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Long-term fluxes of carbonyl sulfide and their seasonality and interannual variability in a boreal forest

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Introduction

This Supplementary Information includes figures that provide additional information on environmental conditions as well as more details on COS flux (FCOS) variation and dependency on environmental variables, and the difference between the Simple Biosphere Model Version 4 (SiB4) FCOS simulations and the upscaled FCOS parameterization. Tables provide information on the weekly, monthly, and seasonal variations of FCOS and start of the growing season by three different methods.

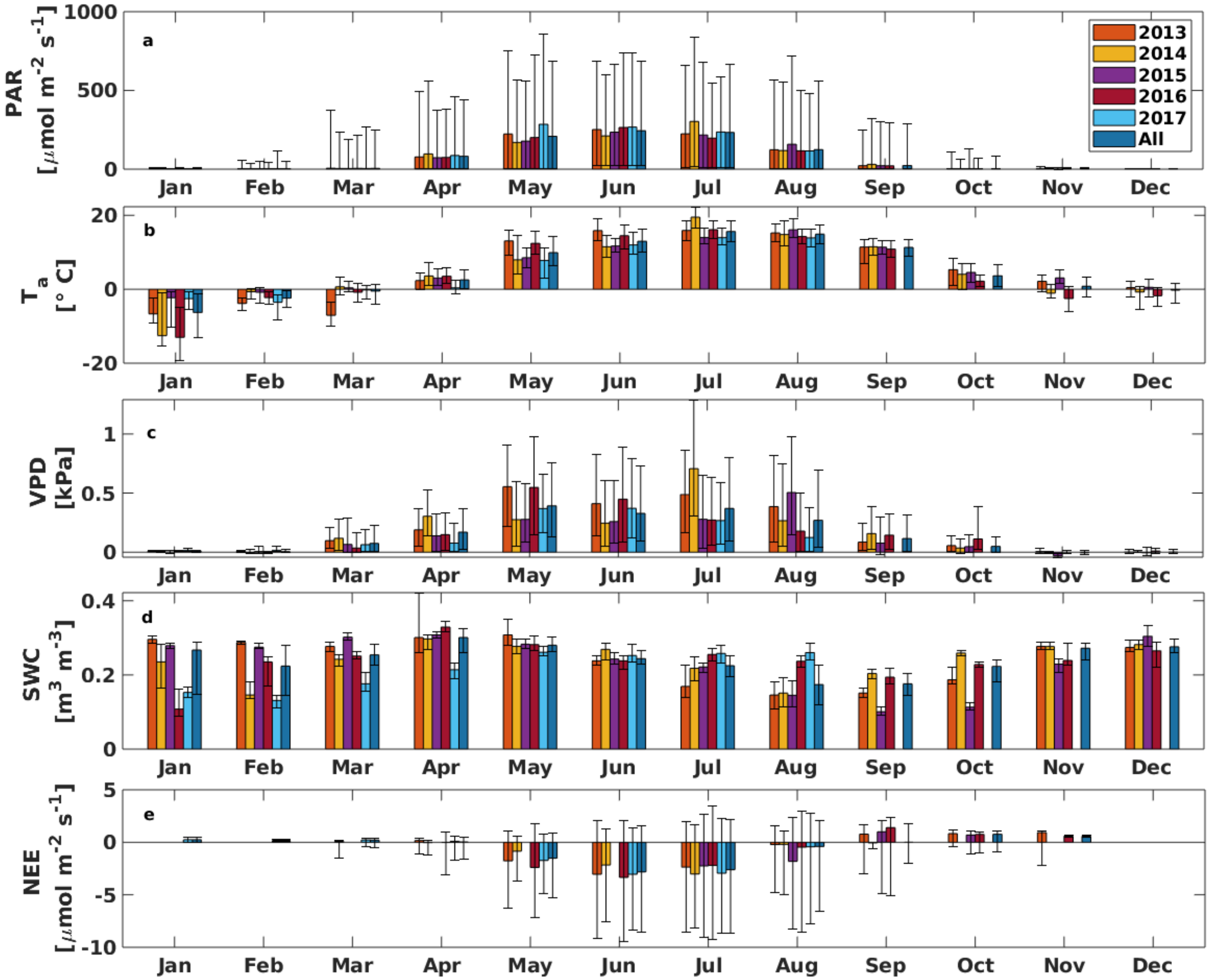

Figure S1. Monthly medians of photosynthetically active radiation (PAR) (a), air temperature (T_a) (b), vapor pressure deficit (VPD) (c), soil water content (SWC) (d), and net ecosystem exchange of CO_2 (NEE) (e) for all measurement years. Error bars show the 25th and 75th percentiles. The monthly median of all years is presented in dark blue.

