New Insights on the Variability of Ecosystem Functioning Across Time Scales

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[5] Department of Water Resources and Environmental Engineering, School of Civil Engineering, National Technical University of Athens, Greece

> New Insights on the Variability of
Ecosystem Functioning[1] Across Time Scales

[1] as seeing from various ecosystem variables, here focusing on *carbon* dynamics

> New Insights on the **Variability**[2] of **Ecosystem Functioning**[1] Across Time Scales

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[3] five orders of magnitude, from one hour to >10 yr

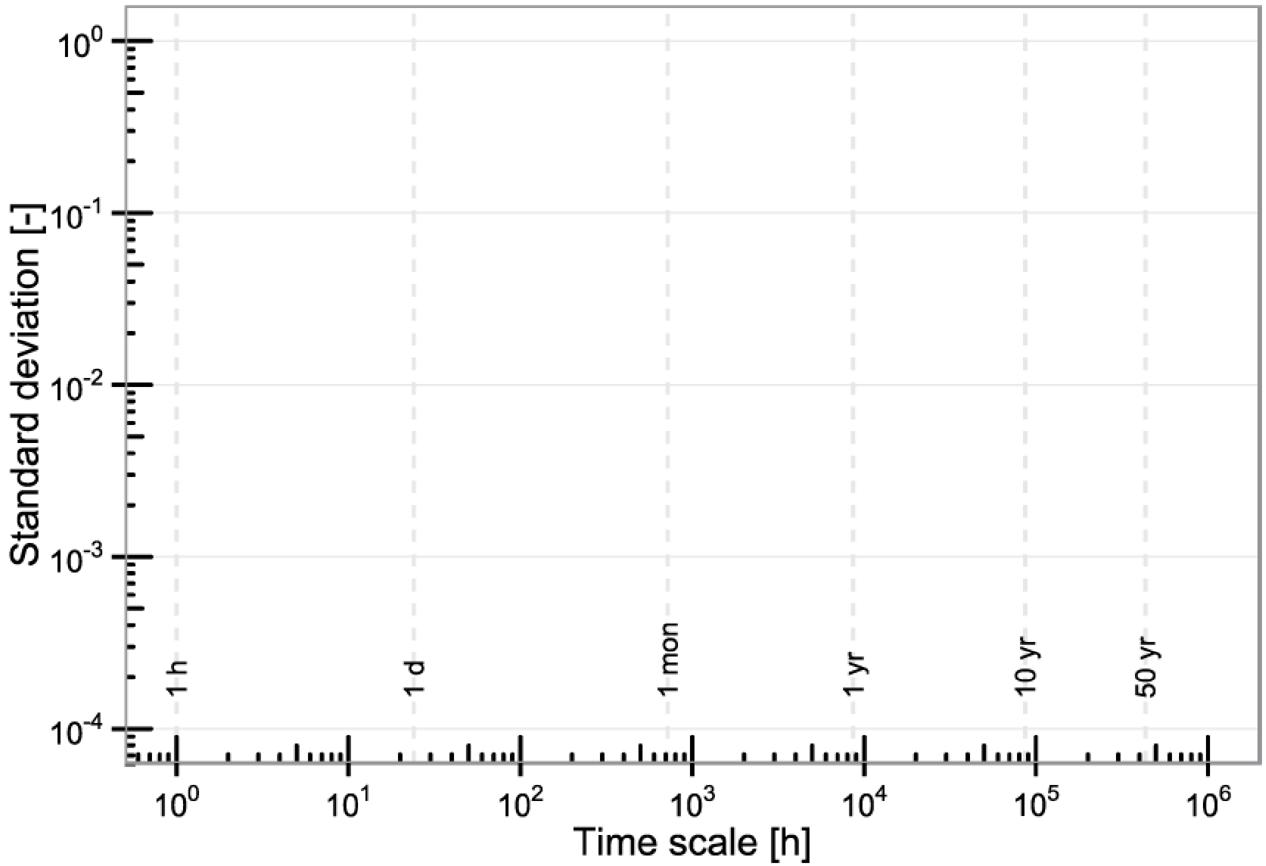
> New **Insights**[4] on the **Variability**[2] of **Ecosystem Functioning**[1] Across **Time Scales**[3]

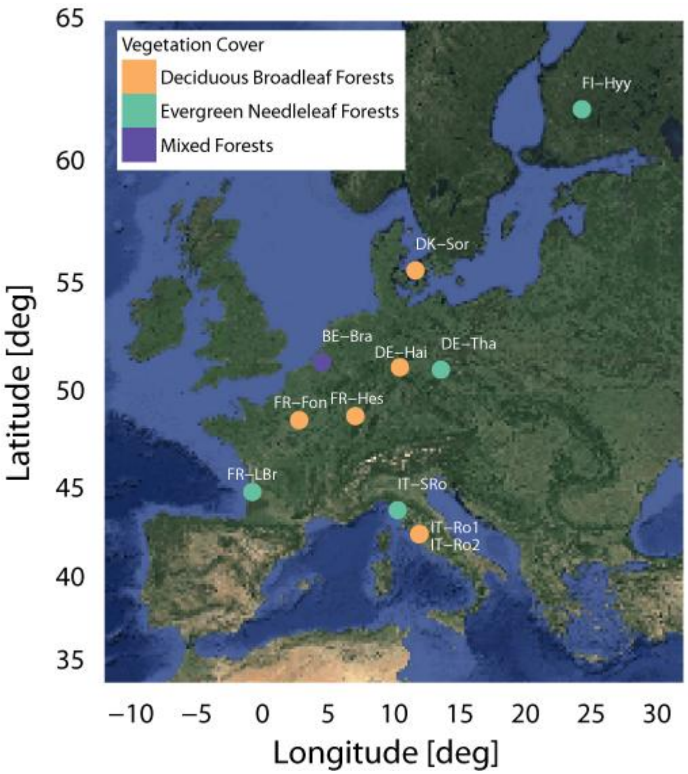
[1] as seeing from various ecosystem variables, here focusing on *carbon* dynamics

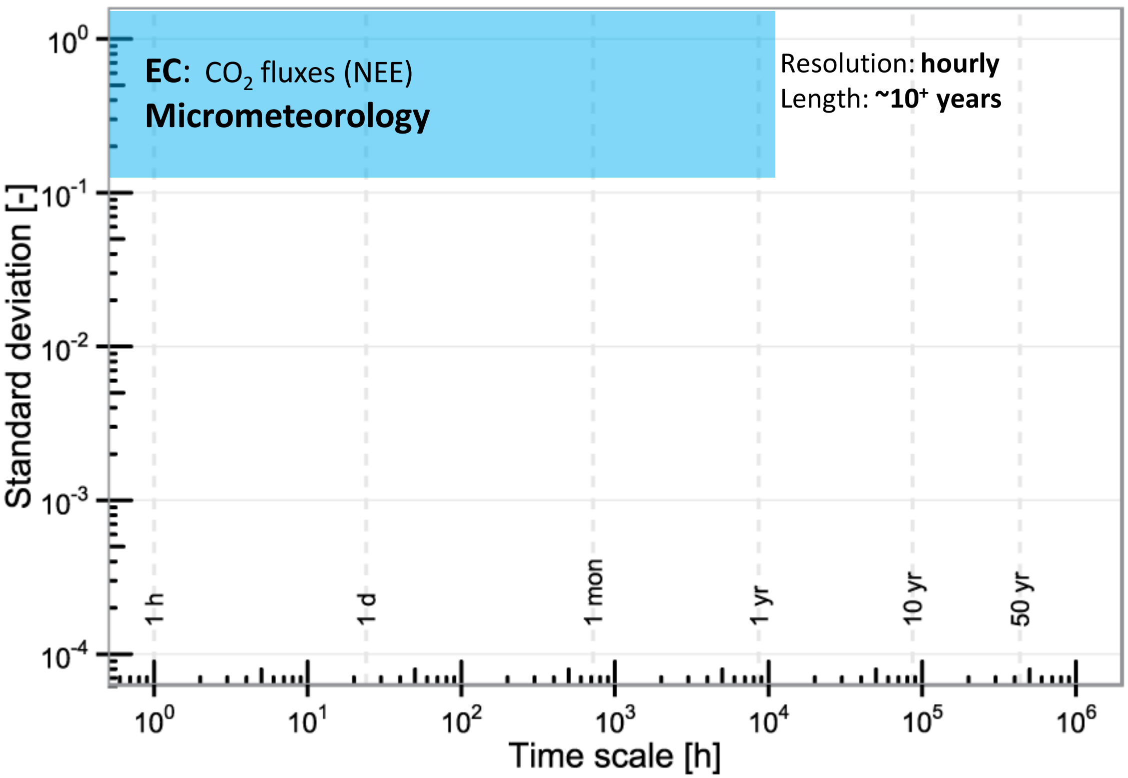
[2] standard deviation, $\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}$, using probability theory and statistics

[3] five orders of magnitude, from one hour to >10 yr

[4] quantify, interpret, and model

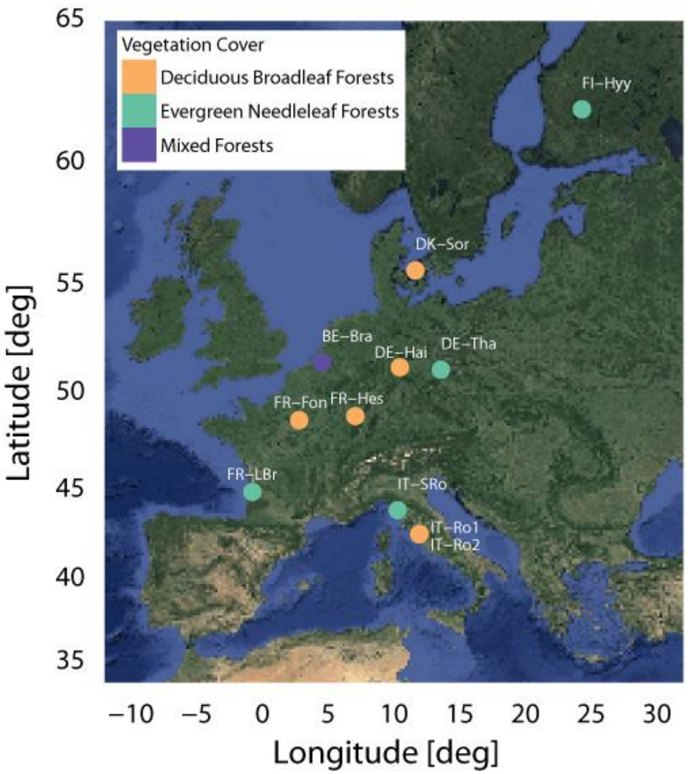

Standard deviation [-]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1 h
1 d
1 mon
1 yr
10 yr
50 yr
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Time scale [h]

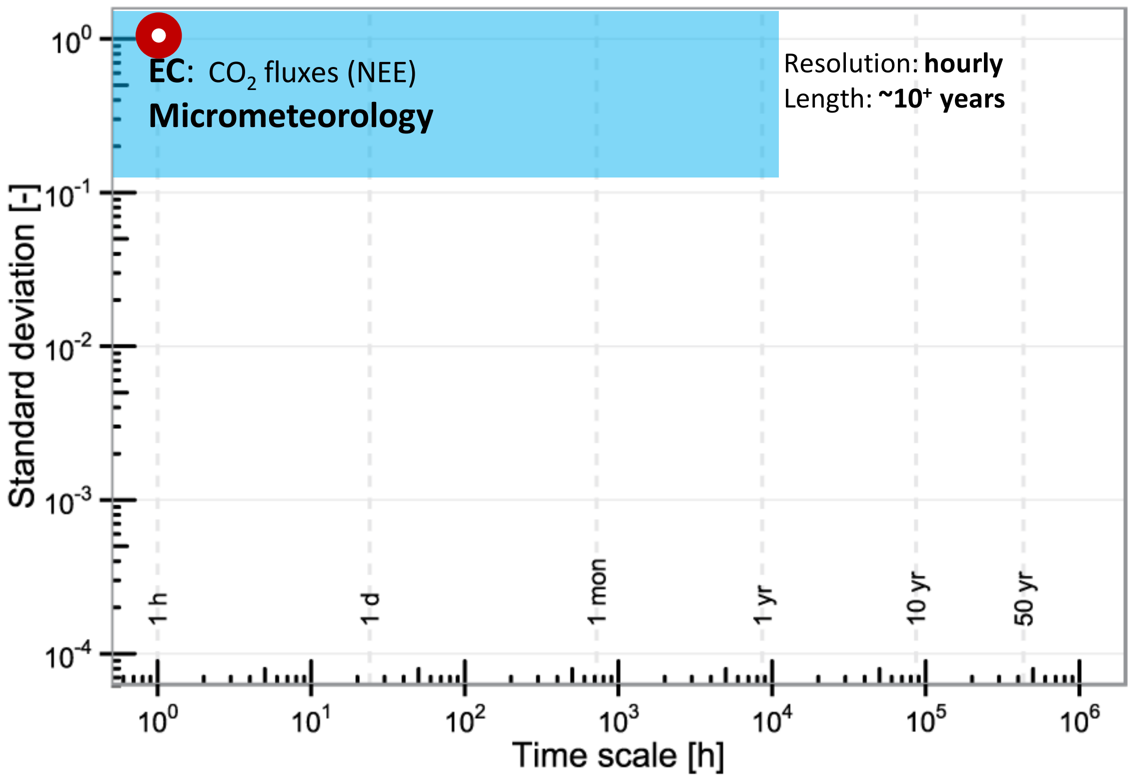




European Fluxes Database: http://www.europe-fluxdata.eu/

Carbo-Extreme: http://www.carbo-extreme.eu/





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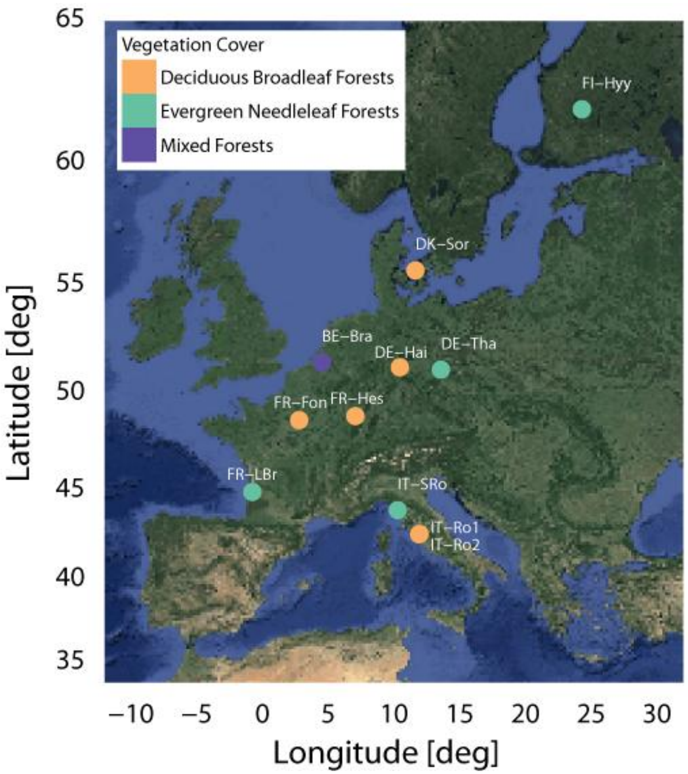
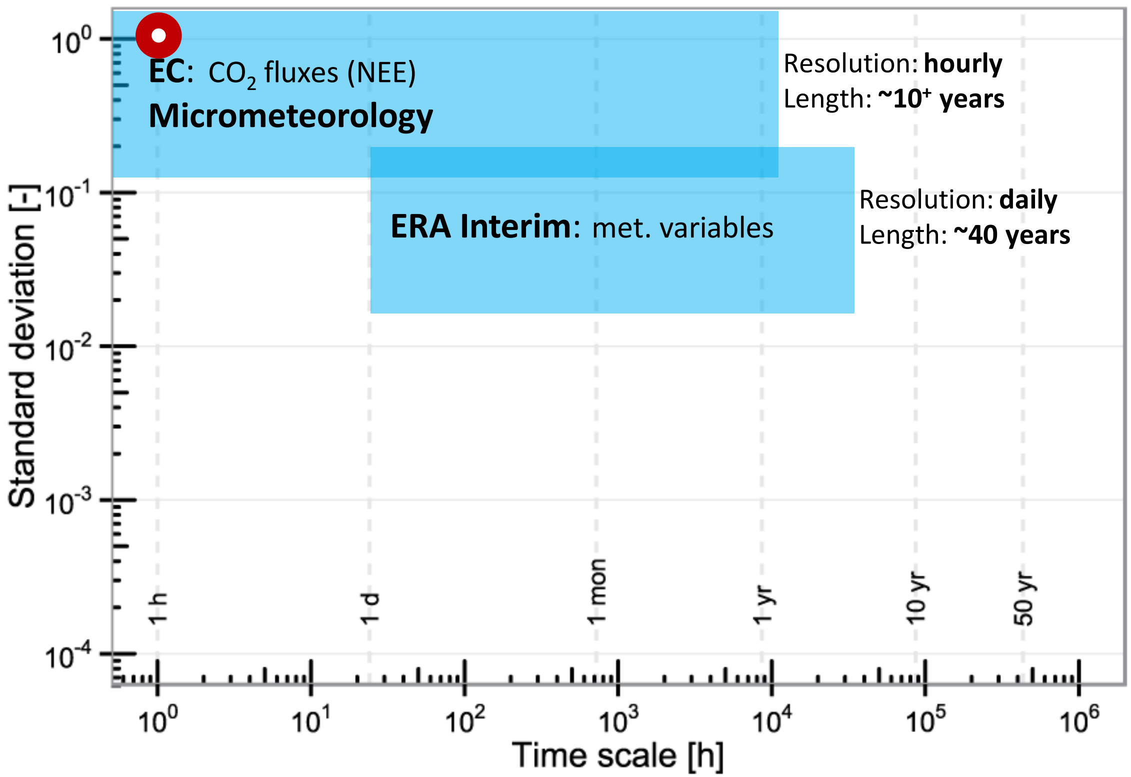
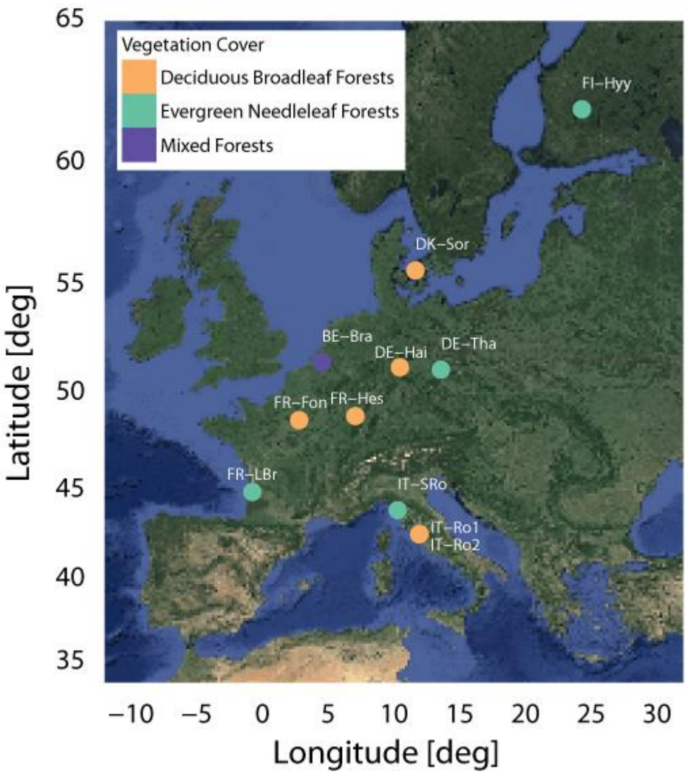
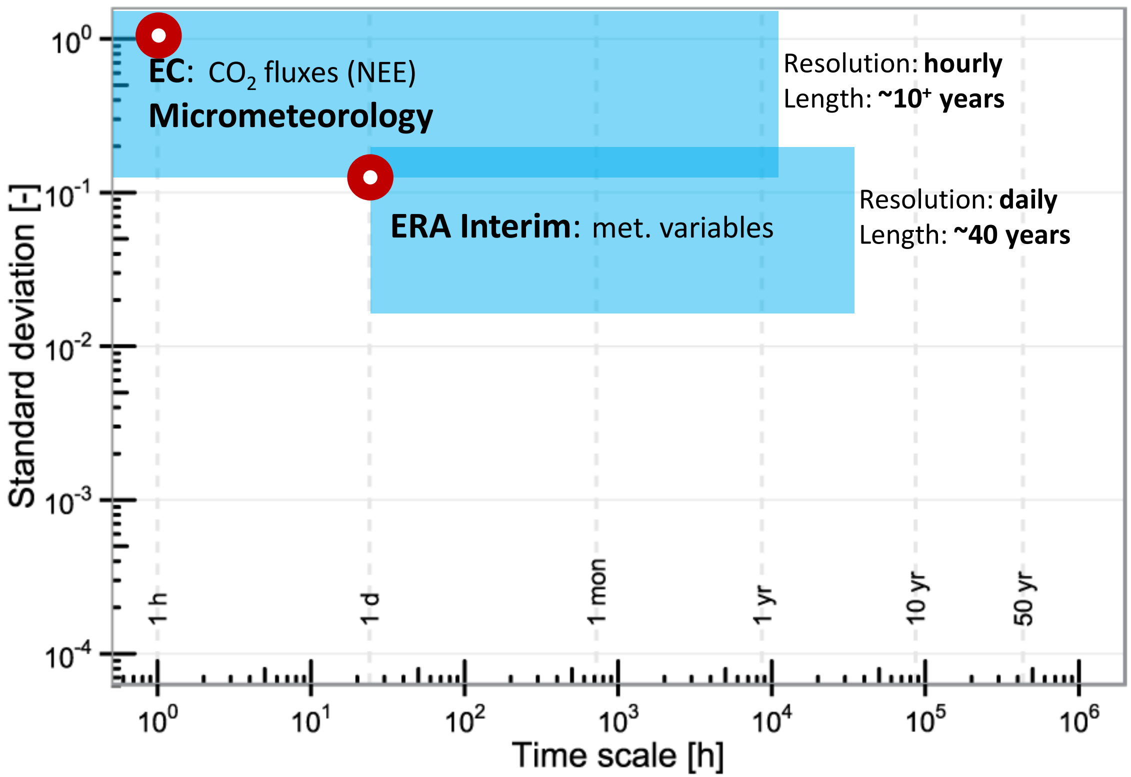
Carbo-Extreme: http://www.carbo-extreme.eu/





Dee, D. P. *et al.* The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Q. J. R. Meteorol. Soc.* **137,** 553–597 (2011).





