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DATA PAPER

Meteorological data series from Swiss long-term forest ecosystem research plots since 1997

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Key message This paper describes meteorological measurements collected since 1997 at 16 ICP Forests Level II sites across the complex topography of Switzerland, both under the canopy and in the open-field nearby. The data offer detailed comparisons of deciduous, mixed, and coniferous forest microclimatic conditions with standard meteorological conditions in the open-field. Contrary to the open-field stations, those under the canopy do not fully correspond to the WMO criteria. Dataset access at https://doi.pangaea.de/10.1594/PANGAEA.868390. Associated metadata are available at https://metadata-afs.nancy.inra.fr/geonetwork/srv/fre/catalog.search#/metadata/12bbda8e-4823-4c34-8061-35118f24e8f8

Contribution of the co-authors Martine Rebetez wrote the original and the reviewed draft. Georg von Arx, Arthur Gessler, Elisabeth Graf Pannatier, John L. Innes, Peter Jakob, Markéta Jetel, Marlen Kube, Magdalena Nötzli, Marcus Schaub, Maria Schmitt, Flurin Sutter, Anne Thimonier, Peter Waldner, and Matthias Haeni contributed to parts of the drafts and verified the whole manuscript. Matthias Haeni, Martine Rebetez, and Arthur Gessler processed and published the data to data repository. Markéta Jetel, Marlen Kube, Magdalena Nötzli, and Matthias Haeni curated the data. Peter Jakob and Matthias Haeni organized the respectively original and present databases. Flurin Sutter prepared Fig. 1. Peter Waldner prepared the dataset template. John L. Innes and Martine Rebetez conceived the original measurement methodology. John L. Innes, Marcus Schaub, Peter Waldner, and Arthur Gessler coordinated the LWF project.

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1 Background

The specific impacts of climate change need to be analyzed in all biomes and ecosystems. In forests, the climate is strongly modulated by the forest ecosystem itself (Morecroft et al. 1998). The characteristics of the microclimate inside the forest and how it is changing relative to changes outside the forest need to be better understood to improve the quality and reliability of models for forest growth and biogeochemistry and to formulate management recommendations. High-quality meteorological data below canopy are needed for long-term forest ecosystem research, particularly in the light of global change, as climate values under the canopy may differ considerably from the standard meteorological measurements recorded outside forests. The dataset described here originates from various forest stands and allows a comparison between standard meteorological data and forest conditions under the canopy. Contrary to the open-field stations, those under the canopy do not fully correspond to the WMO criteria.

2 Methods

Meteorological measurements have been carried out throughout Switzerland since 1997 at 16 forest observation sites of the Long-term Forest Ecosystem Research Programme (LWF), being part of the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) and the European Long-Term Ecosystem Research Network (LTER-Europe).

3 Data access and metadata description

The dataset, comprising air temperature (TTT [°C]), relative humidity (RH [%]), precipitation (precip [mm/h]), photosynthetically active radiation expressed in units of photosynthetic photon flux density (PAR [μmol m^{-2} s^{-1}]), and wind speed (ff [m/s]), can be accessed through the Pangaea archiving system at the following address: https://doi.pangaea.de/10.1594/PANGAEA.868390 (Haeni et al. 2016, supplement to the present paper). Associated metadata are available at https://metadata-afs.nancy.inra.fr/geonetwork/srv/fre/catalog.search#/metadata/12bbda8e-4823-4c34-8061-35118f24e8f8

Meteorological measurements have been carried out throughout Switzerland since 1997 at 16 forest sites within the Long-term Forest Ecosystem Research Programme (LWF: https://www.wsl.ch/en/forest/forest-development-and-monitoring/long-term-forest-ecosystem-research-lwf.html). At 14 of these sites, paired meteorological stations have recorded climate variables below canopy and in an open-field less than 2 km away (see Schneiter et al. 2004). The measurement sites differ in altitude, topography, exposition, and forest type. At the remaining two sites, measurements were made below canopy only.