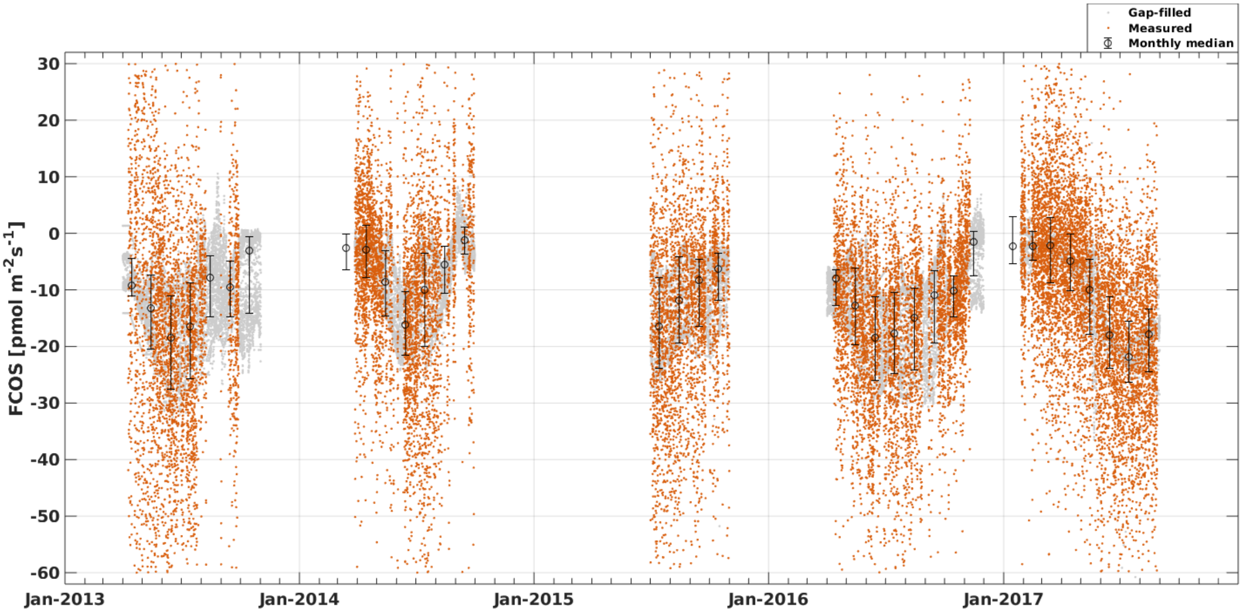

Figure S2. Measured (orange) and gap-filled (gray) 30 min carbonyl sulfide flux (FCOS) in 2013–2017. Black circles represent the monthly median FCOS and whiskers show the 25th and 75th percentiles.

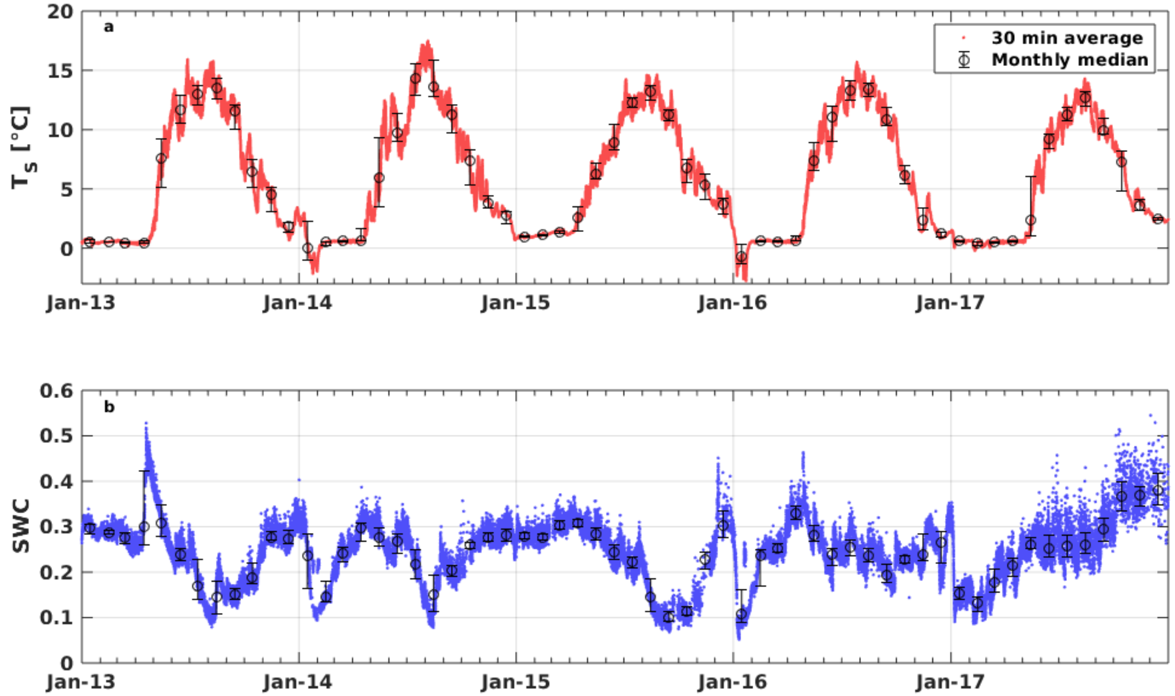

Figure S3. Soil temperature (*T_s*) (a) and soil water content (SWC) (b) in Hyytiälä. Colored dots represent the 30 min average values, while black circles and whiskers are the monthly medians and their 25th and 75th percentiles, respectively.