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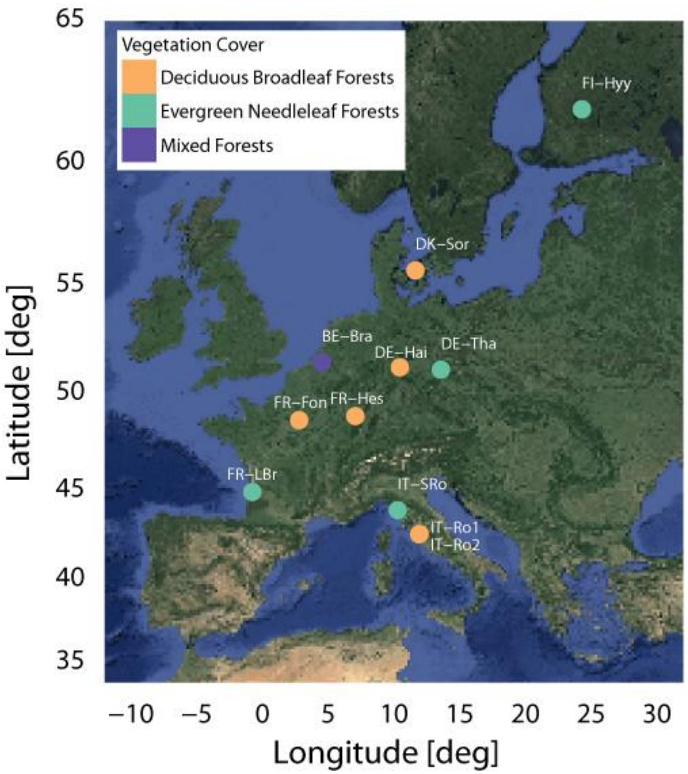
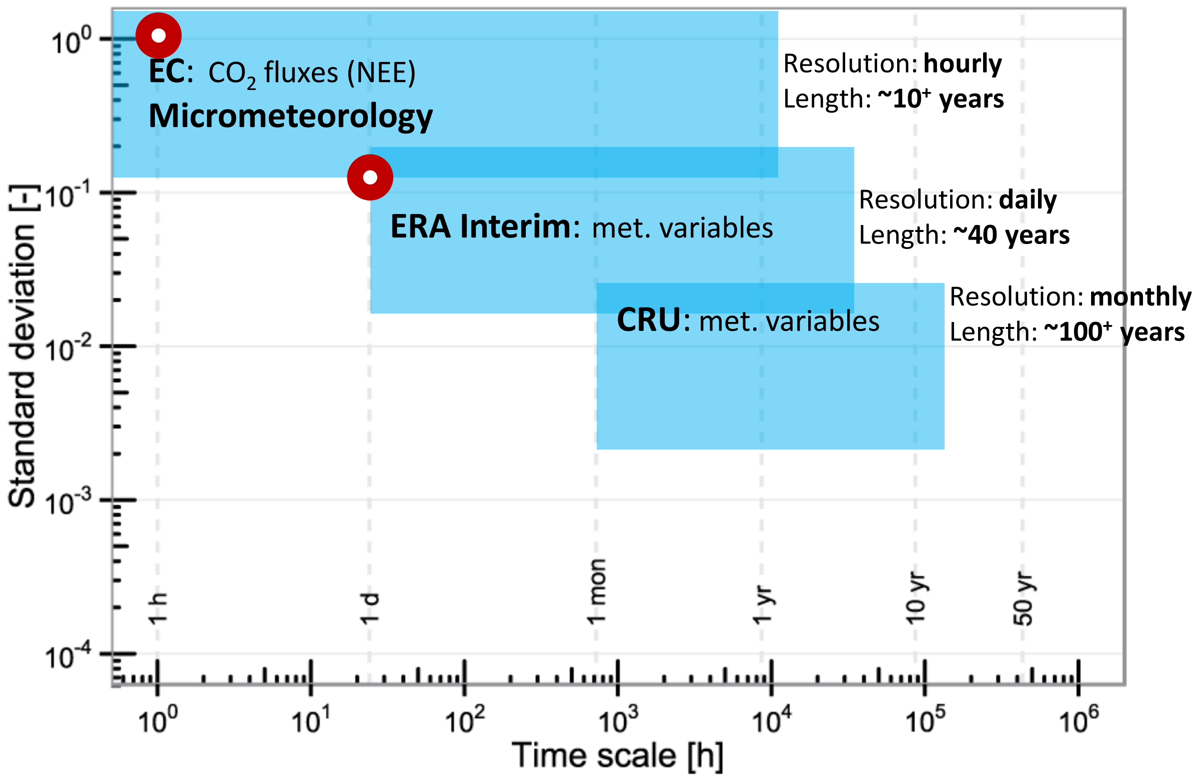
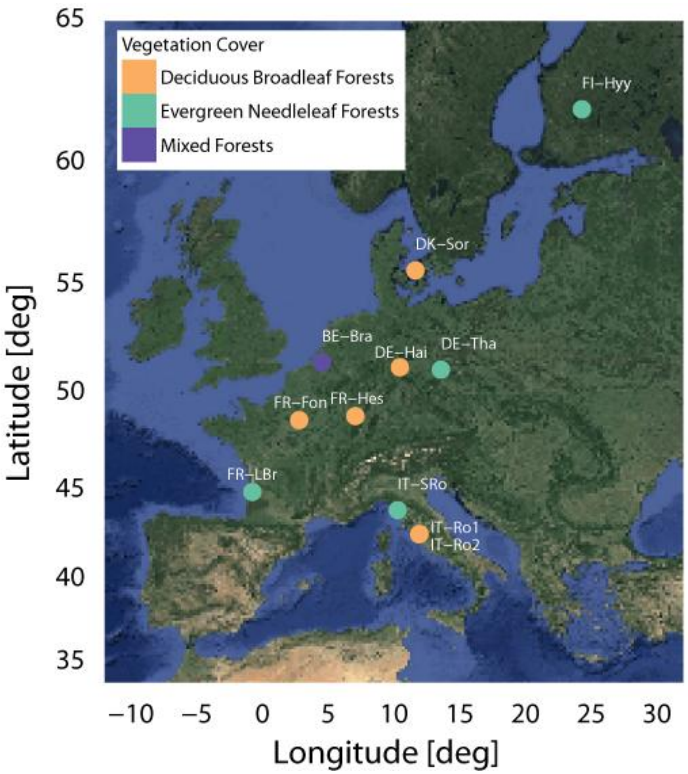
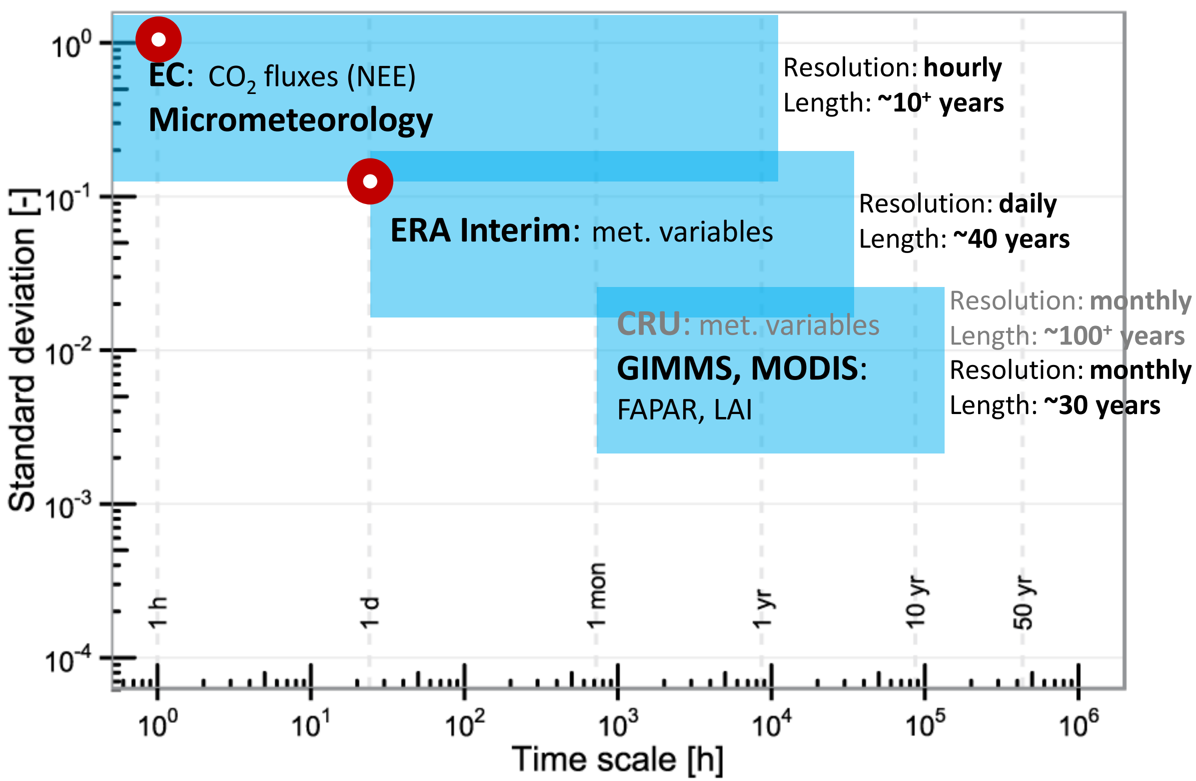




Harris, I., Jones, P. D., Osborn, T. J. & Lister, D. H. Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 Dataset. *Int. J. Climatol.* **34,** 623–642 (2014).

Mitchell, T.D., Carter, T.R., Jones, P.D., and Hulme,M., 2004: A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901-2000) and 16 scenarios (2001-2100). *Tyndall Centre Working Papers*.





Zhu, Z. *et al.* Global Data Sets of Vegetation Leaf Area Index (LAI)3g and Fraction of Photosynthetically Active Radiation (FPAR)3g Derived from Global Inventory Modeling and Mapping Studies (GIMMS) Normalized Difference Vegetation Index (NDVI3g) for the Period 1981 to 2. *Remote Sens.* **5,** 927–948 (2013).

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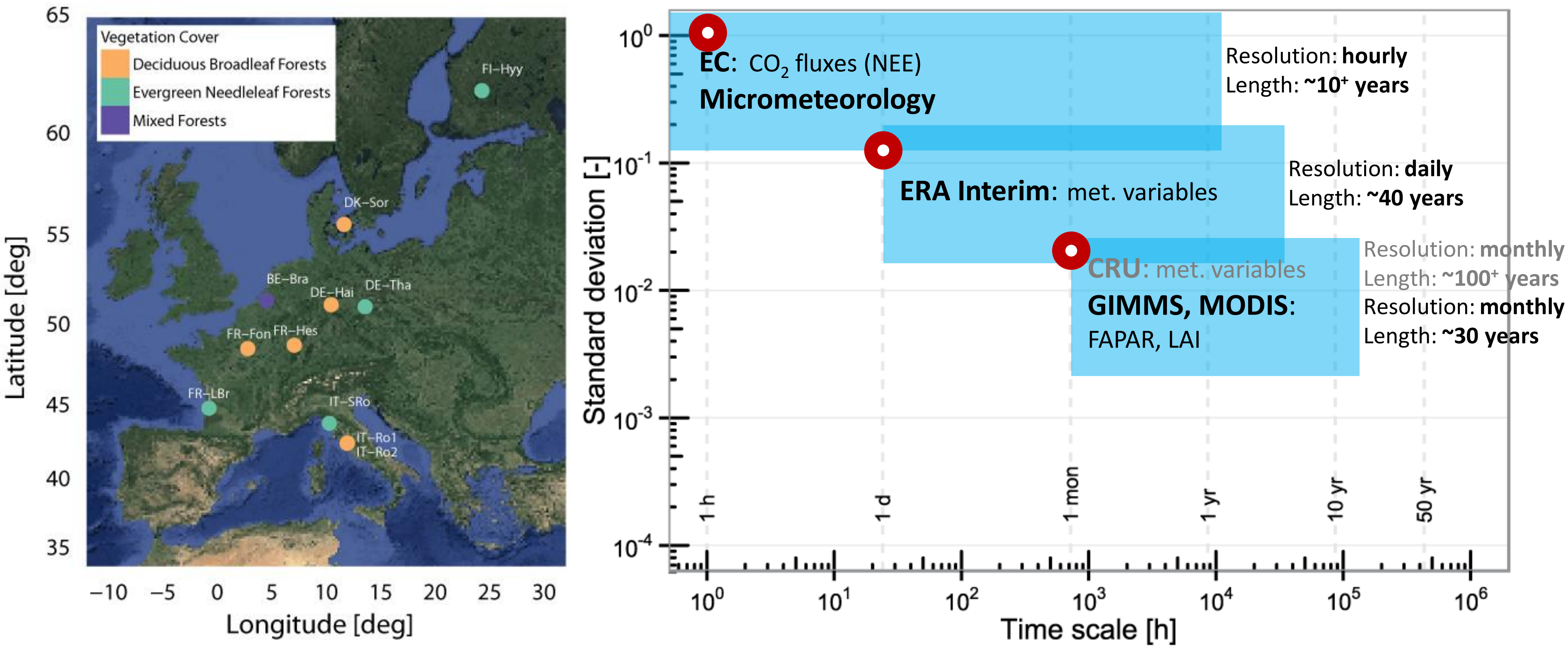

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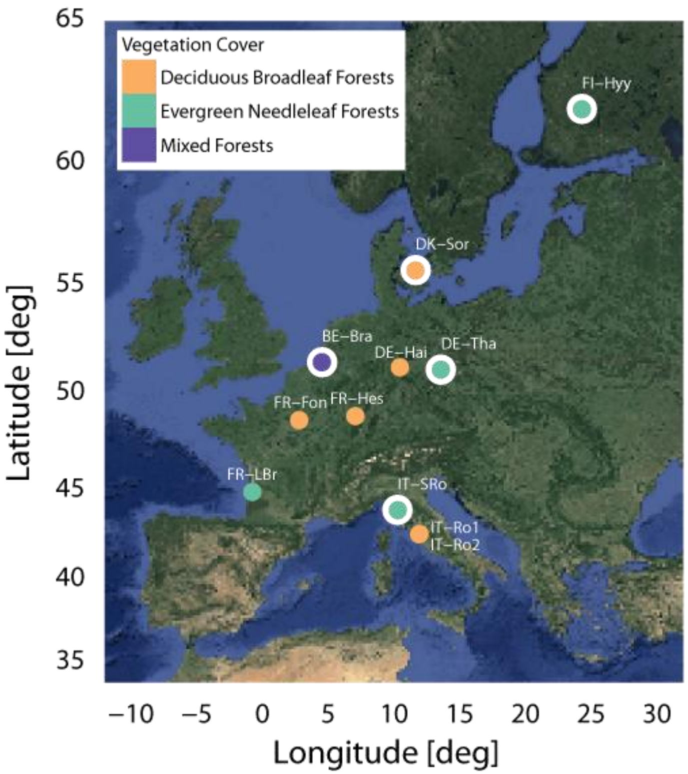

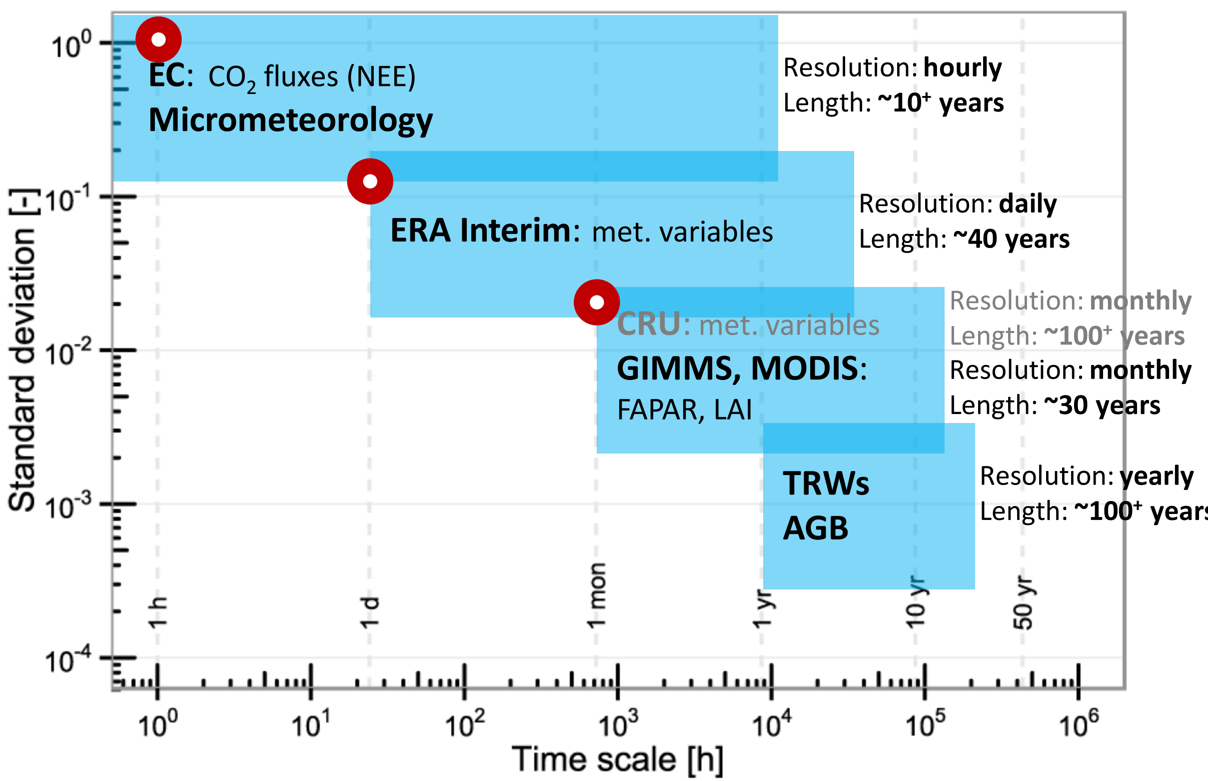

Babst, F., Bouriaud, O., Alexander, R., Trouet, V. & Frank, D. Toward consistent measurements of carbon accumulation: A multi-site assessment of biomass and basal area increment across Europe. *Dendrochronologia* **32,** 153–161 (2014).

