available.

These figures show that for the warm season (April – September) the Penman-Monteith and the Makkink are very similar. This is most obvious for the timeseries shown for Norwich (UK), but this is seen over larger areas in Europe. In southern Europe, for the stations Porto and Vigo, similarities are still strong between the two.

[1] This formula differs slightly from the original Makkink (1957) formula, who used C=0.61 and an additive term of 0.12mm/day. De Bruin (1987) concludes that the current form describes reasonably well the evapotranspiration of grass.

Overall, the Priestley-Taylor parameterization of ET_0 is always (considerably) above the other estimates. The Penman-Monteith parameterization using cloud cover as proxy for radiation is consistently at the low end of the spectrum.

For the cold season, the values of ET_0 are much lower, as is to be expected. Here the Priestley-Taylor parameterization underestimates the values for ET_0 while the others are more similar. Absolute differences are small though.

Fig. 1: Reference EvapoTranspiration as calculated using the various parameterizations. PM stands for Penman-Monteith, where the addition CL means that radiation is based on an estimate from cloud cover while RS uses radiation data directly. MK and PT stand for the Makkink and Priestley-Taylor parameterizations respectively. Data are for the gridbox closest to Norwich (UK), Vigo (ES) and Porto (PT) for the warm season (April – September).

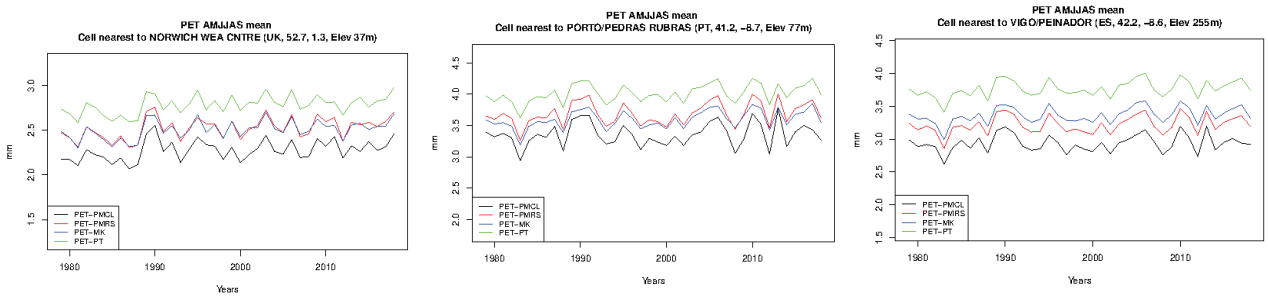
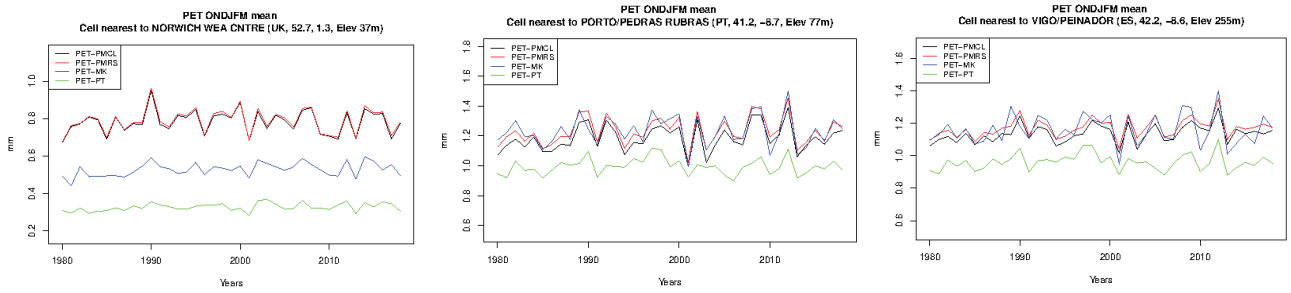


Fig. 2. Similar to Fig. 1, but now for the cold season (October – March).



5. Sensitivity for the temporal resolution of the input data

There are ample examples in the literature (e.g. Van der Schrier et al. 2013, Vicente-Serrano et al., 2011) in which values of the Reference EvapoTranspiration (ET_0) are calculated with a temporal resolution of a month using input data that is aggregated to the same monthly level. A brief analysis, of which the results are shown here, indicate that a significant difference exists between monthly ET_0 values based on input data that is aggregated to the monthly level, or calculations which are based on input data with a daily temporal resolution and for which the result is aggregated to the monthly level.