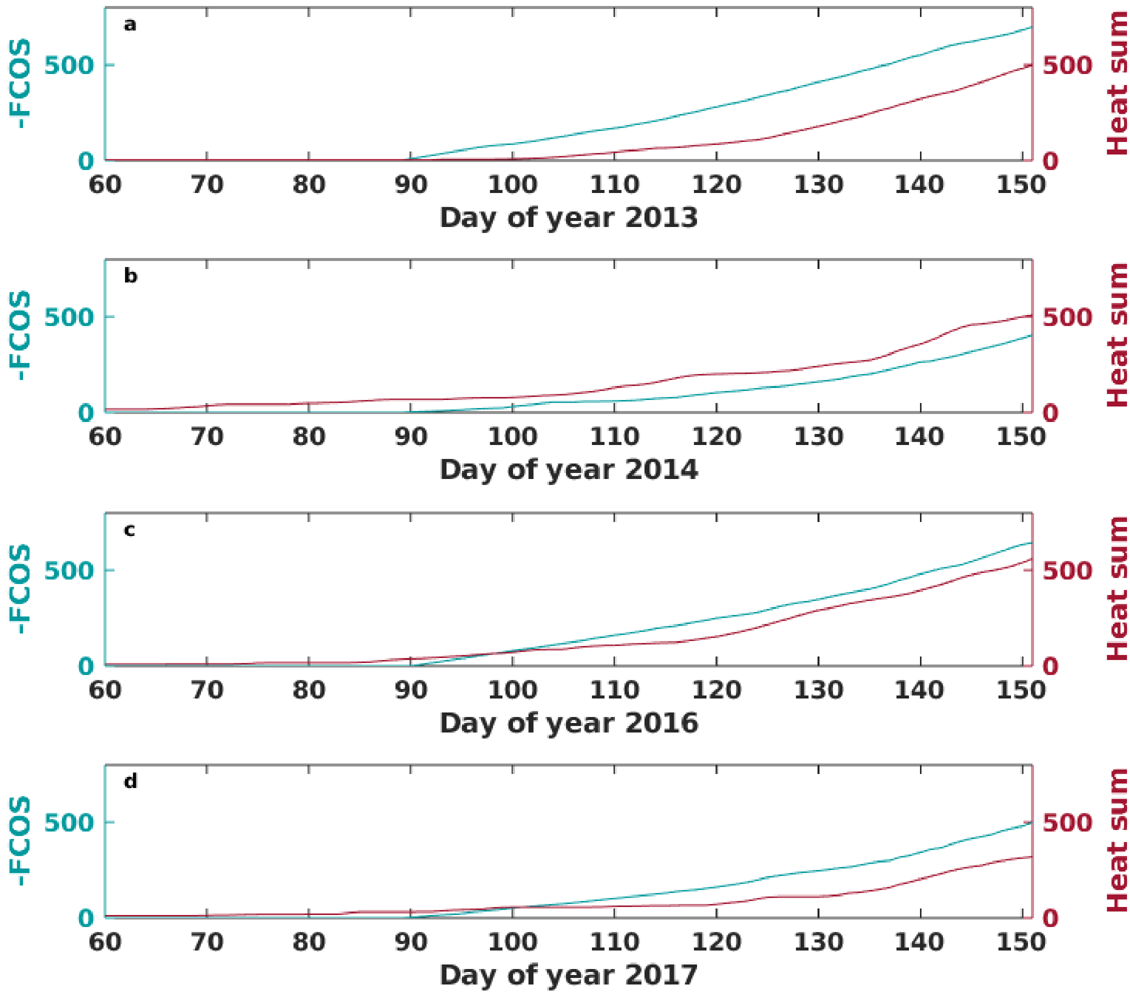

Figure S4. Cumulative carbonyl sulfide flux (FCOS) (left, in pmol m^{-2} s^{-1}) and heat sum (right, in °C) since the beginning of the year in different years. Note that the start date of FCOS measurements differs between years. FCOS measurements started on day 91 in 2013, day 87 in 2014, day 92 in 2016, and day 27 in 2017.