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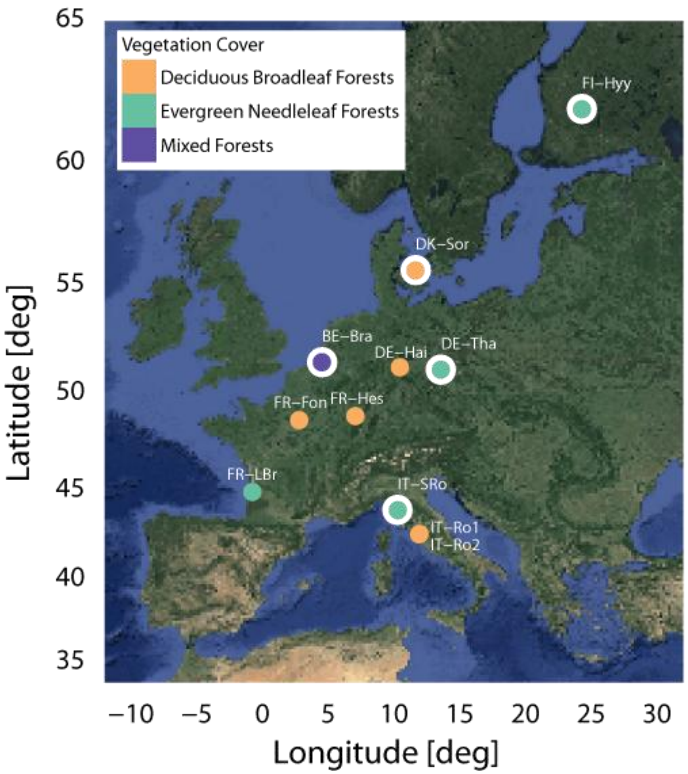

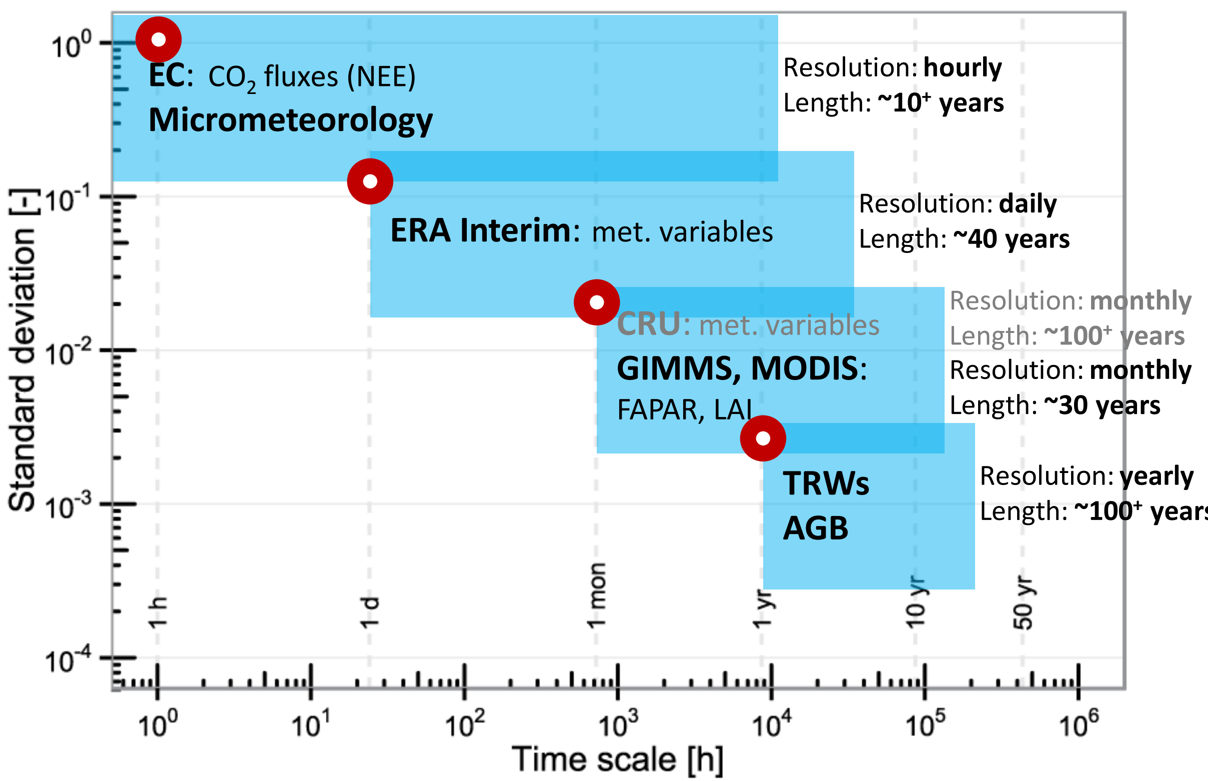

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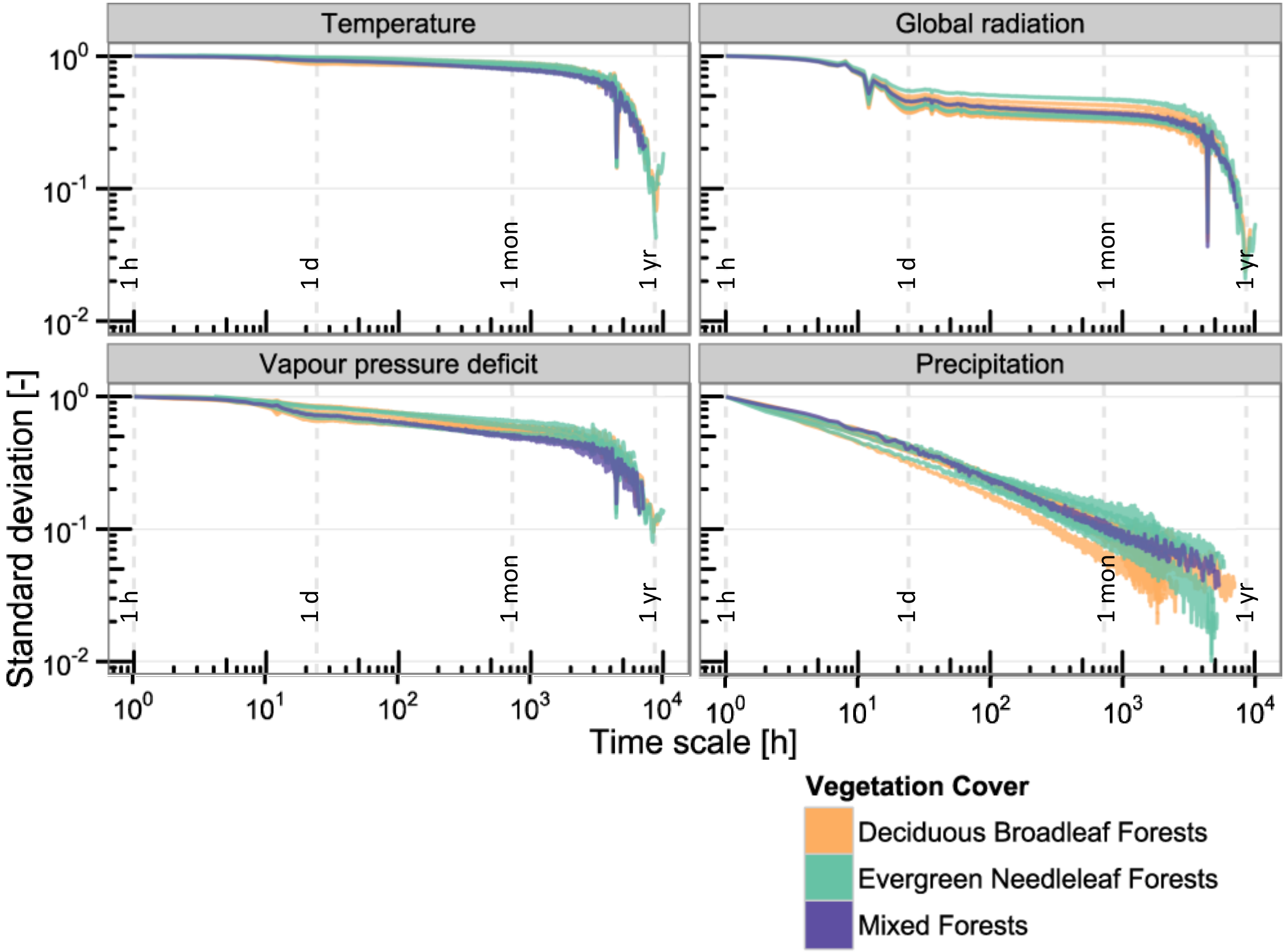
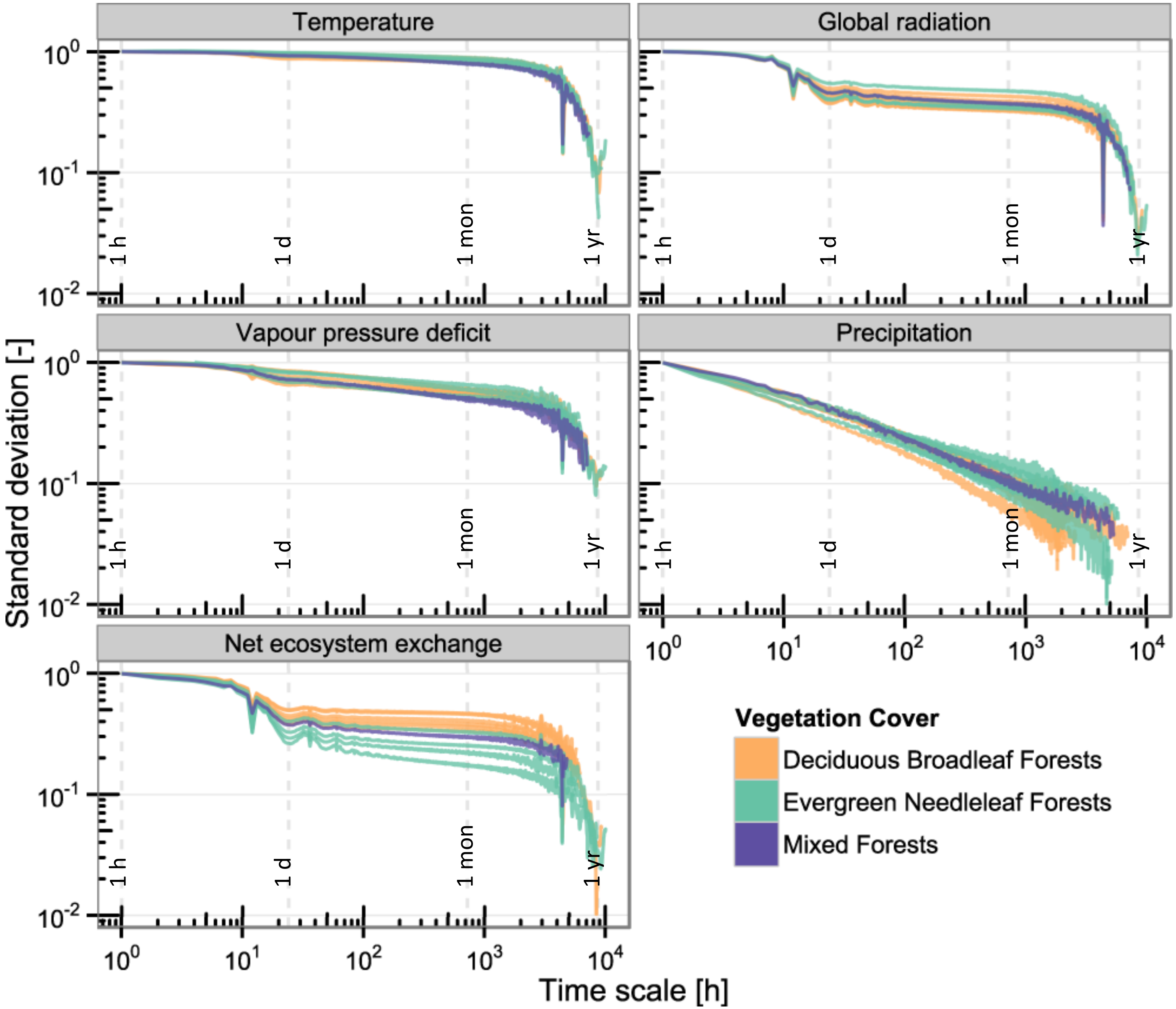
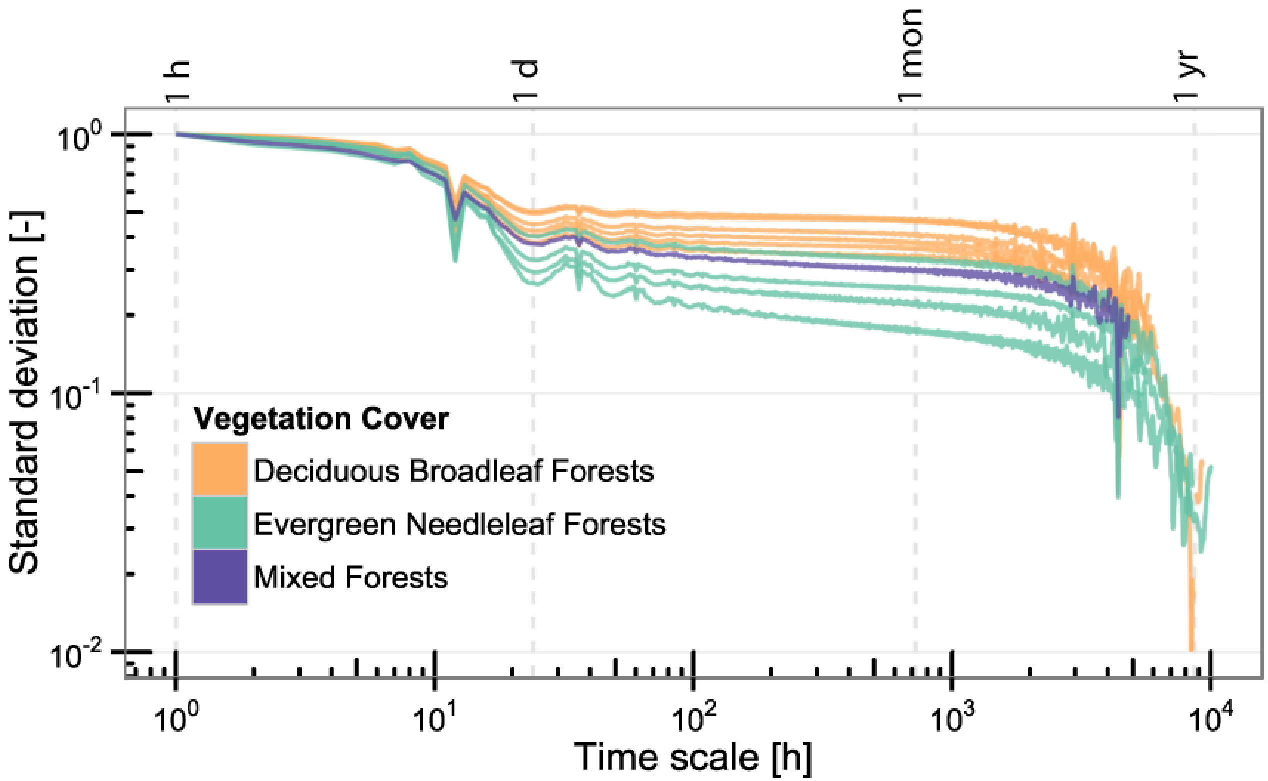
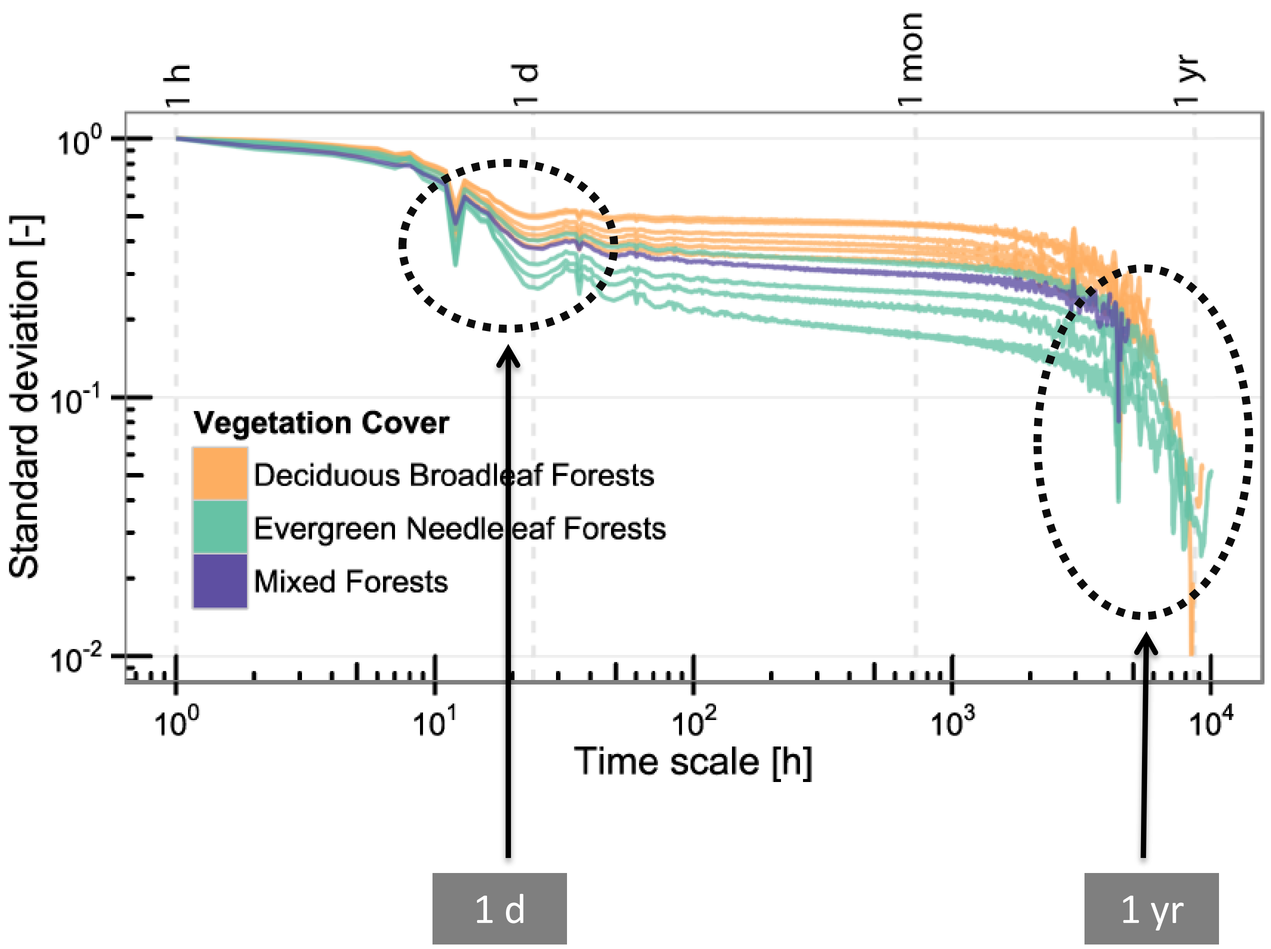
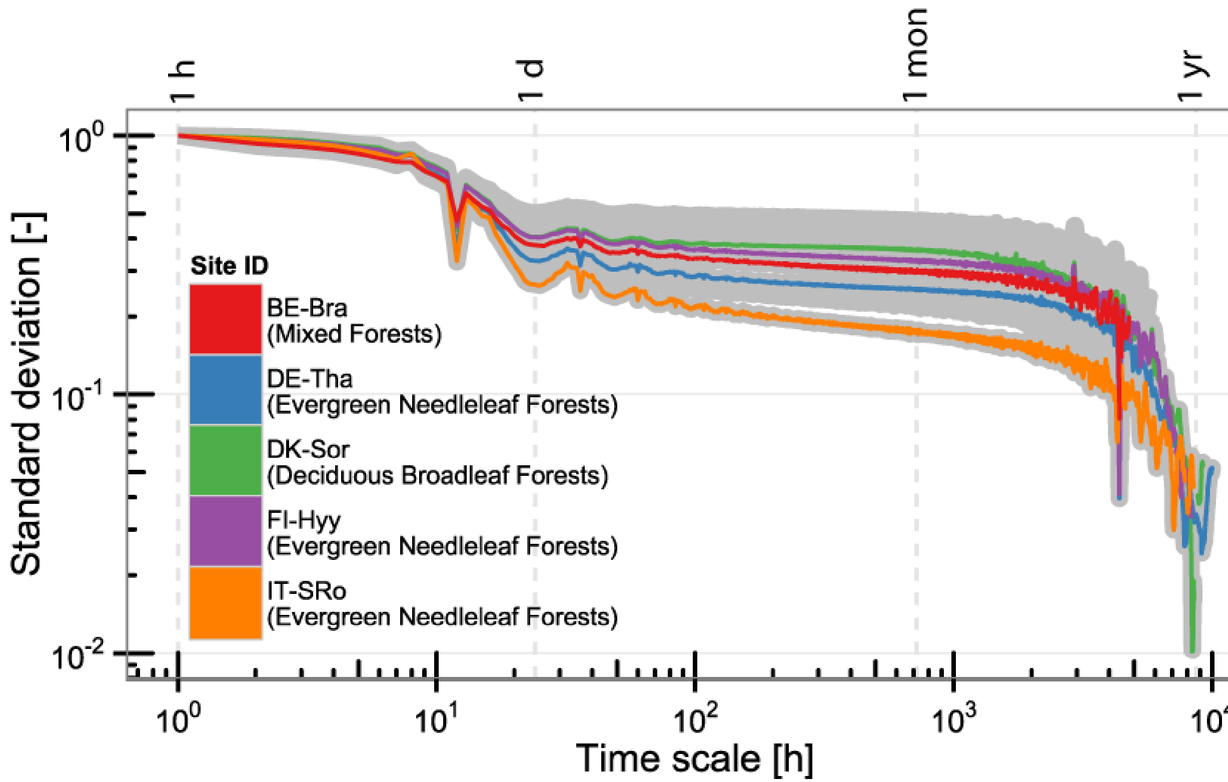
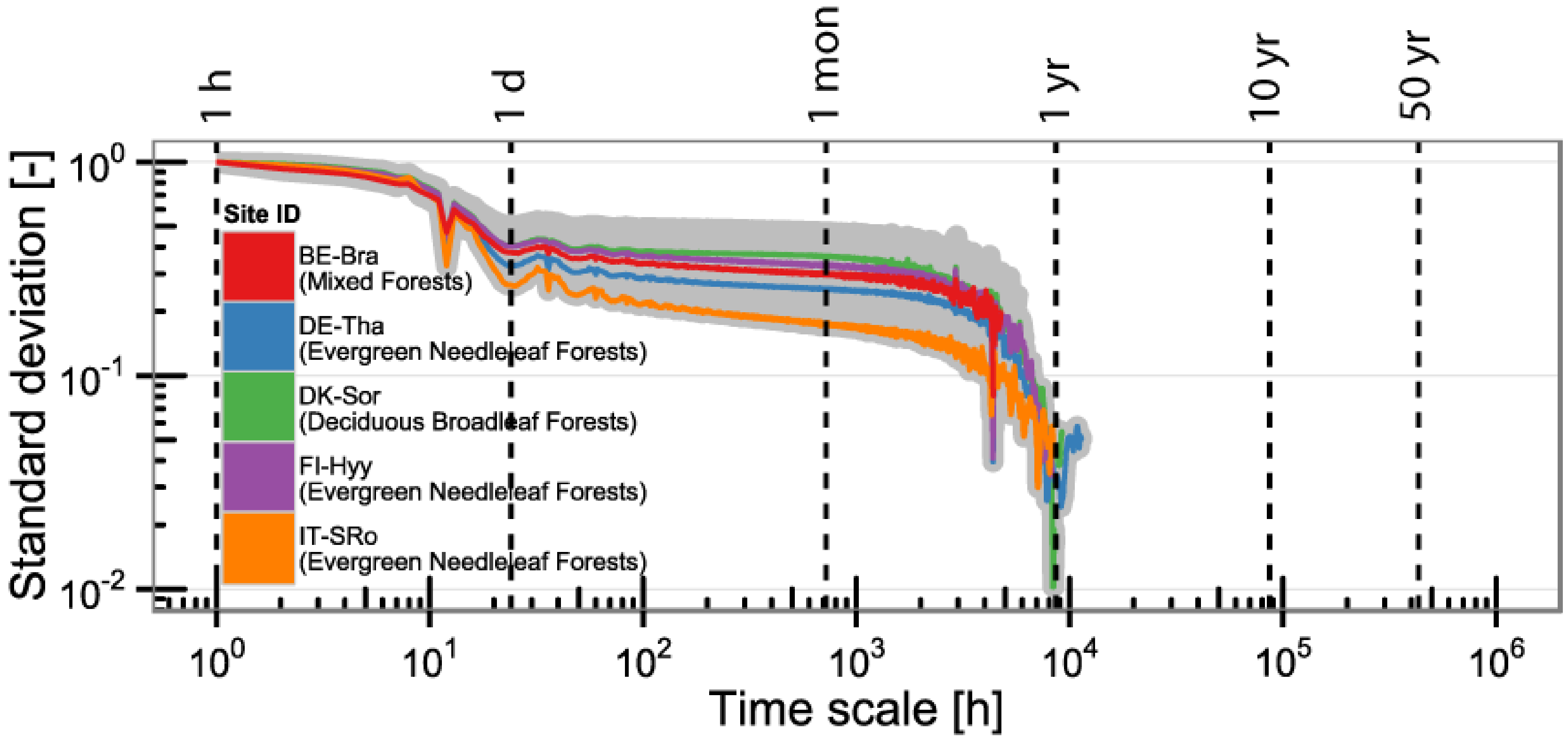