A sensitivity experiment is made by using data from the British meteorological station Rothamsted and both approaches to calculate monthly aggregated ET_0 values are compared. Figure 1 shows that monthly PET values based on daily input data are systematically higher in spring and summer (March to July) while for the autumn (September-November) the reverse is the case.

Given the strong effect on using monthly aggregate input data of the final value of ET_0 estimates, we recommend to use daily input values, and aggregated daily ET_0 values to a higher aggregation level (rather than aggregating the input data).

Figure 3 – Values for Reference EvapoTranspiration (ET_0) for a 30 year period for Rothamsted (UK), presented for the 12 months in the year. The black lines represent monthly PET values which are based on input data that has been aggregated to the monhtly level prior to the calculation of ET_0. The red lines represent monthly ET_0 values based on input data with a daily resolution, and where the aggregation to a monthly level is done after the calculation of ET_0.

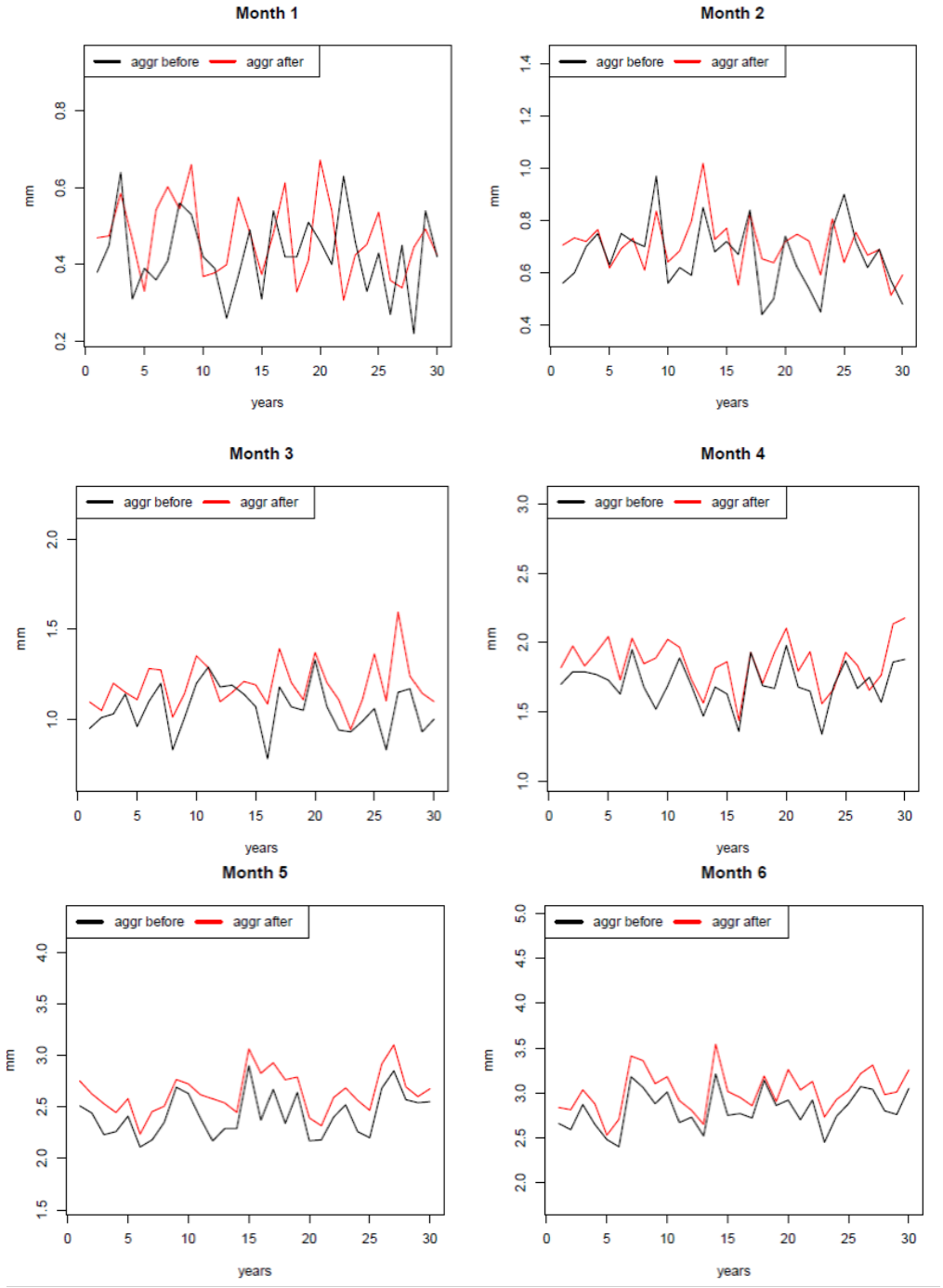
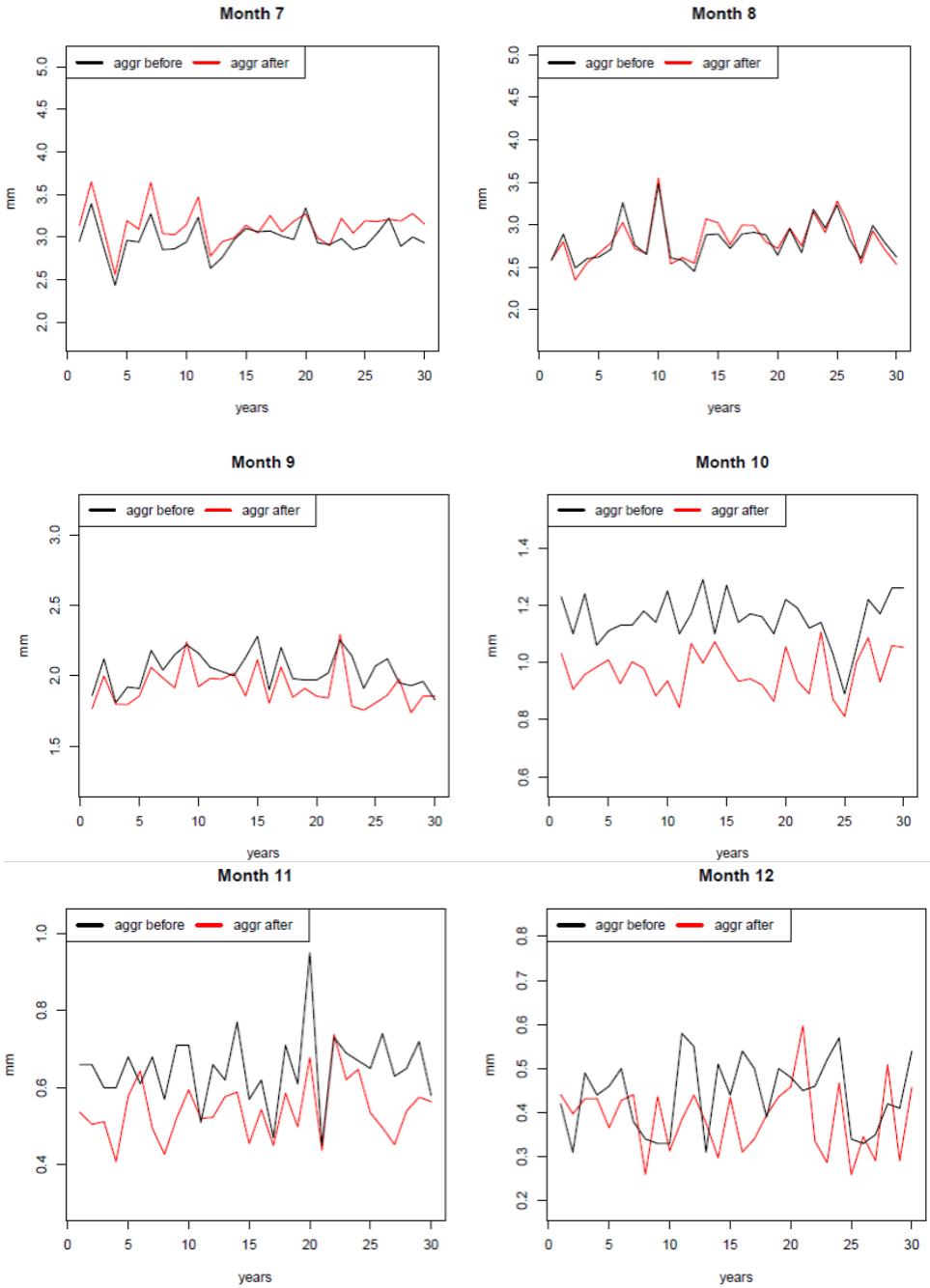


Figure 3 – Continued



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