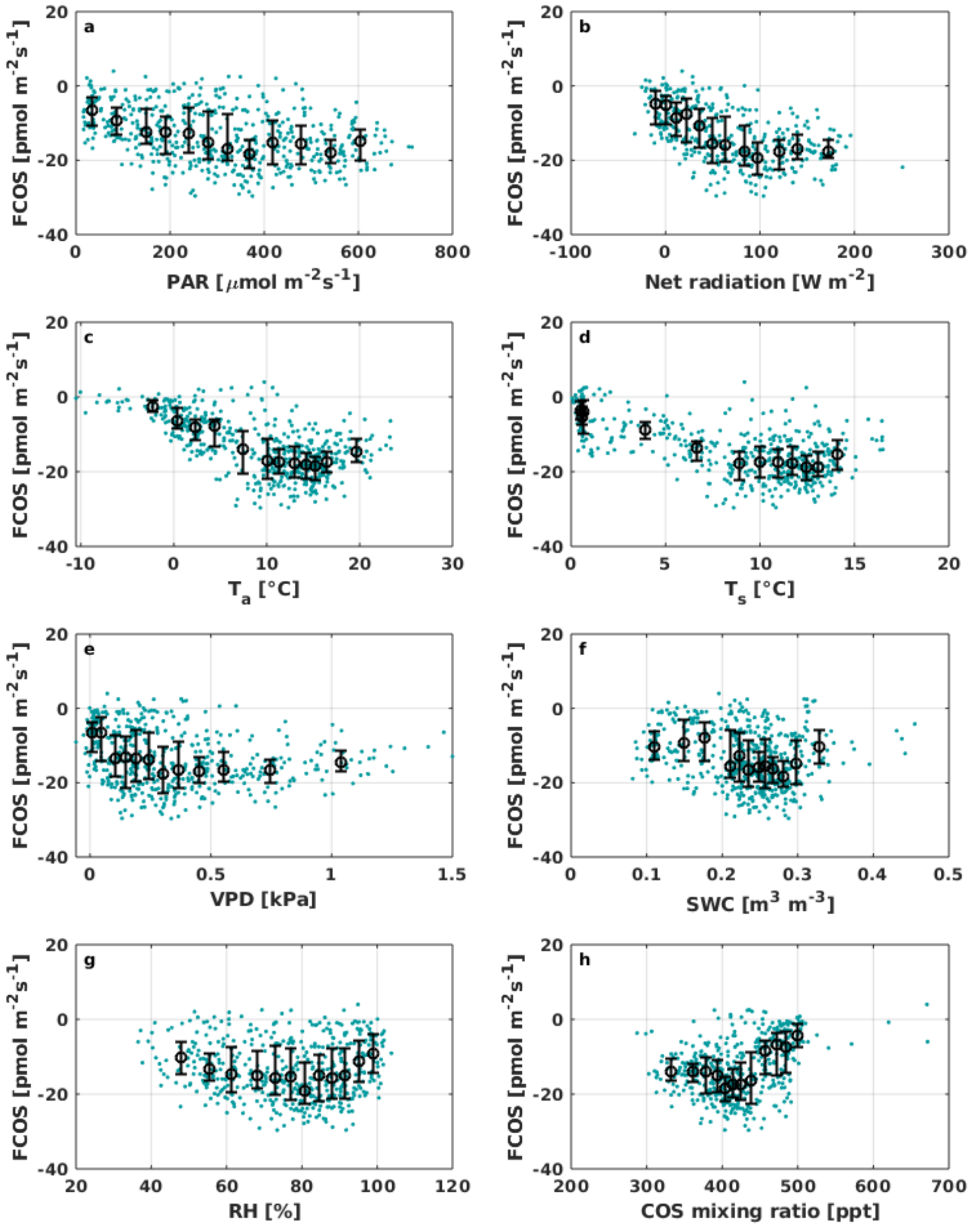

Figure S5. Daily median carbonyl sulfide flux (FCOS, measured data only) against daily median of environmental variables: photosynthetically active radiation (PAR), net radiation, air temperature (T_a), soil temperature (T_s), vapor pressure deficit (VPD), soil water content (SWC), relative humidity (RH), and carbonyl sulfide (COS) mixing ratio. Black circles represent medians of data divided into 12 equal sized bins and black whiskers are the 25th and 75th percentiles.