Temperature
Global radiation
Vapour pressure deficit
Precipitation
Standard deviation [-]
Time scale [h]
1 h
1 d
1 mon
1 yr
Vegetation Cover
Deciduous Broadleaf Forests
Evergreen Needleleaf Forests
Mixed Forests

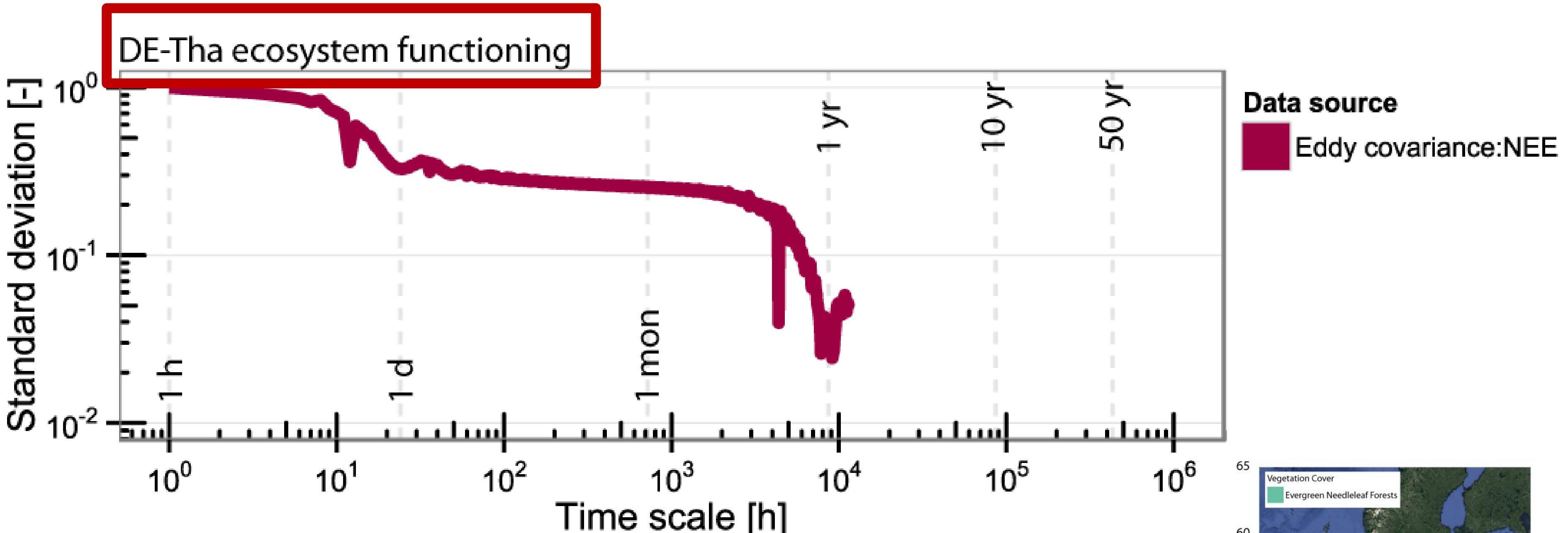

Temperature
Global radiation
Vapour pressure deficit
Precipitation
Net ecosystem exchange
Standard deviation [-]
Time scale [h]
1 h
1 d
1 mon
1 yr
10^0
10^{-1}
10^{-2}
10^0
10^1
10^2
10^3
10^4
Vegetation Cover
Deciduous Broadleaf Forests
Evergreen Needleleaf Forests
Mixed Forests

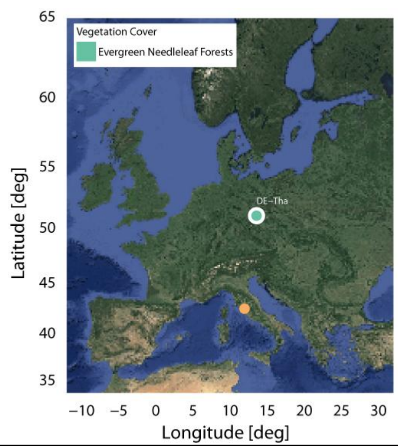

1 h
1 d
1 mon
1 yr
Standard deviation [-]
10^0
10^{-1}
10^{-2}
Vegetation Cover
Deciduous Broadleaf Forests
Evergreen Needleleaf Forests
Mixed Forests
10^0
10^1
10^2
10^3
10^4
Time scale [h]


1 h
1 d
1 mon
1 yr
10^0
10^{-1}
10^{-2}
Standard deviation [-]
Vegetation Cover
Deciduous Broadleaf Forests
Evergreen Needleleaf Forests
Mixed Forests
10^0
10^1
10^2
10^3
10^4
Time scale [h]
1 d
1 yr


1 h
1 d
1 mon
1 yr
Site ID
BE-Bra
(Mixed Forests)
DE-Tha
(Evergreen Needleleaf Forests)
DK-Sor
(Deciduous Broadleaf Forests)
FI-Hyy
(Evergreen Needleleaf Forests)
IT-SRo
(Evergreen Needleleaf Forests)
Standard deviation [-]
10^0
10^{-1}
10^{-2}
10^0
10^1
10^2
10^3
10^4
Time scale [h]


1 h
1 d
1 mon
1 yr
10 yr
50 yr
Standard deviation [-]
10^0
10^-1
10^-2
Site ID
BE-Bra
(Mixed Forests)
DE-Tha
(Evergreen Needleleaf Forests)
DK-Sor
(Deciduous Broadleaf Forests)
FI-Hyy
(Evergreen Needleleaf Forests)
IT-SRo
(Evergreen Needleleaf Forests)
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Time scale [h]


DE-Tha ecosystem functioning
Standard deviation [-]
10^0
10^{-1}
10^{-2}
1 h
1 d
1 mon
1 yr
10 yr
50 yr
10^0 10^1 10^2 10^3 10^4 10^5 10^6
Time scale [h]
Data source
Eddy covariance:NEE

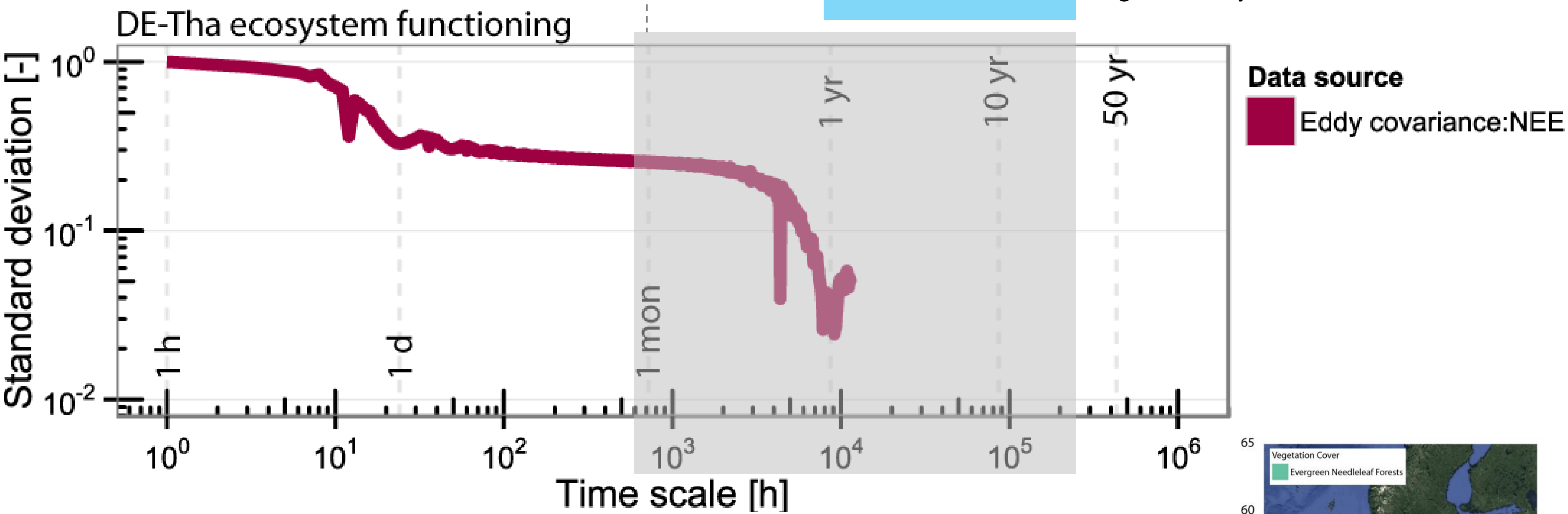

Vegetation Cover
Evergreen Needleleaf Forests
DE–Tha
Latitude [deg]
Longitude [deg]

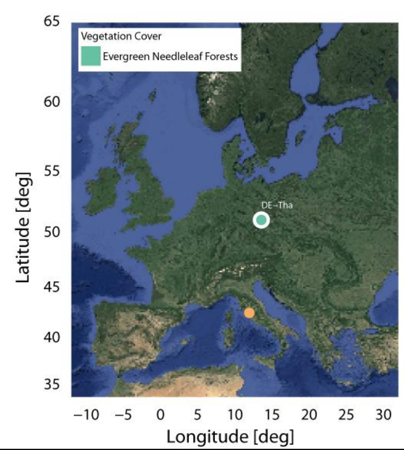
GIMMS, MODIS:
FAPAR, LAI

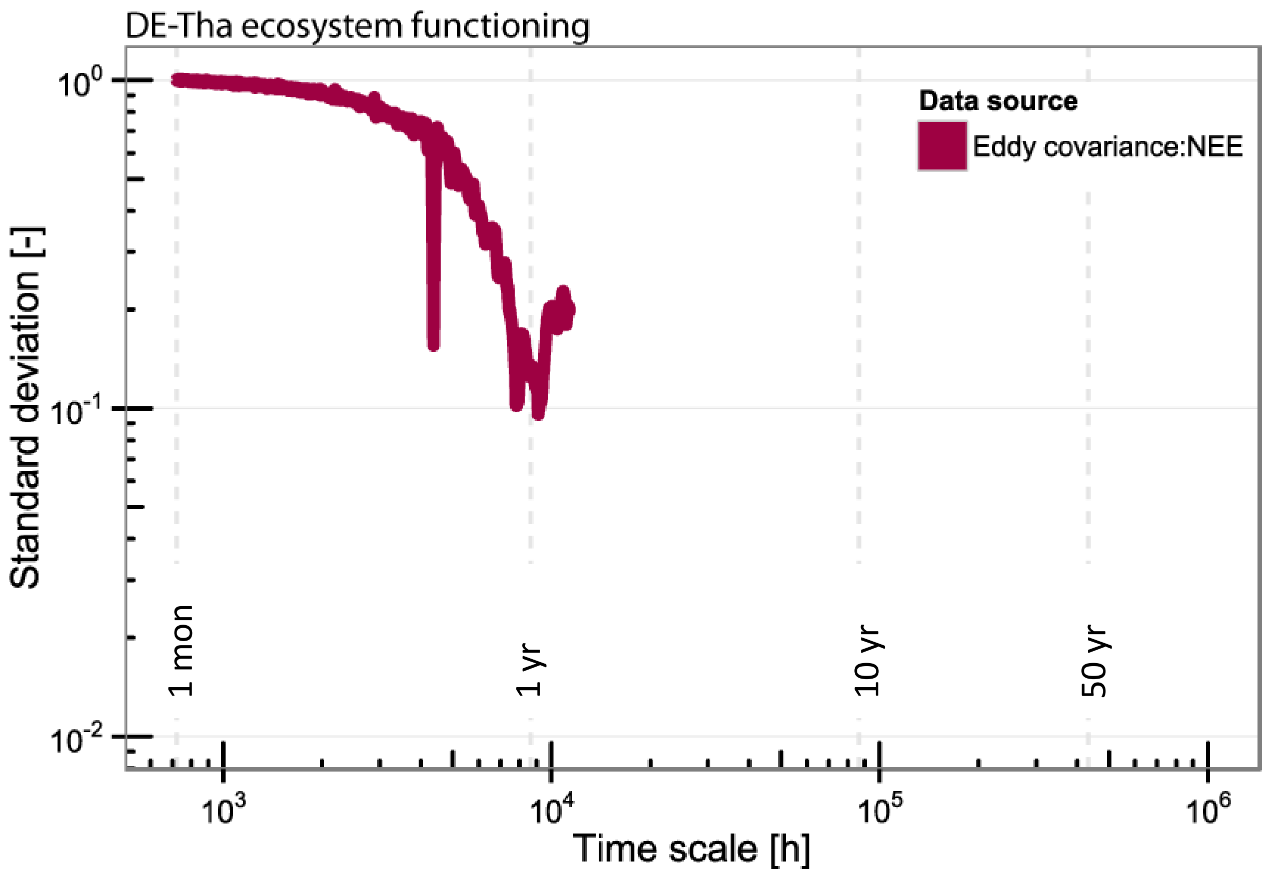
Resolution: **monthly**
Length: **~30 years**

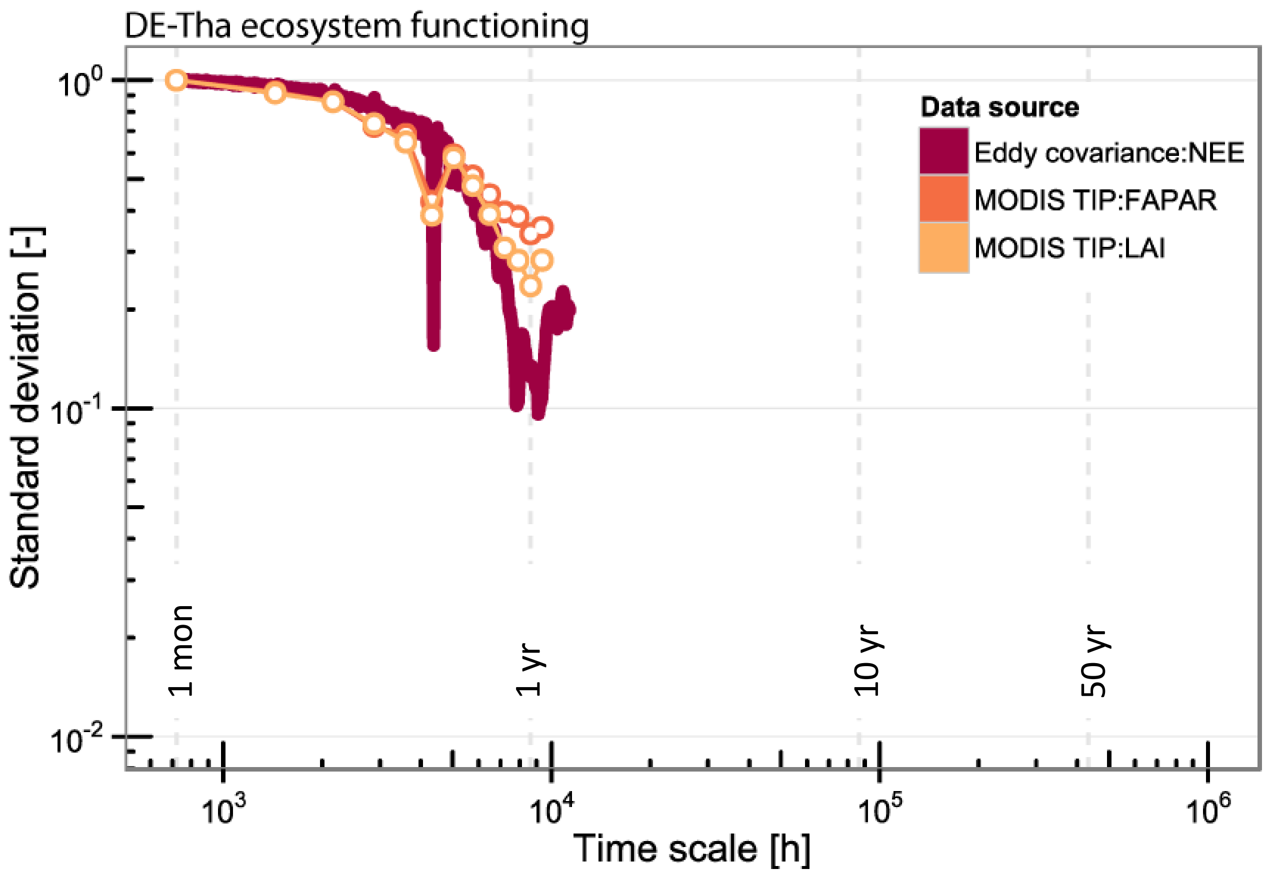
TRWs, AGB

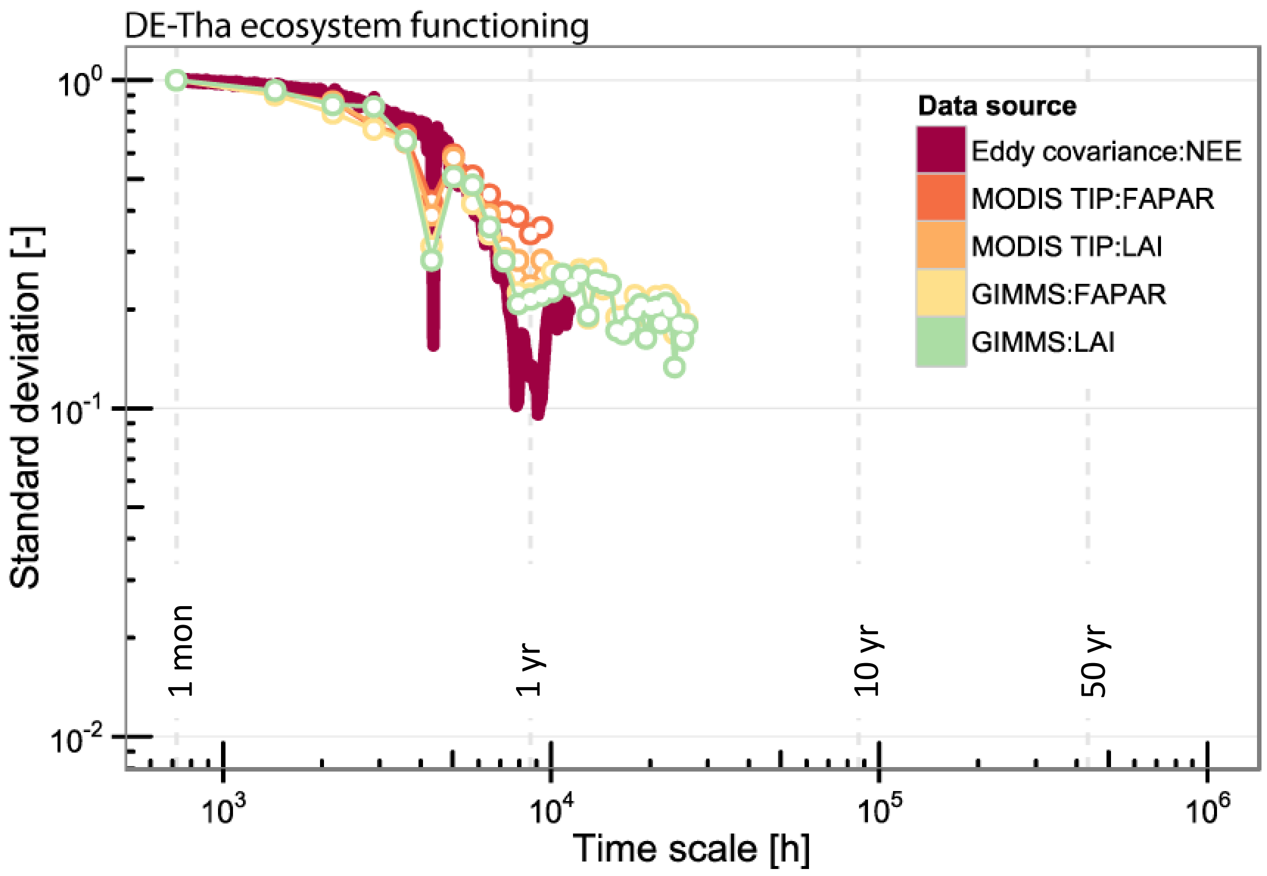
Resolution: **yearly**
Length: **~100+ years**