The meteorological stations were installed and tested in 1996 and 1997 (Rebetez and Logeay 2000). The measurements have been organized with a long-term perspective, and are expected to last for at least 50 years. The data have been continuously recorded, calibrated, and checked for quality since 1997.

The dataset contains the following parameters, measured at high (10 min or hourly) temporal resolution (Table 1): air temperature, relative humidity, global radiation, UV-B radiation, photosynthetically active radiation (PAR), precipitation, and wind speed and direction. Under the canopy, the measurements were restricted to air temperature and relative humidity, PAR, precipitation, and wind speed (see Table 1 for sensors' technical details). The time standard is UTC.

The electric power required to operate the meteorological stations is provided by photovoltaic solar panels. All data are presently stored on CR10X data loggers (Campbell Scientific Ltd., Loughborough, UK) and transmitted daily via CSD-GSM data connection to the Swiss Federal Research Institute WSL where automated data quality checks are carried out taking the specific climate characteristics into account. The details of this process and the related concepts and methods are described in Jakob et al. (2007). All data are stored in an Oracle database at WSL.

The main characteristics of the observation sites are described in Table 2, and their locations are shown in Fig. 1. Full characteristics of the observation sites, including metadata, are available from the Dynamic Ecological Information Management System (DEIMS) LTER-Europe: https://data.lter-europe.net/deims/site/list?field_ilter_network_country_value%5B%5D=CH

4 Technical validation

The following standards have been applied for hardware installation, calibration, and data checks for quality assurance of the measurements:

The meteorological stations that are located in the open-field were set up according to the World Meteorological Organization (WMO 2008) standards. However, due to the specific objectives of the LWF research program, the stations under the canopy do not fully correspond to the WMO criteria (2008).

Hardware installations as well as data quality checks are based on the ICP Forests (International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests) Manual, part IX on Meteorological Measurements.[1] Detailed information can also be found in

[1] Url: http://icp-forests.net/page/icp-forests-manual

Table 1 Equipment of the meteorological stations (adapted from QuaLMet Handbook, Jetel and Schneiter 2015)

Parameter	Height	Sensor	Manufacturer	Type	Accuracy[a]	Temporal resolution
Air temperature	2 m	Sheltered, non-ventilated	Rotronic AG, Bassersdorf, Switzerland, www.rotronic.ch	MP103A-CG01B5-W4W	± 0.3 °C	10 min
Relative humidity	2 m	Sheltered, non ventilated		MP103A-CG01B5-W4W	± 1.5%	1 h/10 min
Precipitation	1.5 m	Unheated tipping bucket (254-mm funnel diameter, 0.2 mm per tip)	Environmental Measurements Ltd., North Shields, UK, www.emldt.net	ARG 100	± 1 mm	1 h/10 min
Global radiation[2]	3 m	Pyranometer	Skye Instruments Ltd.,Powys, UK www.skyeinstruments.com	SKS 1110	± 3%	10 min
Photosynthetic active radiation (PAR)	3 m	PAR sensor		SKP 210	± 3%	10 min
UV-B radiation[b]	3 m	Sensor		SKU 430	± 3%	10 min
Wind velocity[c]	4.6 m	Wind wheel	Windspeed Ldt, Rhyl, UK, www.windspeed.co.uk	A100R	1–2%	10 min
Wind direction[b,d]	4.6 m	Wind vane		W200P/D1	± 3°	10 min

[a] Manufacturer's information

[b] Only open-field station

[c] Operational range 0.2 to 75 m s^{-1}, accuracy 1% for 10 to 55 m s^{-1} and 2% > 55 m s^{-1}

[d] Accuracy for wind speed > 5 m s^{-1}, operational range 0.6 to 75 m s^{-1}

Raspe et al. (2016). Values that are implausible and/or inconsistent with the ICP Forests standard are flagged in the database. Implausibility thresholds were defined for each station and each parameter depending on the local climate conditions including in particular the altitude.