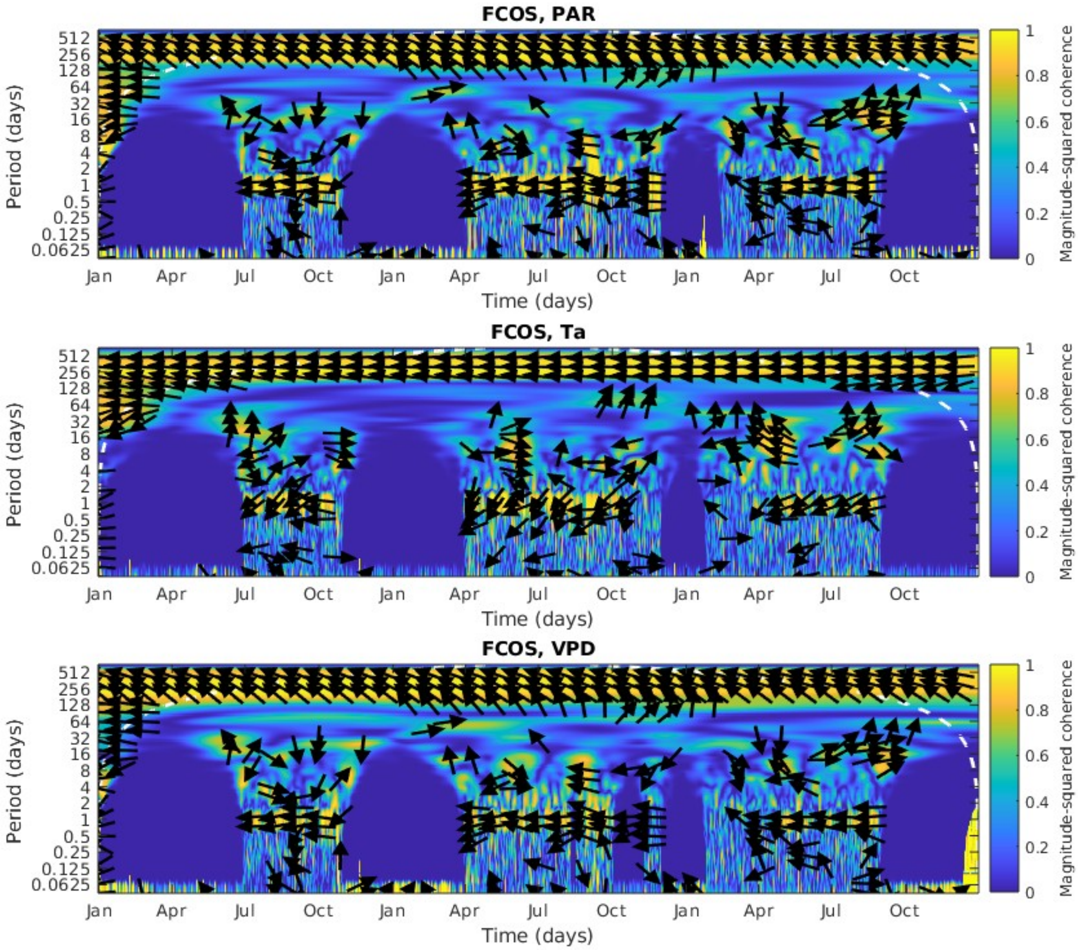

Figure S6. Magnitude-squared wavelet coherence of carbonyl sulfide flux (FCOS) with photosynthetically active radiation (PAR), air temperature (T_a), and vapor pressure deficit (VPD) for the gap-filled data (years 2015–2017). The color shows the coherence between the two variables at each timescale from 30 min to 512 days (y-axis). Arrows show significant correlation and the phase difference between the two time series. Arrows pointing to the right mean that the two time series are in phase, arrows pointing to the left mean antiphase, and arrows pointing upward mean a quarter cycle difference so that the first time series (FCOS) is leading the other.

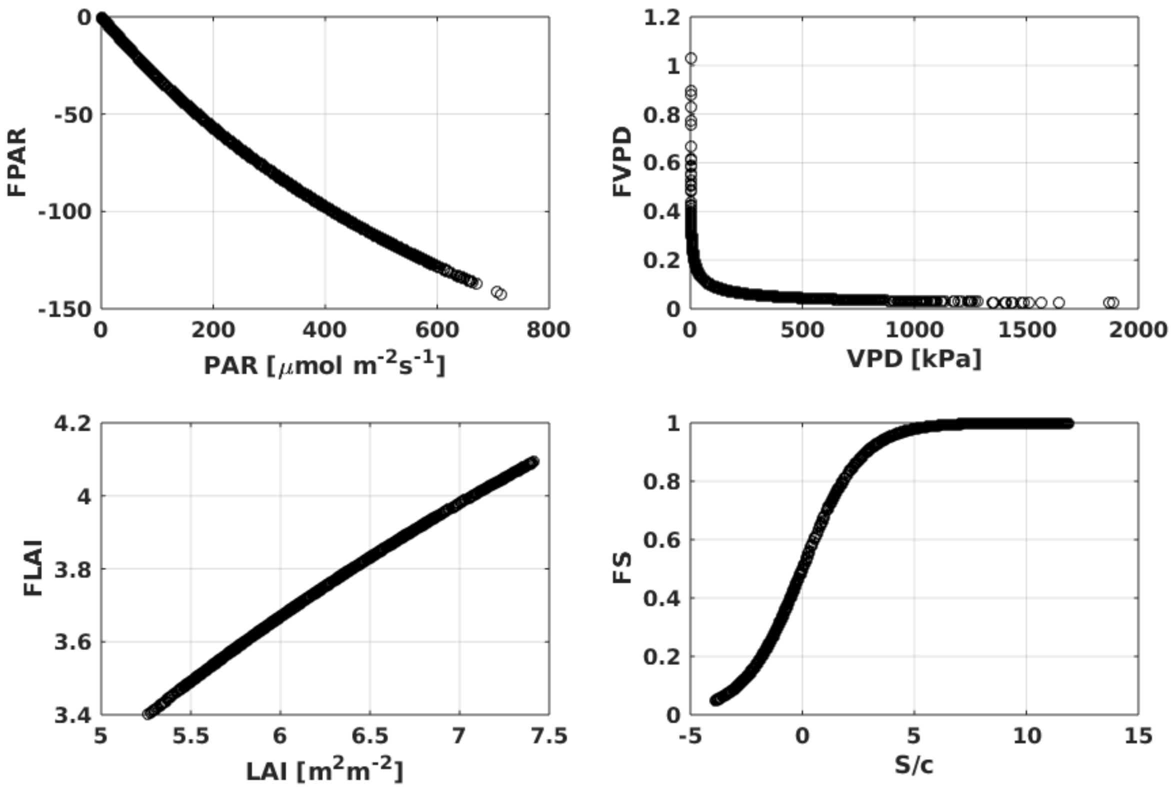

Figure S7. Parameterization functions (FPAR, FVPD, FLAI and FS) against environmental variables (PAR, VPD, LAI and S/c, respectively) that they depend on.