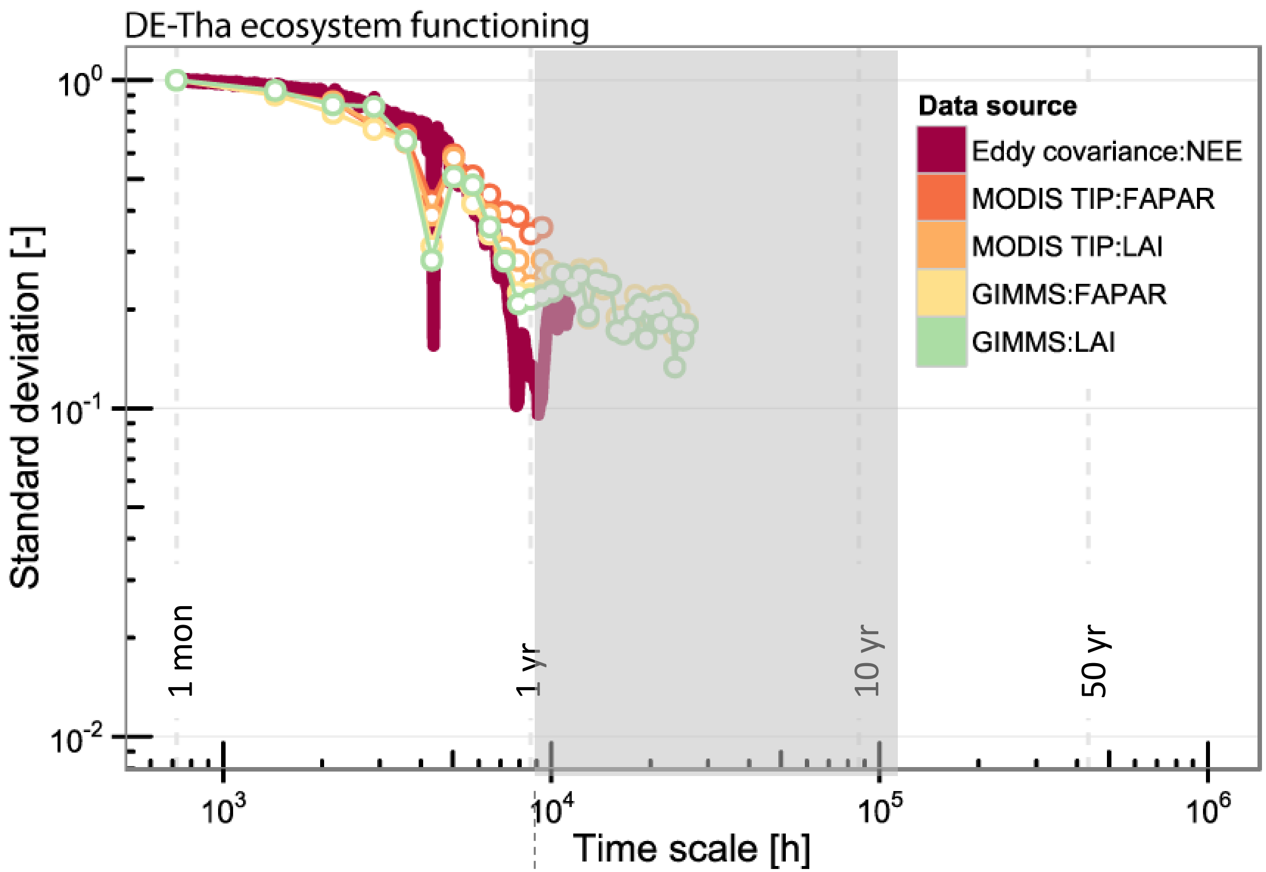





DE-Tha ecosystem functioning
Data source
Eddy covariance:NEE
Standard deviation [-]
10^0
10^{-1}
10^{-2}
1 mon
1 yr
10 yr
50 yr
10^3
10^4
10^5
10^6
Time scale [h]

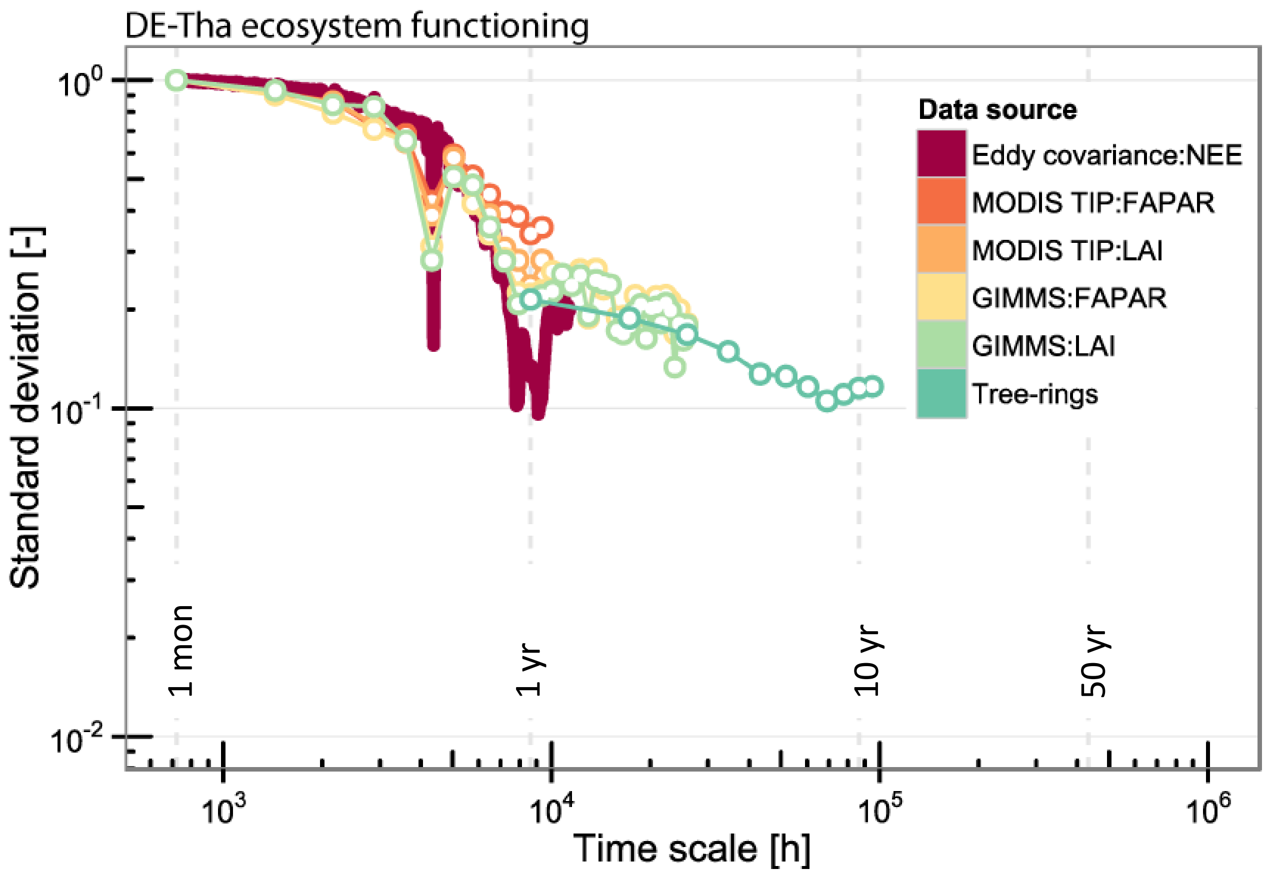

DE-Tha ecosystem functioning
Data source
Eddy covariance:NEE
MODIS TIP:FAPAR
MODIS TIP:LAI
Standard deviation [-]
10^0
10^{-1}
10^{-2}
1 mon
1 yr
10 yr
50 yr
10^3
10^4
10^5
10^6
Time scale [h]

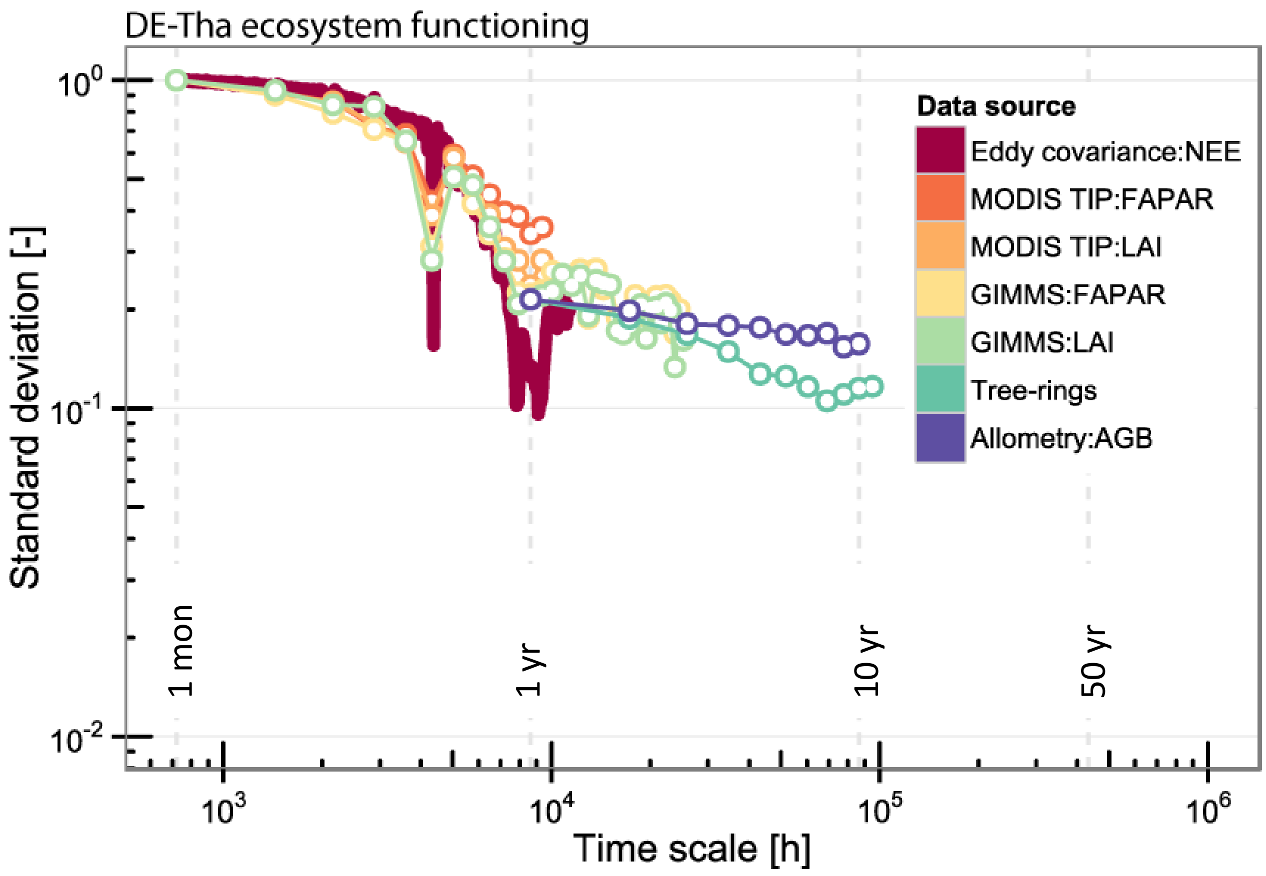

DE-Tha ecosystem functioning
Standard deviation [-]
10^0
10^{-1}
10^{-2}
1 mon
1 yr
10 yr
50 yr
10^3
10^4
10^5
10^6
Time scale [h]
Data source
Eddy covariance:NEE
MODIS TIP:FAPAR
MODIS TIP:LAI
GIMMS:FAPAR
GIMMS:LAI

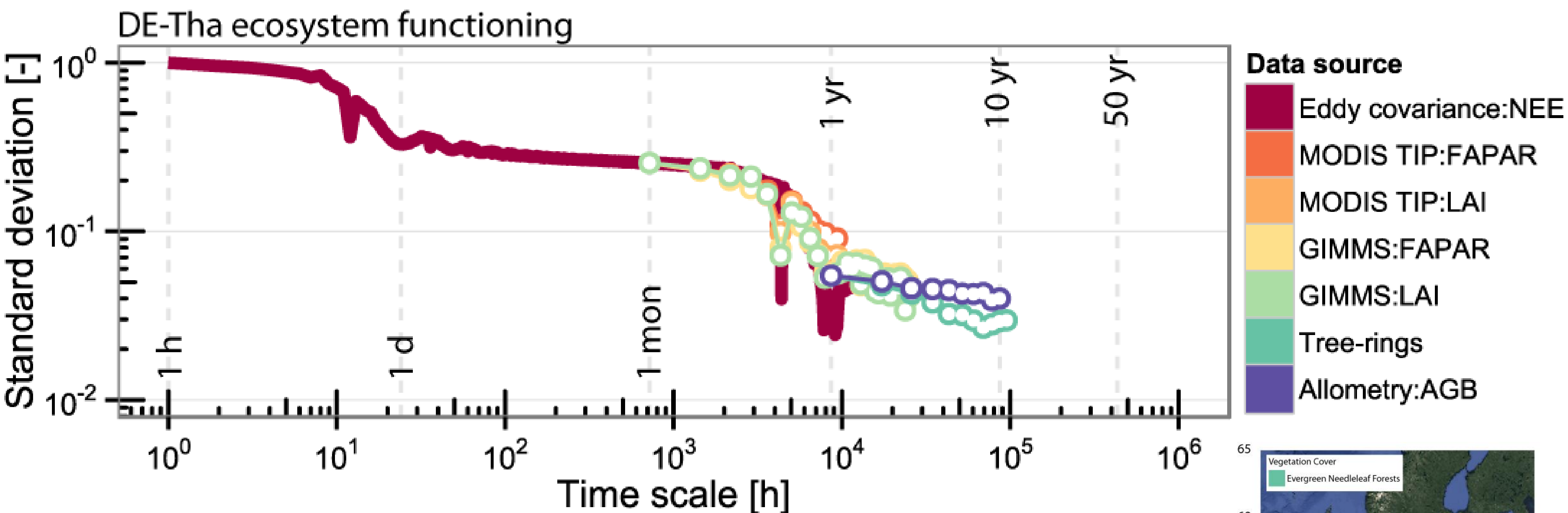


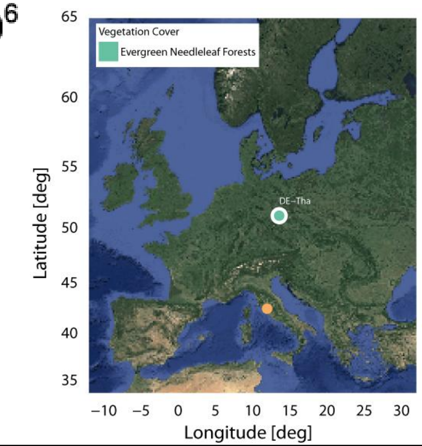
TRWs, AGB

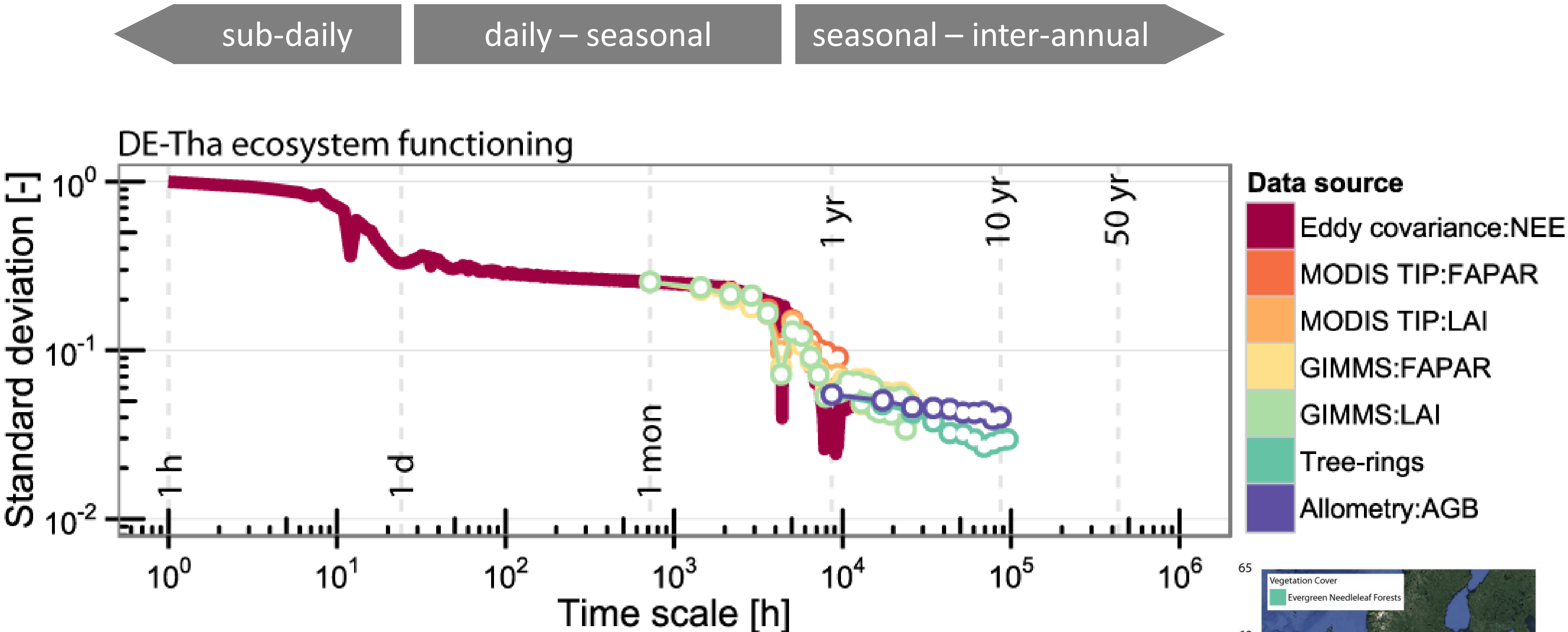
Resolution: **yearly**
Length: **~100+ years**

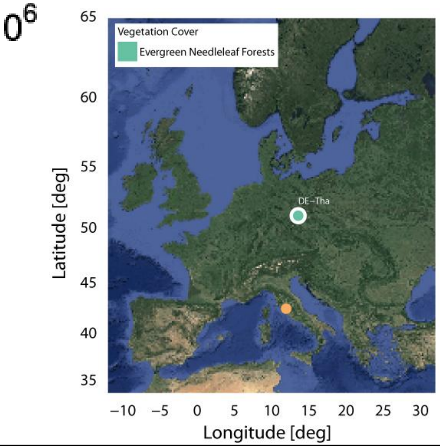

DE-Tha ecosystem functioning
Standard deviation [-]
Time scale [h]
1 mon
1 yr
10 yr
50 yr
Data source
Eddy covariance:NEE
MODIS TIP:FAPAR
MODIS TIP:LAI
GIMMS:FAPAR
GIMMS:LAI
Tree-rings