The precipitation buckets were regularly replaced after 12 to 24 months, including freshly calibrated sensors with official calibration certificates. Other sensors were replaced regularly every 3 to 7 years with freshly certified calibrated sensors. Long-term drifts were detected and corrected in radiation

Table 2 Main characteristics of the observation sites

Site name	Forest type	Altitude [masl]	Orientation forest	LAI[a]	PARJJA[b]	Distance [m][c]	Orientation open area
Alptal	Spruce	1169	W	3.8	NA		No station in the open
Beatenberg	Spruce	1523	S	1.9	6	666	S
Bettlachstock	Beech, silver fir	1001	SE	6.5	3	558	S
Celerina	Larch, Arolla pine	1866	NE	1.2	41	1787	Slope < 5°
Chironico	Spruce	1381	N	3.7	7	729	E
Isone	Beech	1194	N	5.8	2	145	NE
Jussy	Oak	497	None	5.8	2	571	Slope < 5°
Lausanne	Beech, silver fir	806	NE	6.9	1	2867	Slope < 5°
Lens	Scots pine	1070	SE	3.1	NA		No station in the open
National park	Mugo pine	1899	S	1.3	48	924	S
Neunkirch	Beech	562	N	5.2	5	906	Slope < 5°
Novaggio	Oak	929	S	3.8	NA	273	S
Othmarsingen	Beech	475	S	4.6	4	343	W
Schänis	Beech, silver fir	710	W	5.5	3	1693	W
Visp	Scots pine	698	N	2.3	51	1287	Slope < 5°
Vordemwald	Oak, silver fir	482	NW	5.1	3	1883	Slope < 5°

[a] See Thimonier et al. (2010a, b) for more information concerning LAI estimation methods

[b] Below-canopy part of open-site photosynthetically active radiation (PAR) [%], mean summer value (June-July-August) (see Renaud and Rebetez (2009) for more information on PAR percentages)