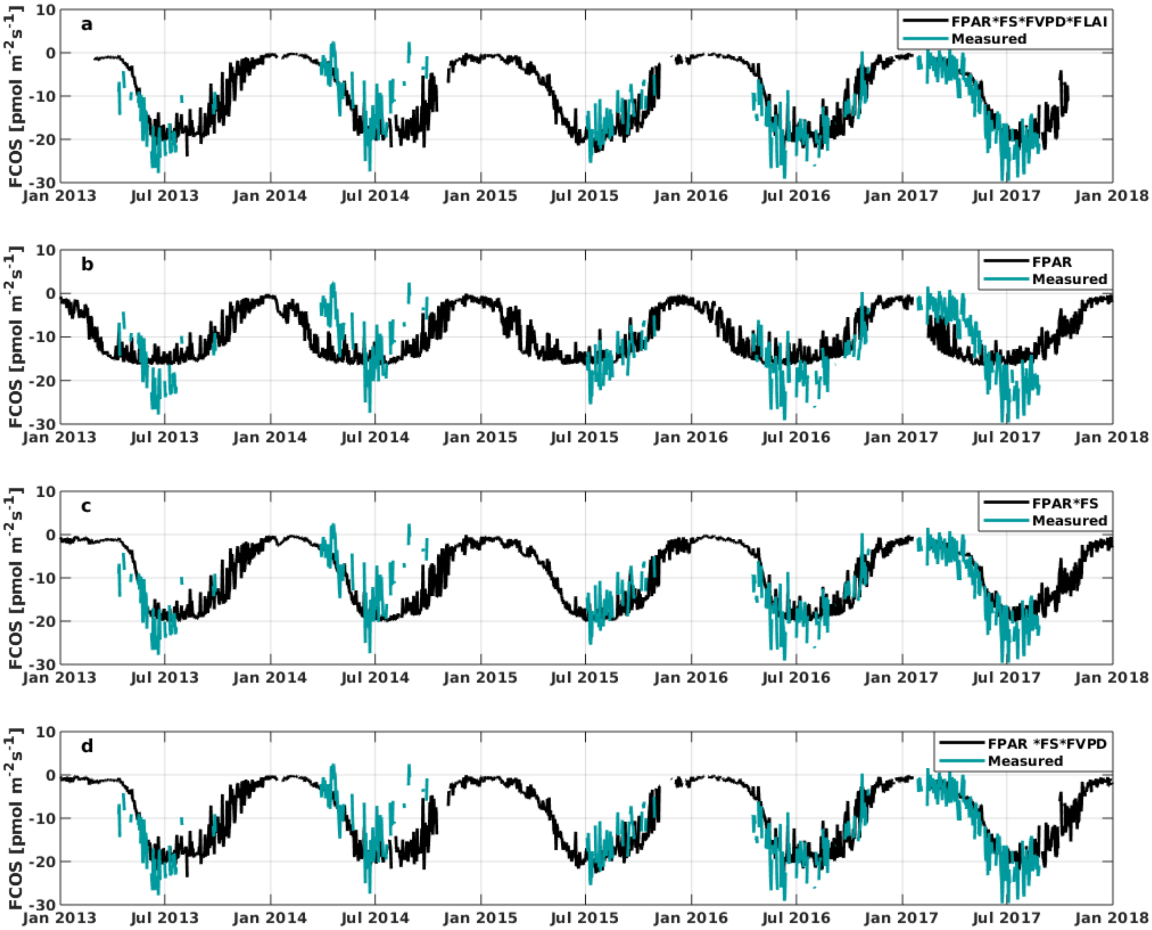

Figure S8. Time series of measured (blue) and parameterized daily carbonyl sulfide flux (FCOS) (black). Subplots a–d show the different combinations of parameter functions, while (a) was chosen as the best option. FLAI = foliage and canopy light penetration, FPAR = stomatal response to PAR, FS = phenology of biochemical reactions, FVPD = stomatal regulation.