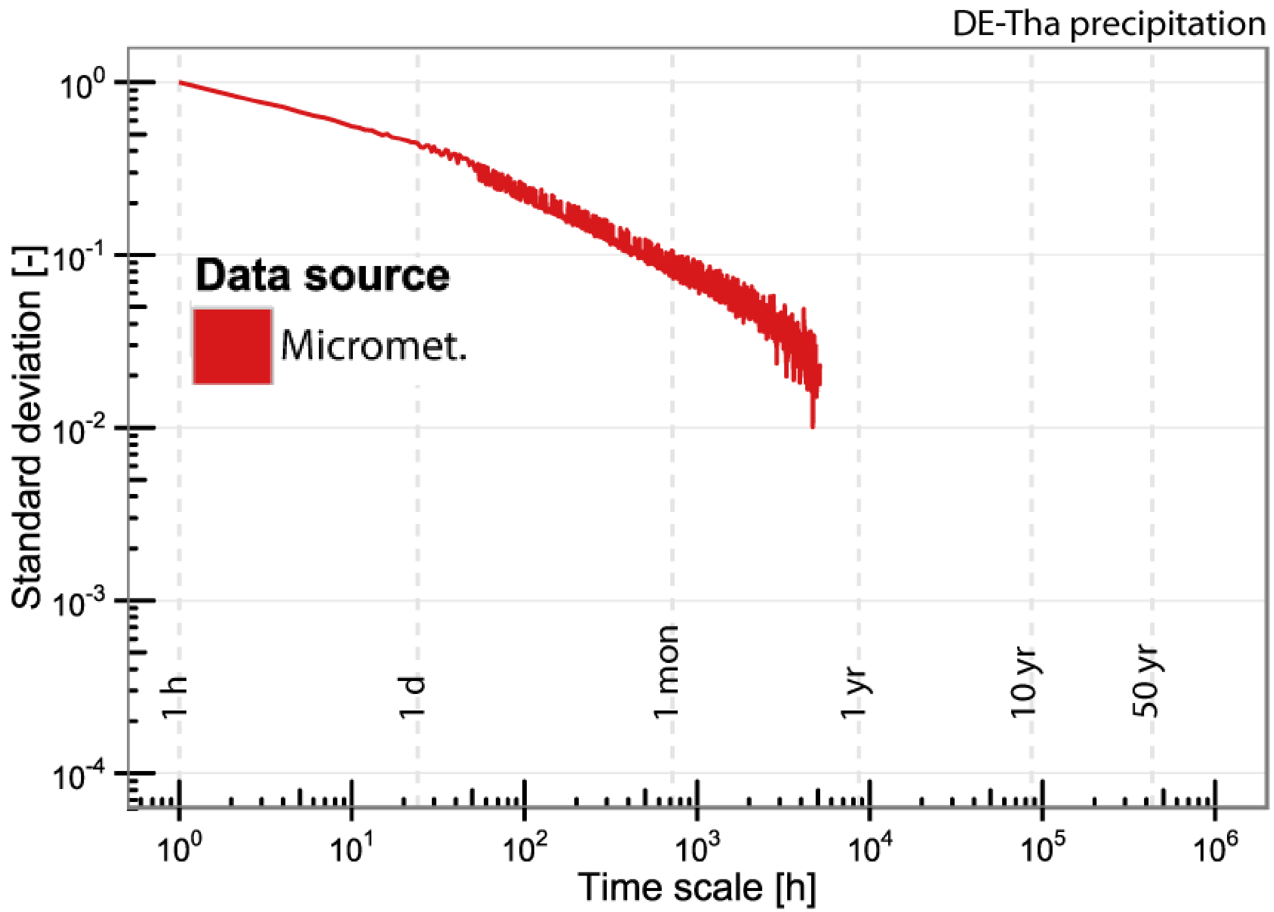

DE-Tha ecosystem functioning
Standard deviation [-]
10^0
10^{-1}
10^{-2}
1 mon
1 yr
10 yr
50 yr
10^3
10^4
10^5
10^6
Time scale [h]
Data source
Eddy covariance:NEE
MODIS TIP:FAPAR
MODIS TIP:LAI
GIMMS:FAPAR
GIMMS:LAI
Tree-rings
Allometry:AGB

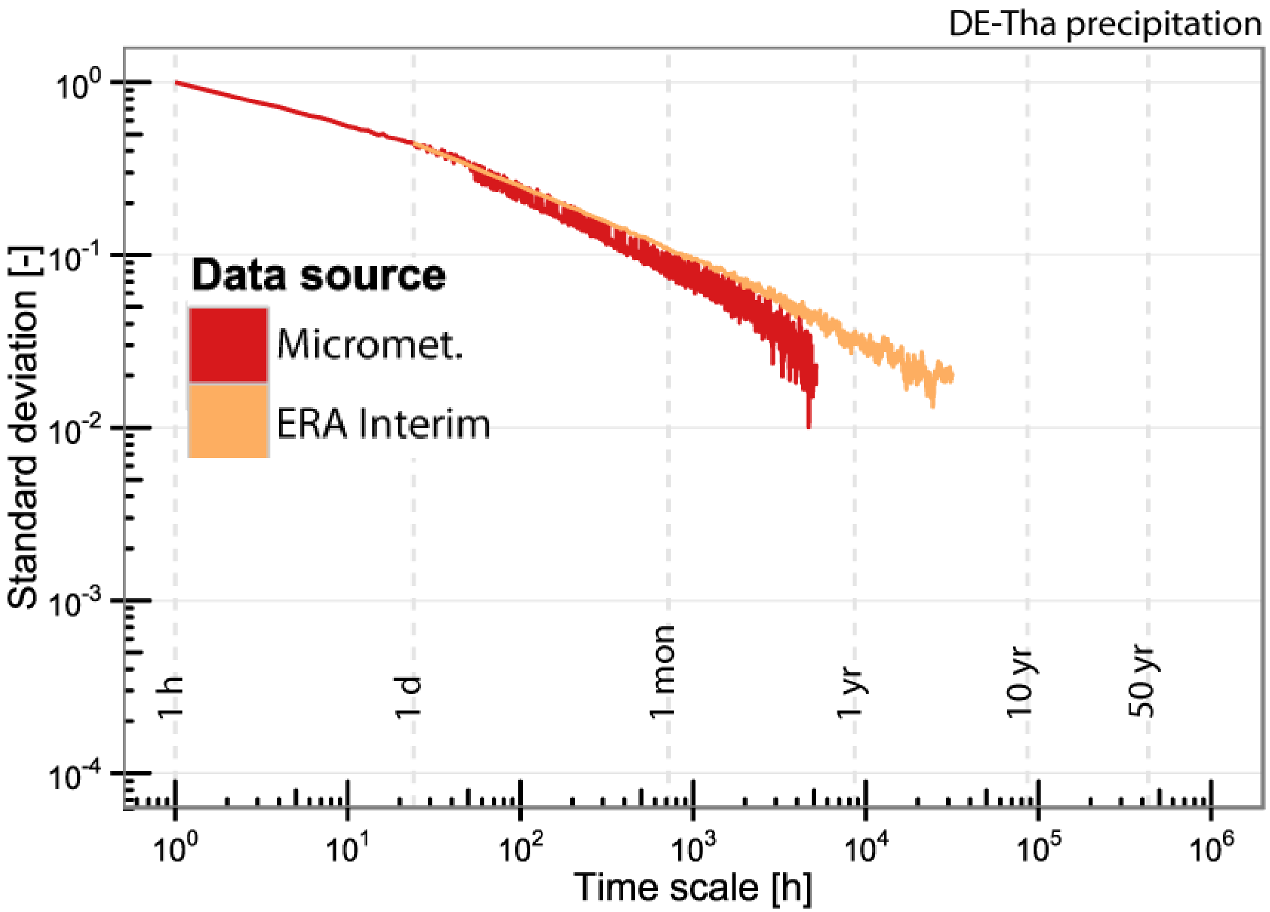

DE-Tha ecosystem functioning
Standard deviation [-]
10^0
10^{-1}
10^{-2}
1 h
1 d
1 mon
1 yr
10 yr
50 yr
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Time scale [h]
Data source
Eddy covariance:NEE
MODIS TIP:FAPAR
MODIS TIP:LAI
GIMMS:FAPAR
GIMMS:LAI
Tree-rings
Allometry:AGB

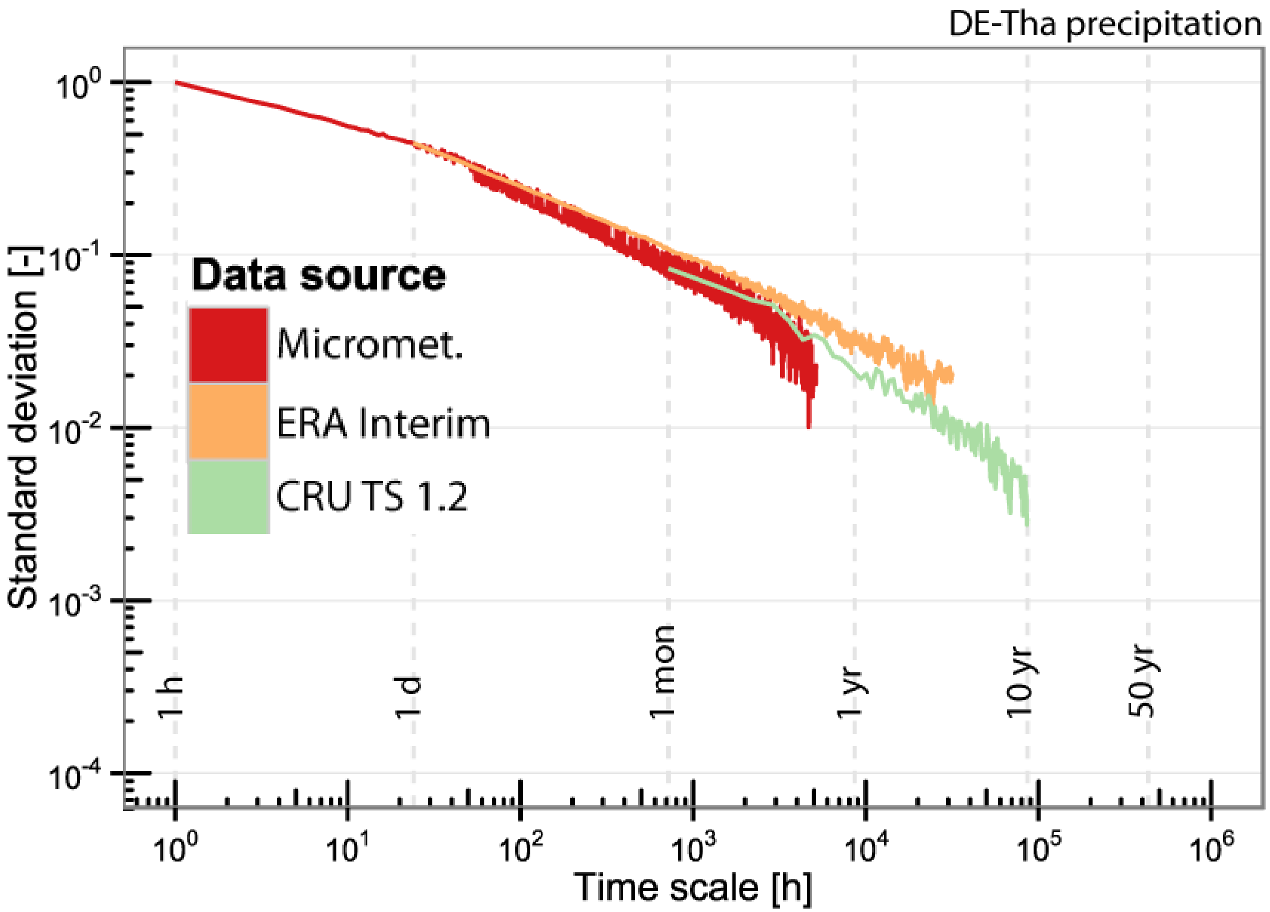

Vegetation Cover
Evergreen Needleleaf Forests
DE-Tha
Latitude [deg]
65
60
55
50
45
40
35
−10
−5
0
5
10
15
20
25
30
Longitude [deg]

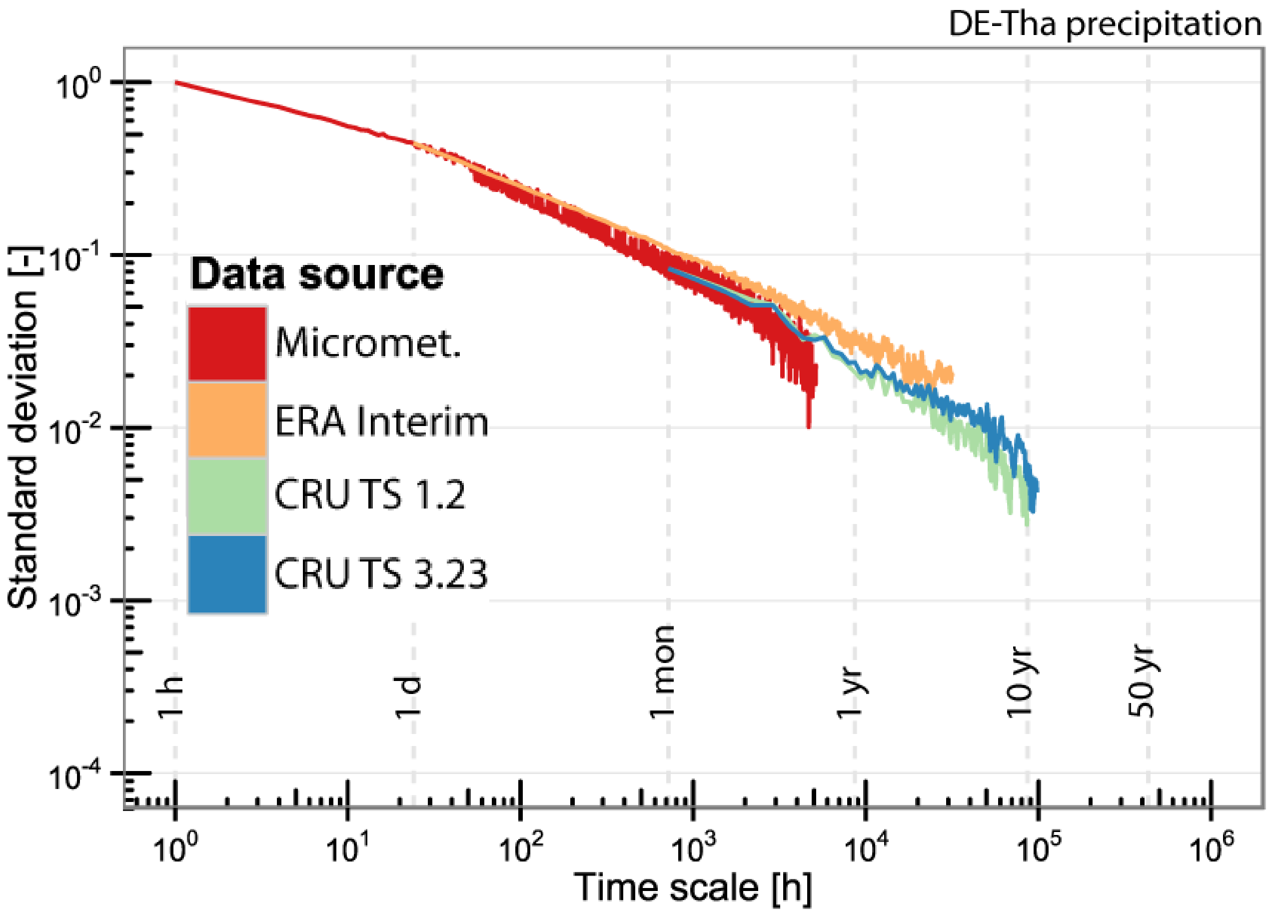

sub-daily
daily – seasonal
seasonal – inter-annual
DE-Tha ecosystem functioning
Standard deviation [-]
Time scale [h]
1 h
1 d
1 mon
1 yr
10 yr
50 yr
Data source
Eddy covariance:NEE
MODIS TIP:FAPAR
MODIS TIP:LAI
GIMMS:FAPAR
GIMMS:LAI
Tree-rings
Allometry:AGB


Vegetation Cover
Evergreen Needleleaf Forests
DE-Tha
Latitude [deg]
Longitude [deg]


DE-Tha precipitation
Standard deviation [-]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Data source
Micromet.
1 h
1 d
1 mon
1 yr
10 yr
50 yr
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Time scale [h]


DE-Tha precipitation
Data source
Micromet.
ERA Interim
Standard deviation [-]
10^0
10^-1
10^-2
10^-3
10^-4
1 h
1 d
1 mon
1 yr
10 yr
50 yr
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Time scale [h]