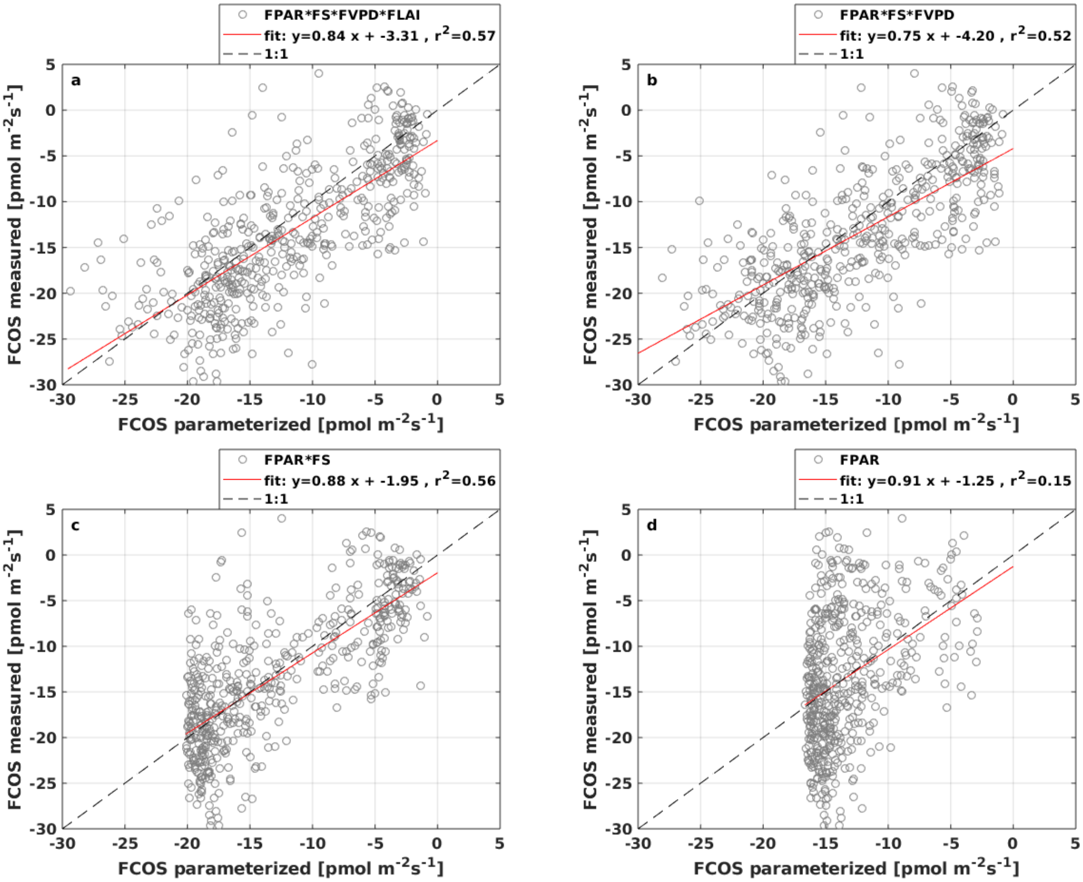

Figure S9. Scatter plots of the daily measured carbonyl sulfide flux (FCOS) against different combinations of parameter functions. Gray dots represent daily values, the red line the least-squares linear fit, and the dashed black line is the 1:1 line. FLAI = foliage and canopy light penetration, FPAR = stomatal response to PAR, FS = phenology of biochemical reactions, FVPD = stomatal regulation.

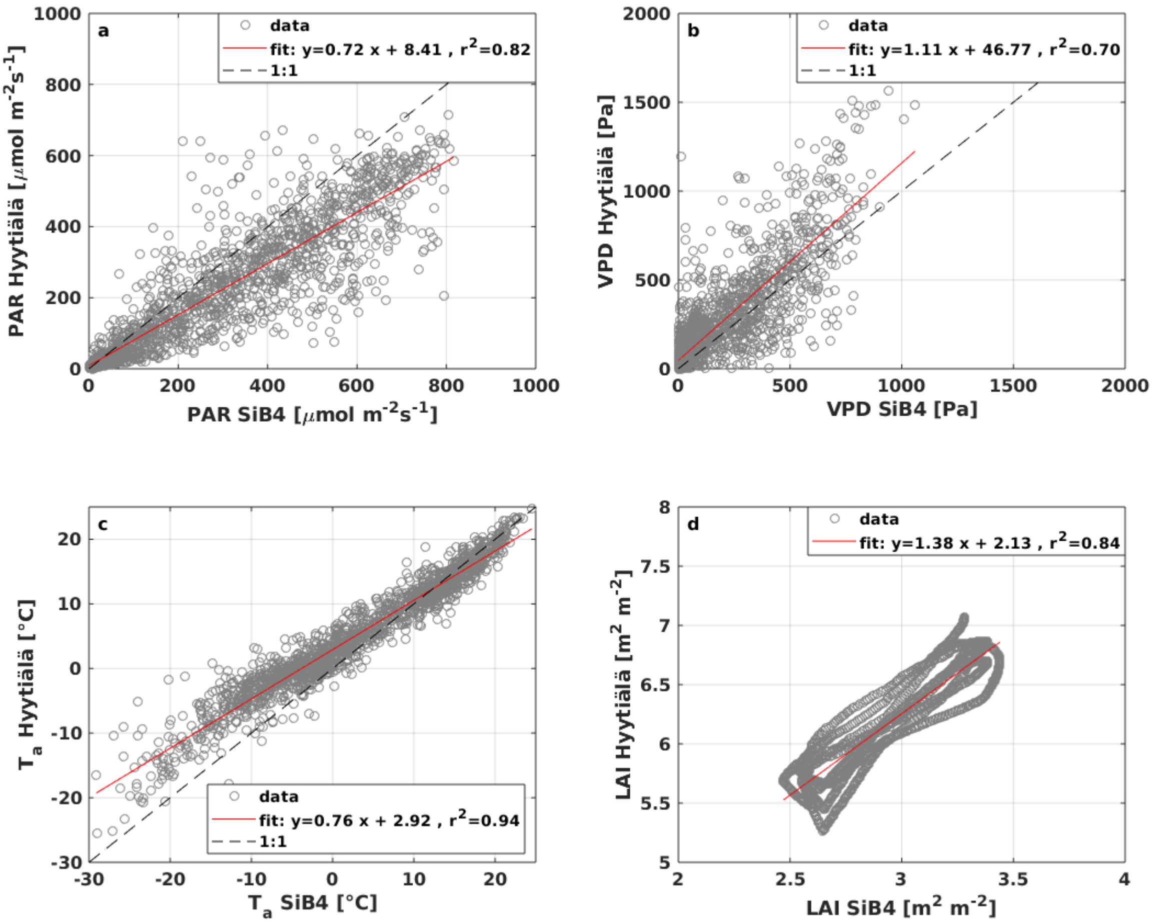

Figure S10. In-situ meteodata from Hyytiälä against SiB4 aggregated meteodata for Hyytiälä grid. The linear relations are used to scale SiB4 meteodata in the FCOS parameterization.