DE-Tha precipitation
Data source
Micromet.
ERA Interim
CRU TS 1.2
Standard deviation [-]
Time scale [h]
1 h
1 d
1 mon
1 yr
10 yr
50 yr
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^0
10^1
10^2
10^3
10^4
10^5
10^6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Data source
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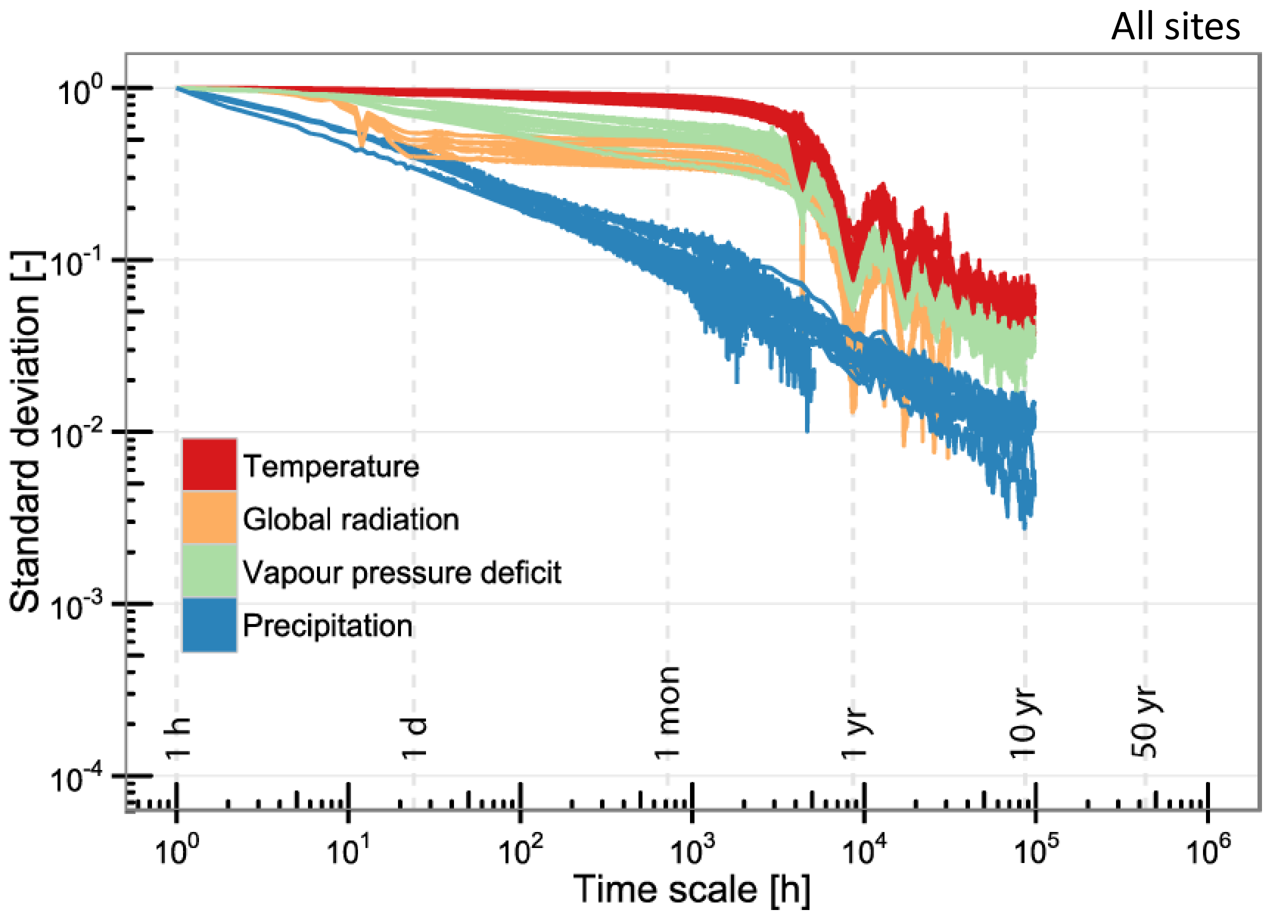
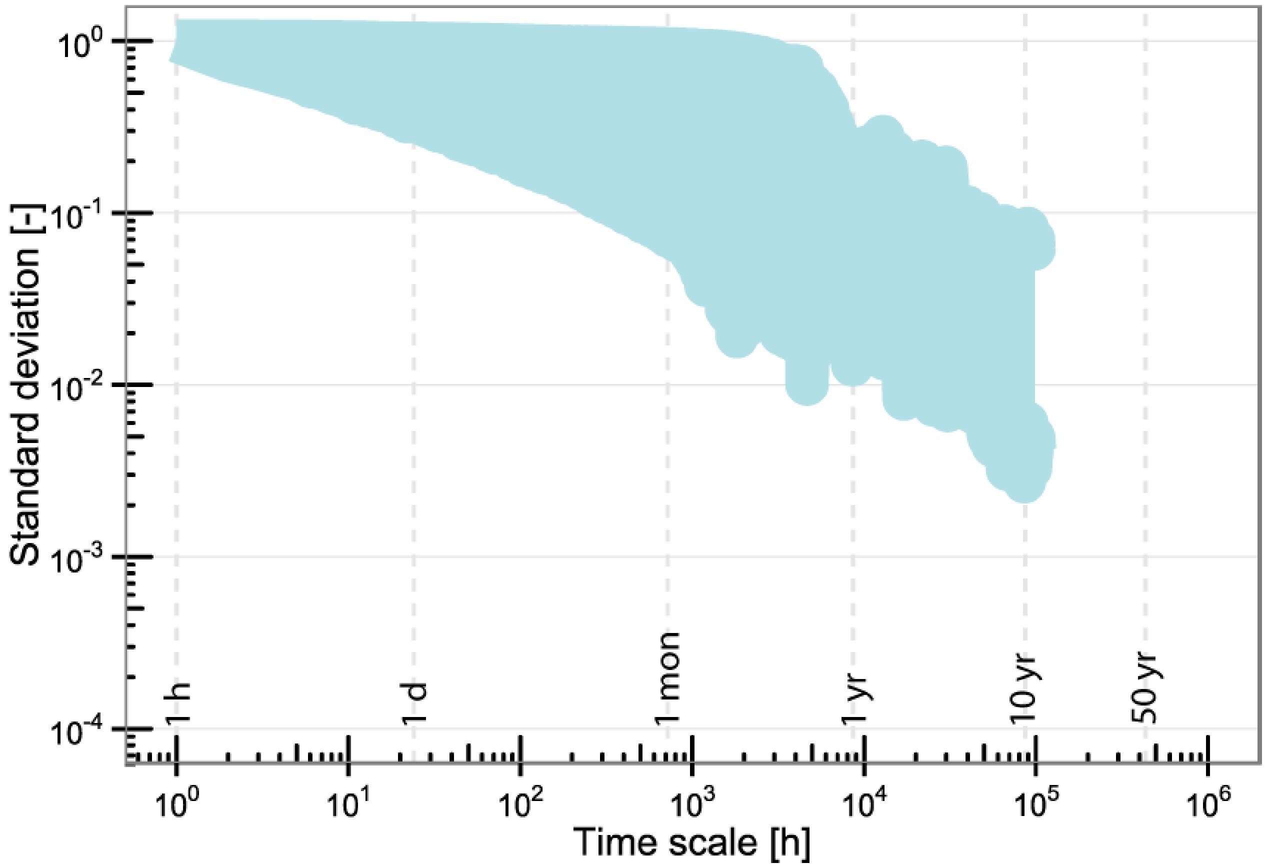
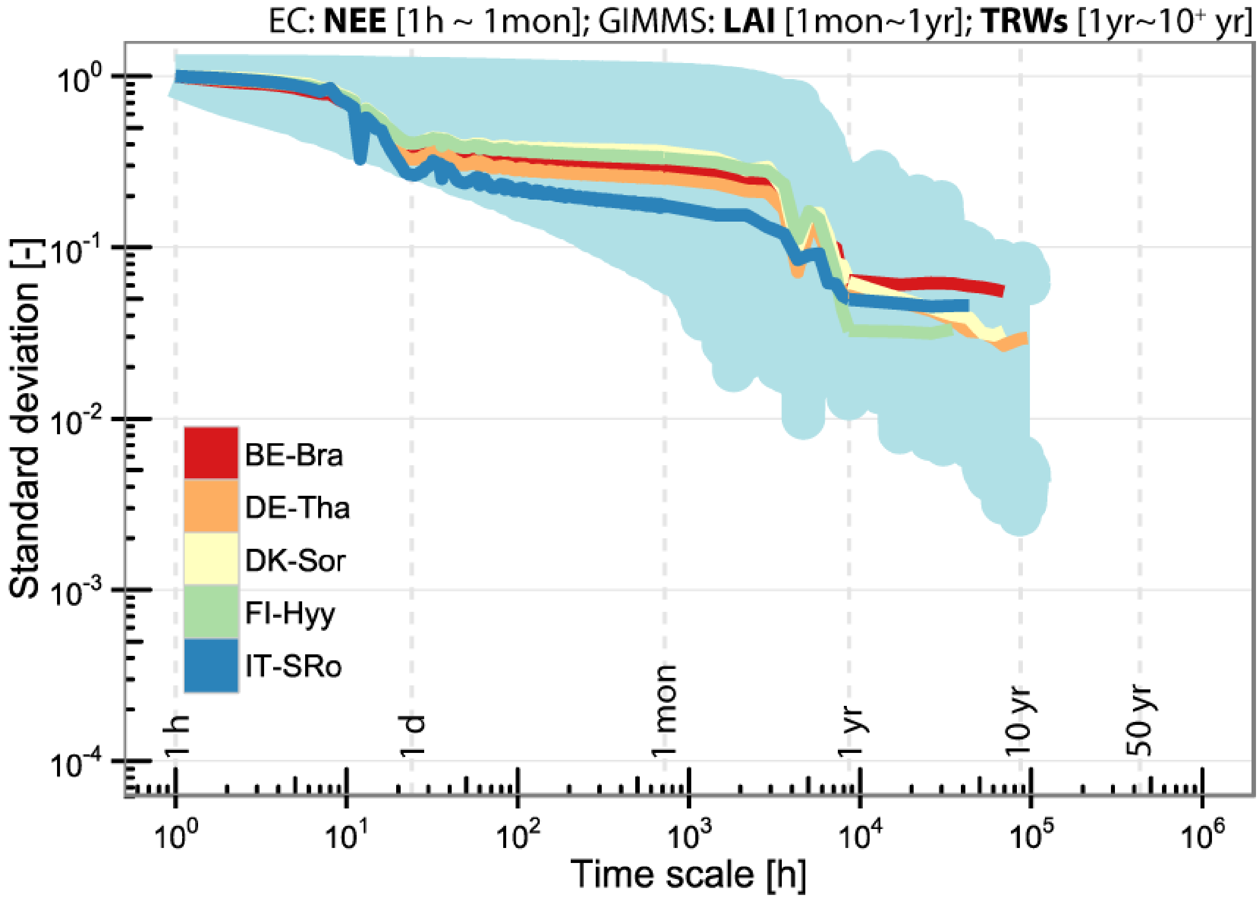
ERA Interim
CRU TS 1.2
CRU TS 3.23
Standard deviation [-]
Time scale [h]
1 h
1 d
1 mon
1 yr
10 yr
50 yr

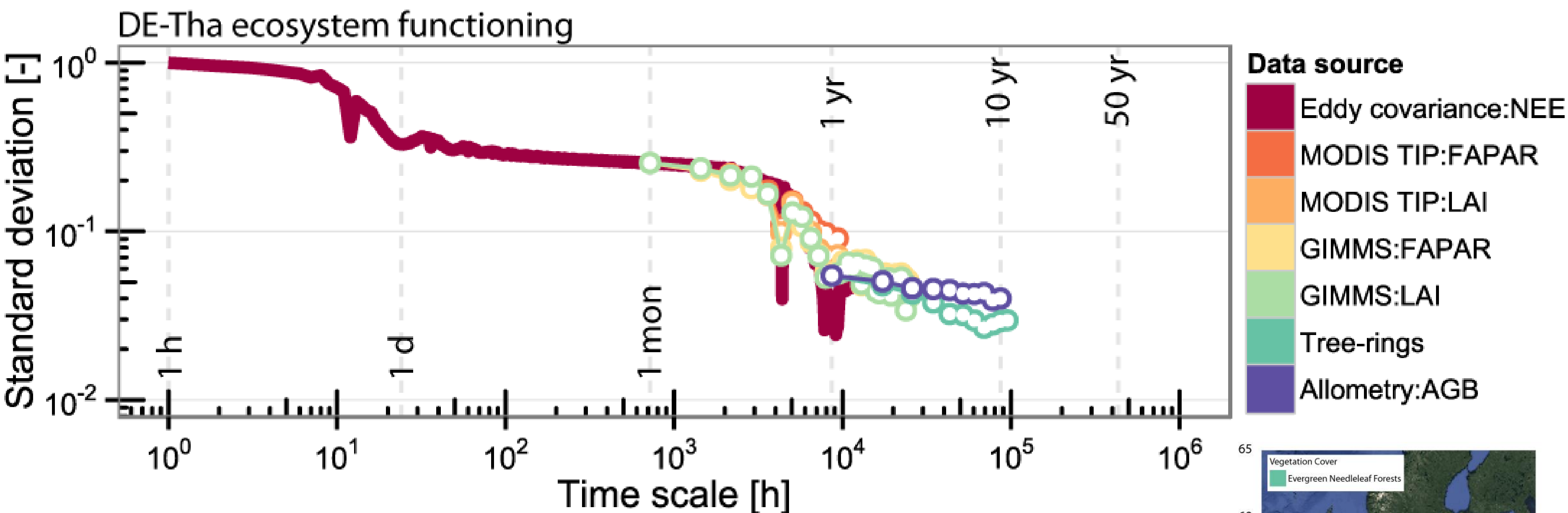

All sites
Standard deviation [-]
Time scale [h]
Temperature
Global radiation
Vapour pressure deficit
Precipitation
1 h
1 d
1 mon
1 yr
10 yr
50 yr

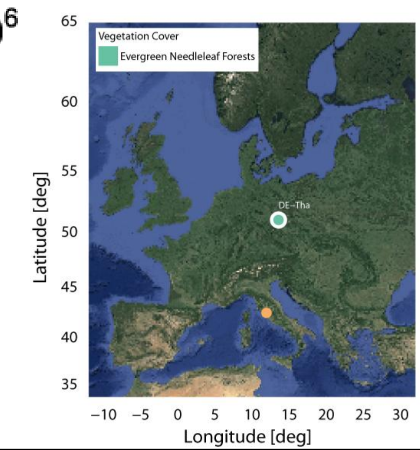

10^0
10^-1
10^-2
10^-3
10^-4
Standard deviation [-]
1 h
1 d
1 mon
1 yr
10 yr
50 yr
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Time scale [h]



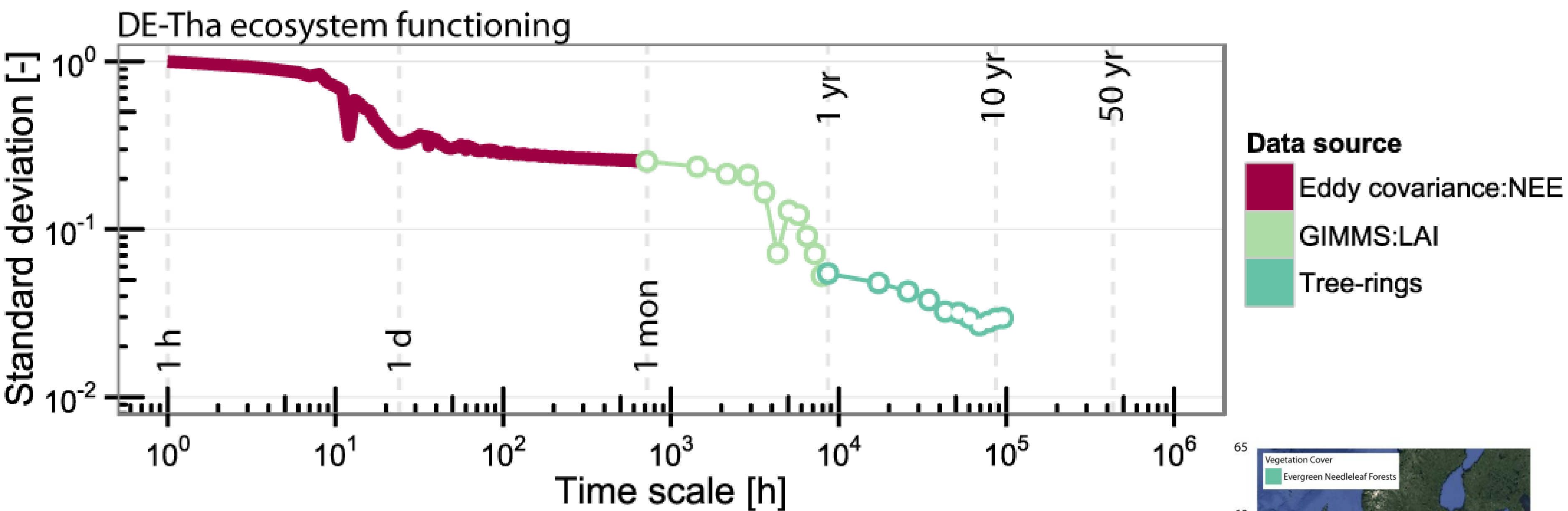
The **variability of ecosystem functioning** is **confined** within the range of **variability of the available resources** (water and energy) from **hourly** to **>decadal** time scales.

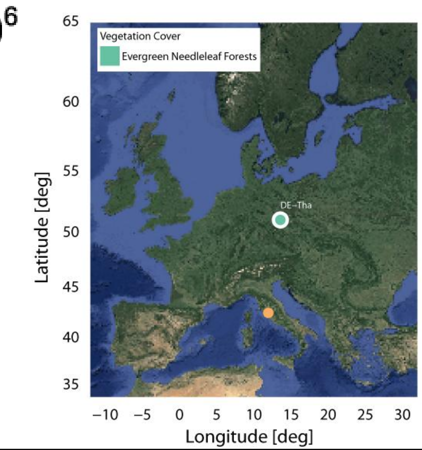
sub-daily | daily – seasonal | seasonal – inter-annual

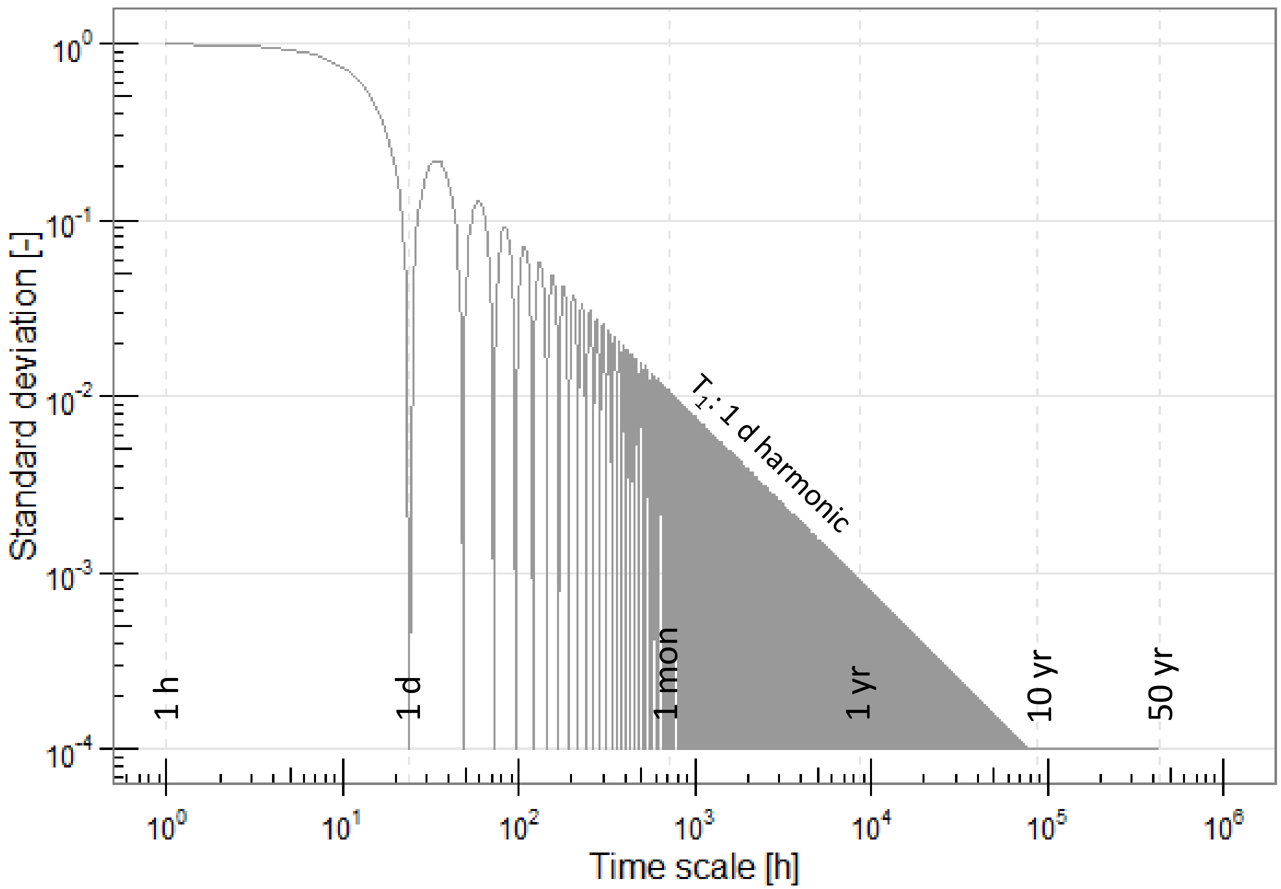




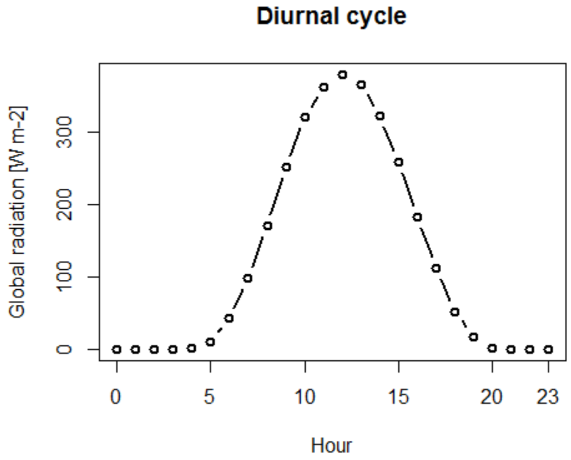
sub-daily | daily – seasonal | seasonal – inter-annual



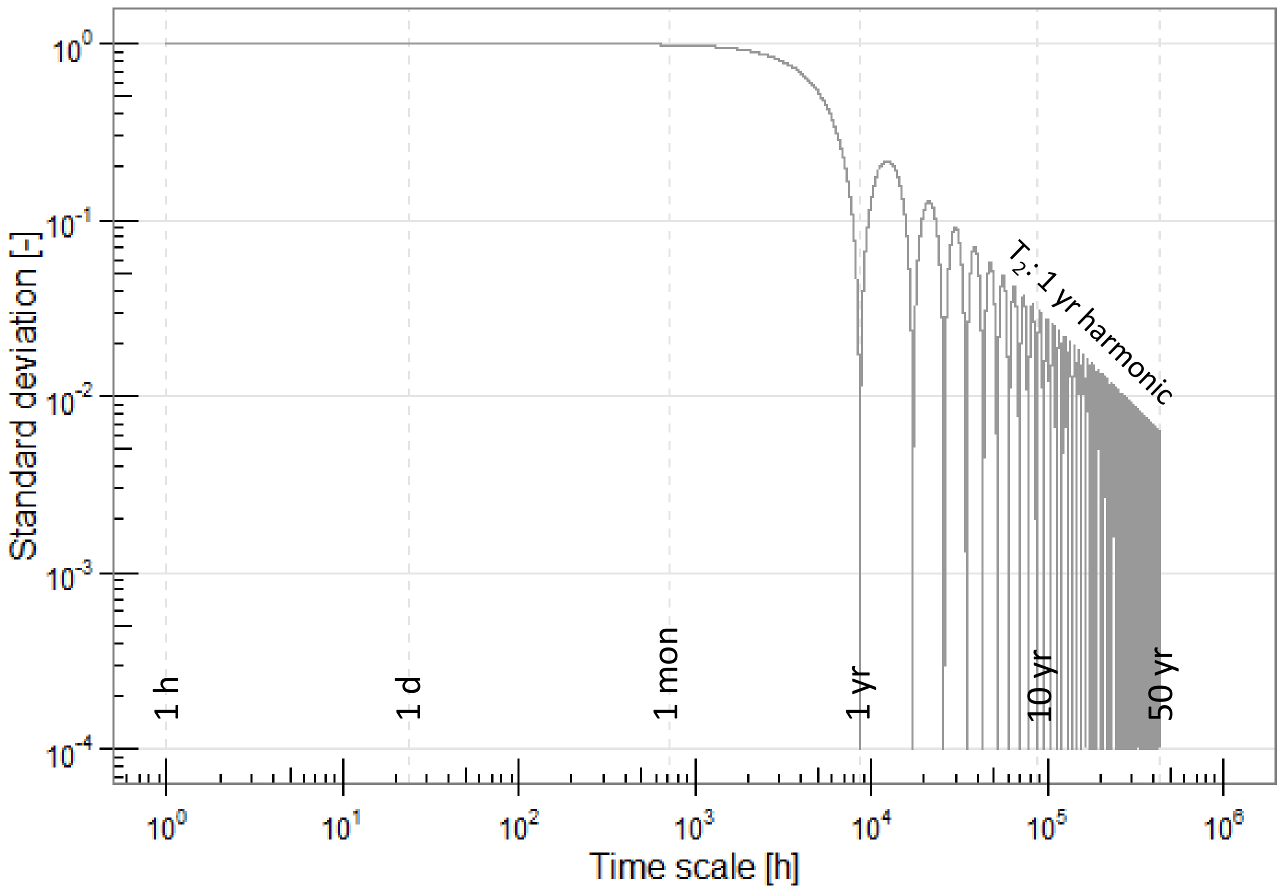




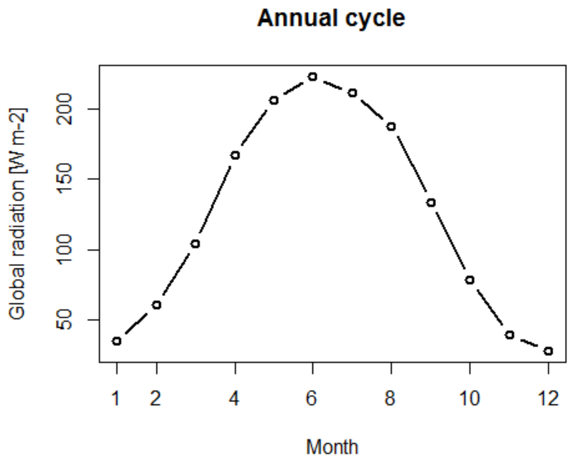
$$\sigma_{T_1}^{(k)} = \frac{T_1}{\pi k}\left|\sin\left(\frac{\pi k}{T_1}\right)\right|$$



Markonis, Y. & **Koutsoyiannis, D.** Climatic Variability Over Time Scales Spanning Nine Orders of Magnitude: Connecting Milankovitch Cycles with Hurst-Kolmogorov Dynamics. *Surv. Geophys.* (2012). doi:10.1007/s10712-012-9208-9



$$\sigma_{T_2}^{(k)} = \frac{T_2}{\pi k}\left|\sin\left(\frac{\pi k}{T_2}\right)\right|$$



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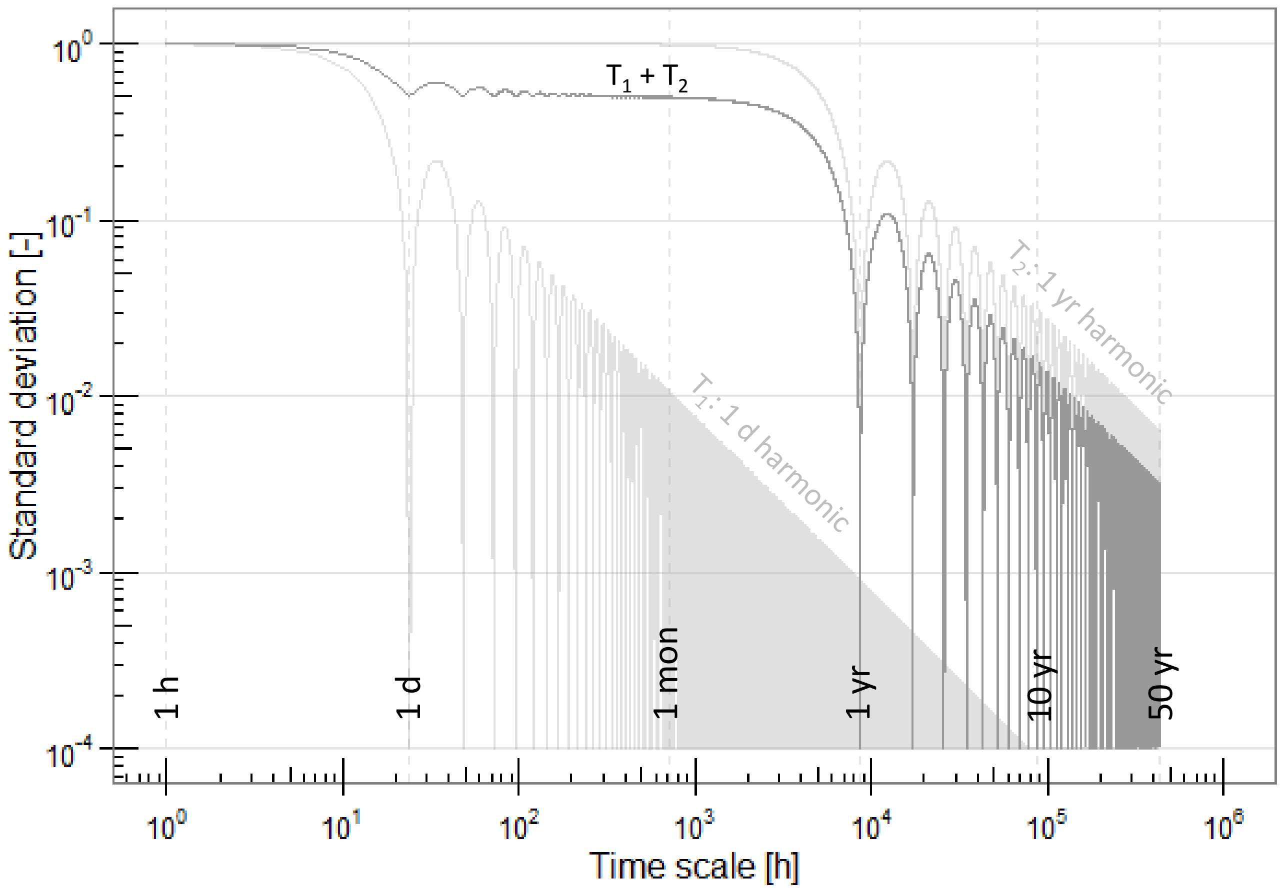
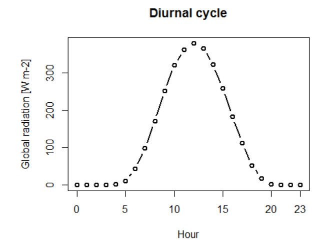
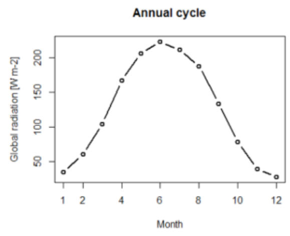


$$\sigma_{T_1+T_2}^{(k)} = 0.5\sigma_{T_1}^{(k)} + 0.5\sigma_{T_2}^{(k)} =$$
$$= 0.5\left(\frac{T_1}{\pi k}\left|\sin\left(\frac{\pi k}{T_1}\right)\right|\right) +$$
$$0.5\left(\frac{T_2}{\pi k}\left|\sin\left(\frac{\pi k}{T_2}\right)\right|\right)$$





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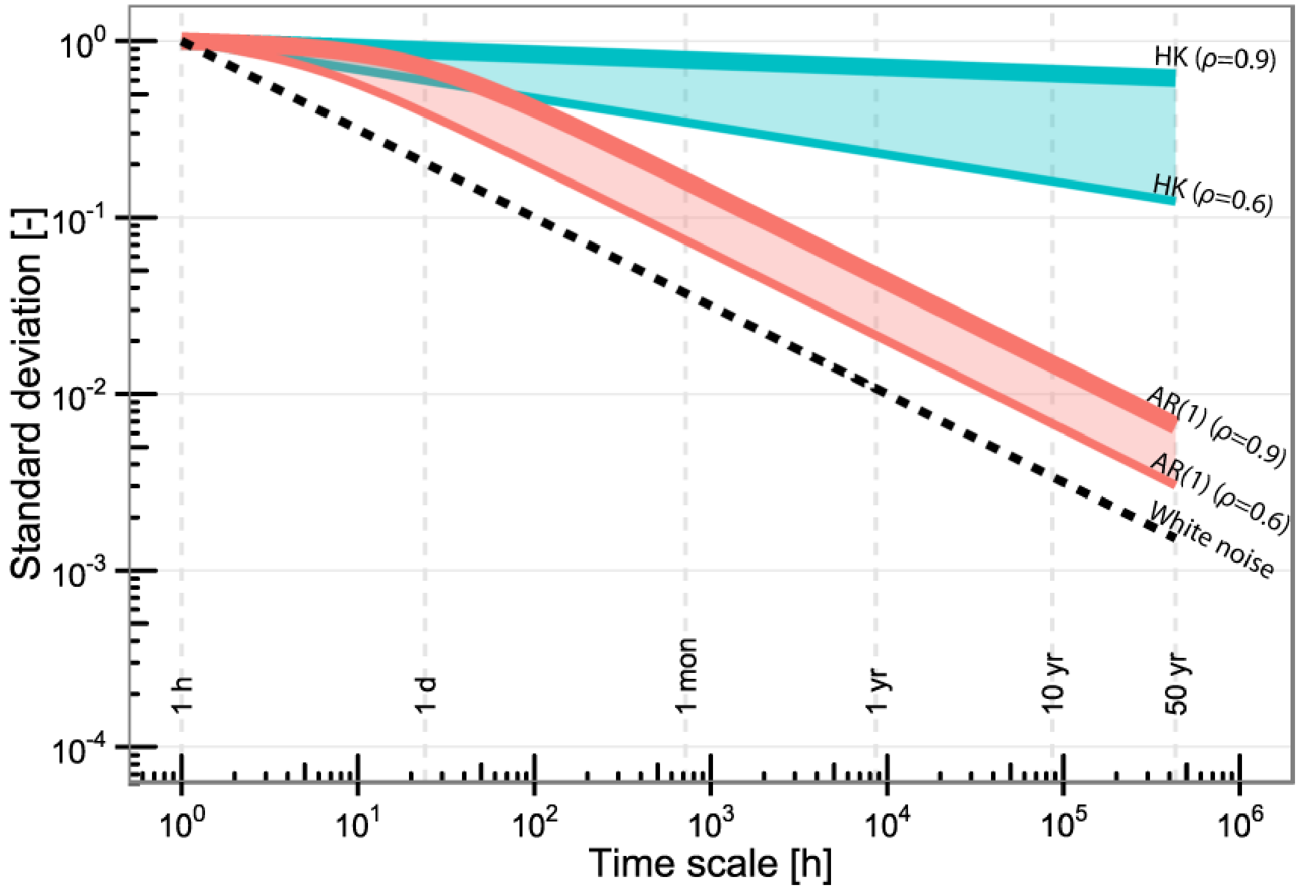


HK: $\sigma^{(k)} = k^{H-1}\sigma^{(1)} = k^{H-1}\sigma$

AR(1): $\sigma^{(k)} = \frac{\sigma}{k^{0.5}}\sqrt{\frac{(1-\rho^2)-2\rho\frac{(1-\rho^k)}{k}}{(1-\rho)^2}}$

WN: $\sigma^{(k)} = \frac{\sigma}{k^{0.5}}$

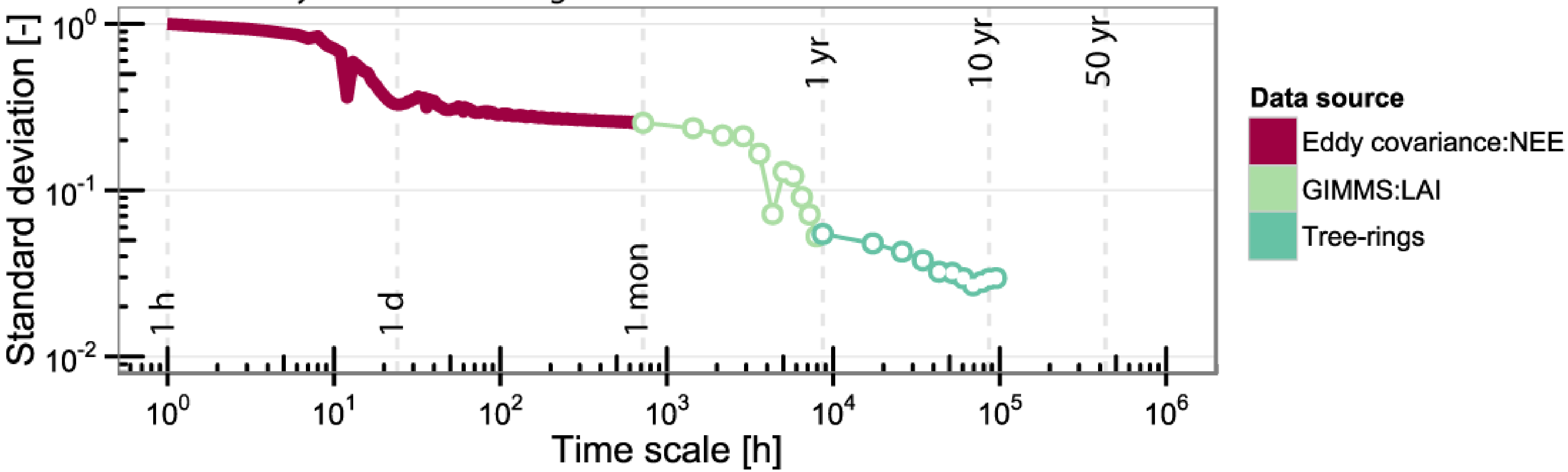
k : time scale
H : Hurst coefficient
ρ : lag-1 autocorrelation coefficient

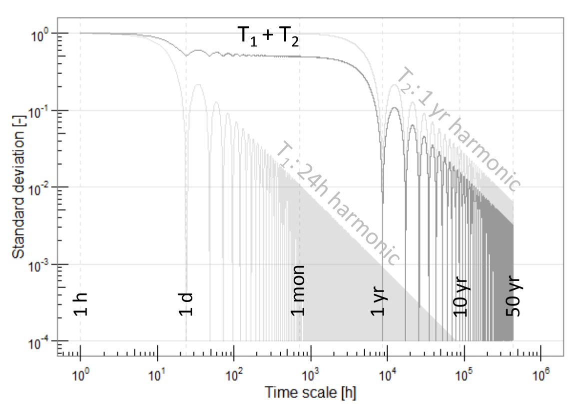
Koutsoyiannis, D. HESS Opinions 'A random walk on water'. *Hydrol. Earth Syst. Sci.* **14,** 585–601 (2010).

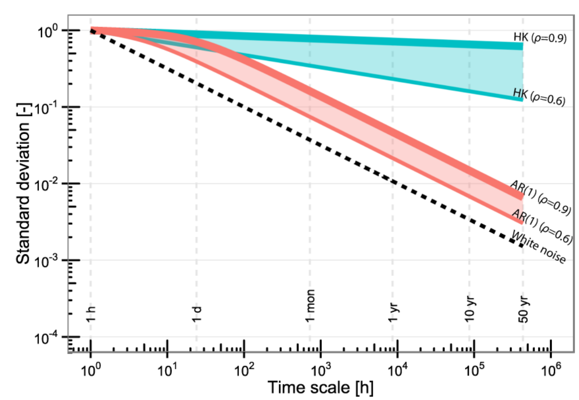
Dimitriadis, P. & **Koutsoyiannis, D.** Climacogram versus autocovariance and power spectrum in stochastic modelling for Markovian and Hurst–Kolmogorov processes. *Stoch. Environ. Res. Risk Assess.* (2015). doi:10.1007/s00477-015-1023-7

sub-daily | daily – seasonal | seasonal – inter-annual

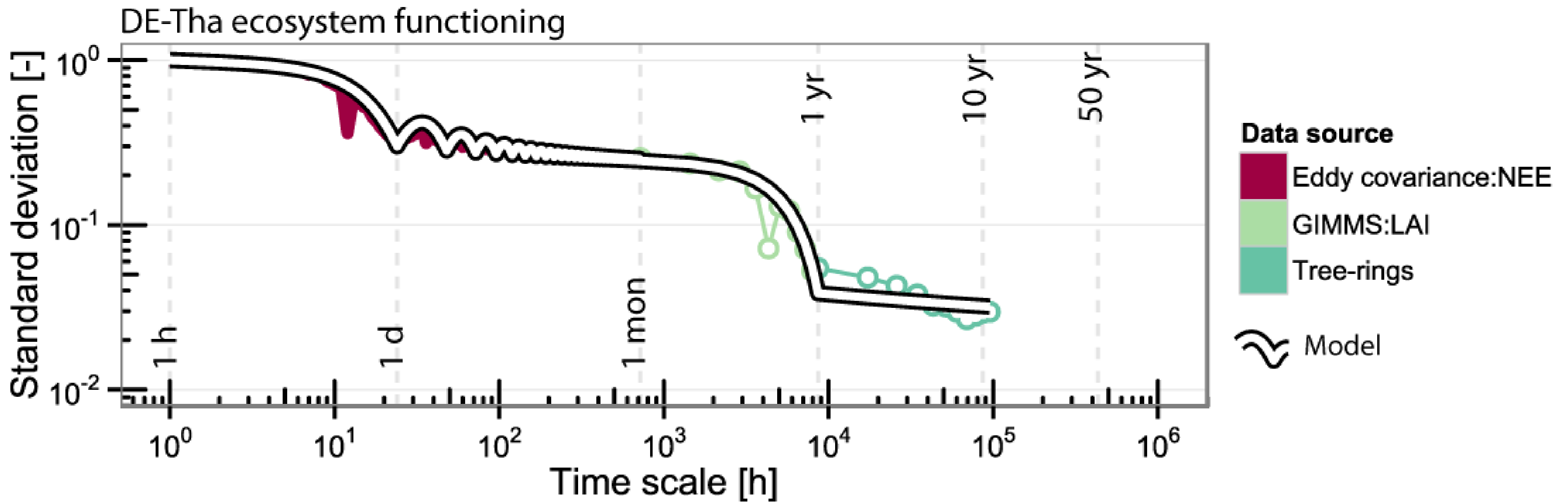
DE-Tha ecosystem functioning





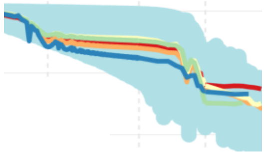


sub-daily | daily – seasonal | seasonal – inter-annual

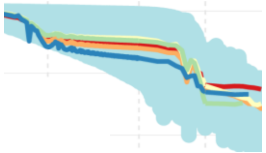


$$\sigma_{\mathrm{EcoFun}}^{(k)} = f\left(w_1, w_2, w_3, w_4, \rho, H, k\right) = w_1\sigma_{\mathrm{AR(1)}}^{(k)} + w_2\sigma_{\mathrm{HK}}^{(k)} + w_3\sigma_{T_1\text{:}1\mathrm{d}}^{(k)} + w_4\sigma_{T_2\text{:}1\mathrm{yr}}^{(k)} =$$

$$= w_1\left(\frac{\sigma}{k^{0.5}}\sqrt{\frac{\left(1-\rho^2\right)-2\rho\frac{\left(1-\rho^k\right)}{k}}{\left(1-\rho\right)^2}}\right) + w_2\left(k^{H-1}\sigma\right) + w_3\frac{T_1}{\pi k}\left|\sin\left(\frac{\pi k}{T_1}\right)\right| + w_4\frac{T_2}{\pi k}\left|\sin\left(\frac{\pi k}{T_2}\right)\right|$$



The **variability of ecosystem functioning** across time scales is **confined** within the range of variability of the **environmental drivers**.



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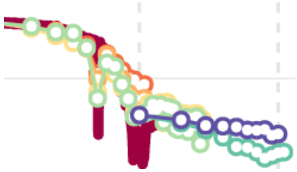
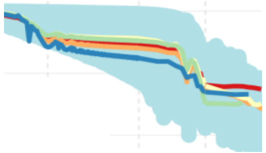


An **overview** of the **variability of ecosystem functioning** across time scales spanning **five orders of magnitude** is presented combining **multivariate datasets**.



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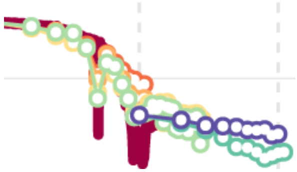

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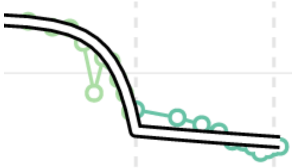
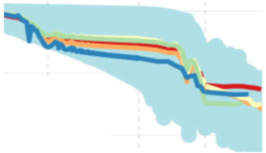


The **variability of ecosystem functioning** across **time scales** can be adequately represented with surprisingly **simple models**.



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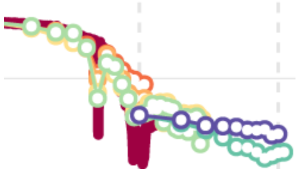

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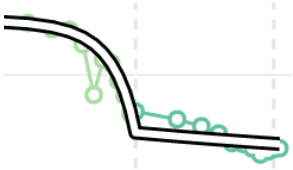

The **variability of ecosystem functioning** across **time scales** can be adequately represented with surprisingly **simple models**.

Implications:

- Long-term terrestrial **carbon source-sink** dynamics and the related CO_2 variability
- **Benchmarking** of process-based terrestrial ecosystem models

Thank you!

Acknowledgements

- EC site PIs
- CRU and ERA Intermin
- GIMMS FPAR3g *&* LAI3g (Ranga B. Myneni) and MODIS TIP (JRC)
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Christoforos Pappas, Miguel Mahecha, David Frank, Demetris Koutsoyiannis