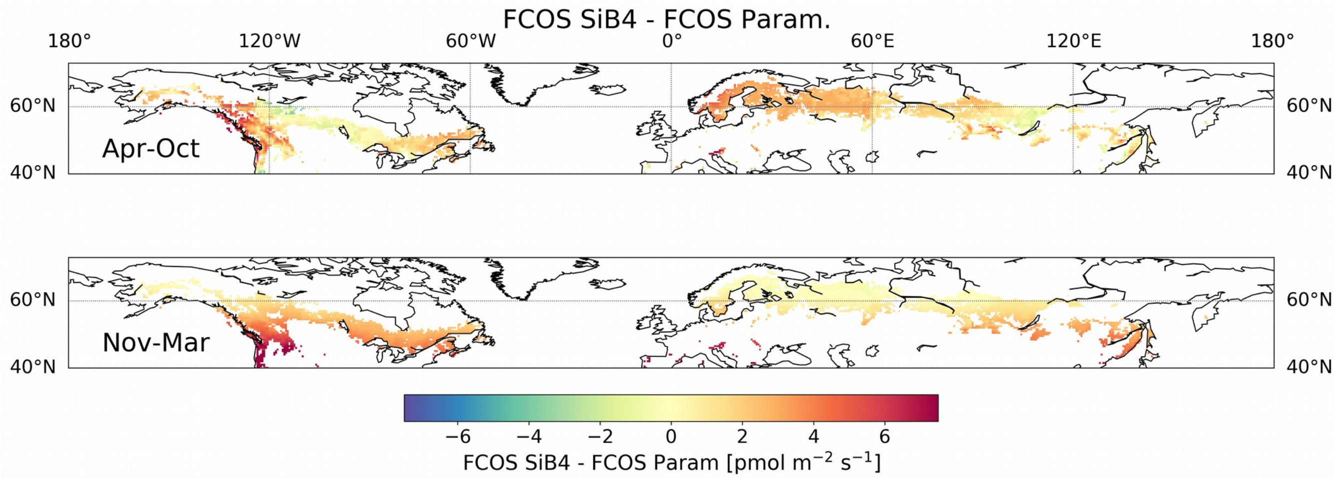

Figure S11. Difference between daily average carbonyl sulfide flux (FCOS) based on the Simple Biosphere Model Version 4 (SiB4) simulations and the upscaled parameterization (Param) for the period April–October (top) and November–March (bottom).

	S/c > 1.81	T_5 > 3.3 °C	FCOS < 0.3*$FCOS_{MIN}$
2013	105	104	105
2014	106	103	118
2015	98	97	NA
2016	88	89	<91
2017	120	120	118

Table S1. Commencement day of the growing season by different methods. Variable S/c describes the stage of physiological spring development (Pelkonen & Hari, 1980) and T_5 is the moving average of air temperature using a 5-day window. The carbonyl sulfide flux (FCOS) criterion was filled when the uptake threshold (< 30 % of $FCOS_{MIN}$) was exceeded for 5 consecutive days without falling back for more than 5 consecutive days.

	2013	2014	2015	2016	2017
January	NA	NA	NA	NA	-2.24 (0.10)
February	NA	NA	NA	NA	−2.35 (0.51)
March	NA	-2.52 (0.09)	NA	NA	−2.17 (0.82)
April	−9.17 (0.26)	−2.95 (0.81)	NA	−7.95 (0.38)	−4.98 (0.76)
May	−13.2 (0.58)	−8.61 (0.39)	NA	−12.8 (0.54)	−9.98 (0.62)
June	−18.5 (0.60)	−16.1 (0.51)	NA	−18.4 (0.54)	−18.1 (0.70)
July	−16.4 (0.62)	−9.96 (0.63)	−16.5 (0.59)	−17.6 (0.52)	−21.9 (0.63)
August	-7.84 (0.12)	−5.58 (0.32)	−11.8 (0.53)	−14.9 (0.49)	−17.8 (0.64)
September	−9.50 (0.29)	-1.21 (0.20)	−8.31 (0.51)	−10.9 (0.35)	NA
October	−3.18 (0.0)	NA	−6.25 (0.40)	−10.2 (0.61)	NA
November	NA	NA	NA	-1.48 (0.16)	NA
December	NA	NA	NA	NA	NA

Table S2. Monthly median carbonyl sulfide flux (pmol m^{-2} s^{-1}) in different years. Fraction of monthly measured 30 min fluxes (non-gapfilled) are indicated in the brackets.

	2013	2014	2015	2016	2017
$FCOS_{MAX}$	−23.2	−19.2	−19.8	−22.3	−23.9
Date	18.6	19.6	11.7	9.6	23.7
Week	25	25	28	23	29

Table S3. Maximum weekly median carbonyl sulfide flux (FCOS) (pmol m^{-2} s^{-1}) and its occurrence date and week.