[c] Distance between the paired stations located in the forest vs open-field

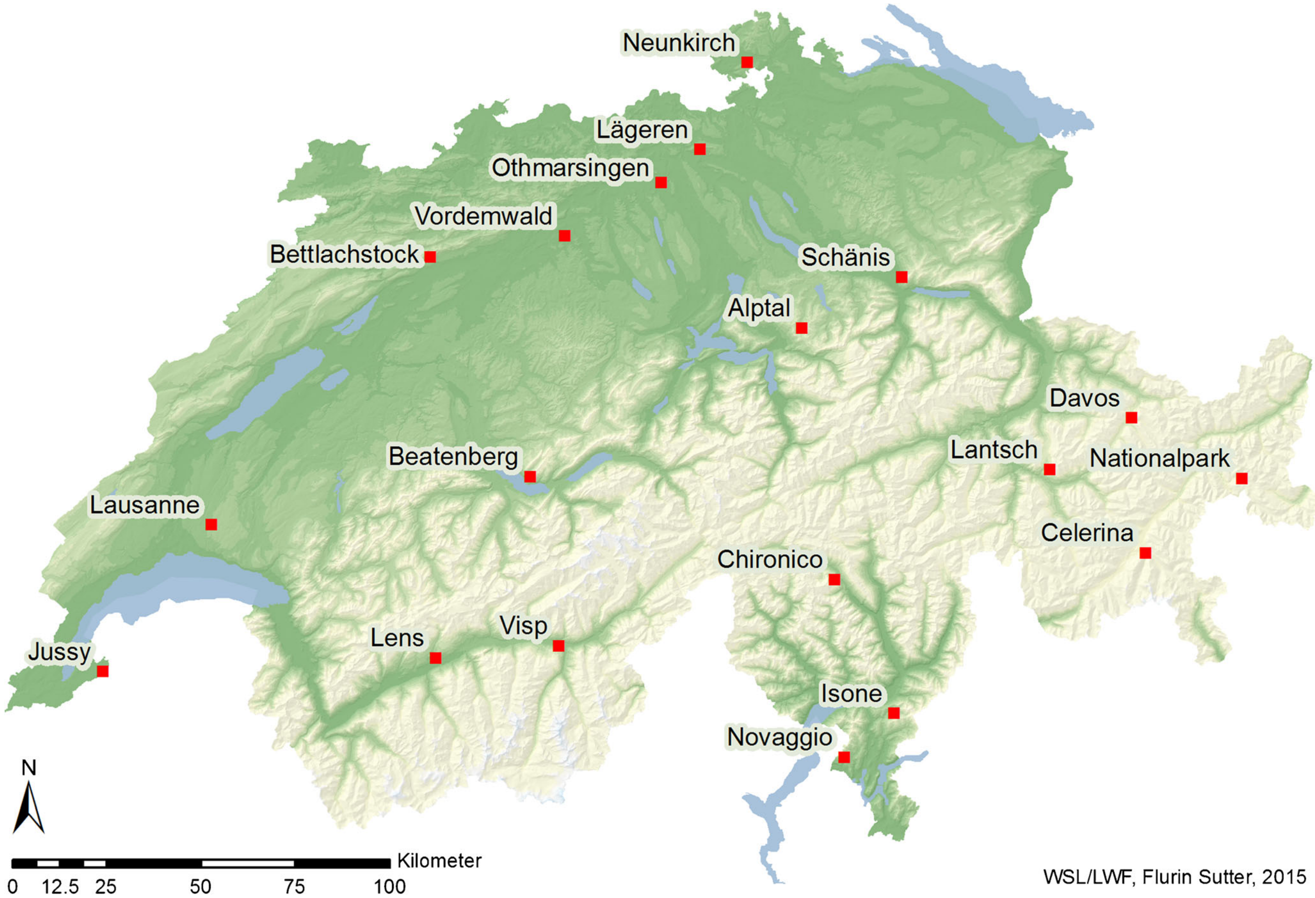

Fig. 1 Map of the observation sites

measurements. Sensor drifts in relative humidity (RH) were detected and quantified by Von Arx et al. (2013a). They have not yet been removed in the database. Drifts were noticed in 40.6% of the relative humidity data with strongest trends for values close to 100%. Average trends were 1.96%, 20% of the data reached 2.75% or more, and 10% of the data 4.75% or more.

In a retrospective quality check initiated in 2011, standard verifications and corrections were processed in collaboration with the Federal Office of Meteorology and Climatology (MeteoSwiss), financed by the WSL project "Quality management of LWF-meteorological data" (QuaLMet) in order to benefit from the MeteoSwiss quality assessment procedure and to make the data available via the MeteoSwiss data portal. All data were checked for consistency according to Musa et al. (2003) and validated by a standard quality assessment tool following WMO guidelines (WMO 1992). Potential data issues that could not be resolved automatically were transferred for manual verification with a graphical interface. This data validation process was completed in 2014 for all data from 1997 to mid 2014.

Since 2015, data have been processed internally using R statistical software [R Development Core Team (2016)] version 3.3.0 on a CentOS Linux server (release 7.3.1611). Every hour, incoming data are checked for outliers and large differences between the forest and the open-field stations. Small gaps (< 2 h) are linearly gap-filled except for precipitation data where no gap-filling is conducted. Every half year, data are homogenized and manually verified if needed.

5 Reuse potential and limits

After the first years of measurements, the reliability of the LWF meteorological data was checked for two sites against data from standard nearby MeteoSwiss stations (Rebetez and Logeay 2000), with excellent results but also some issues:

- Temperature data were very similar to the reference data. Deviations were found when temperature changed rapidly, as the LWF sensors reacted more slowly.
- Precipitation data showed specific deviations when air temperatures fell below zero; these were related to the lack of heating of the collector. The remaining deviations were below 10% (most of them below 5%) and could be explained by the spatial variability between two pluviometers.

- Relative humidity data showed mean deviations of 5–6%, mainly because the sensors are protected with a radiation shield but not fully against precipitation. The sensors are also less sensitive to short-term variations, showing hourly deviations up to 20% during sudden changes in relative humidity.
- Global radiation data were very similar to the reference data, except in winter, when radiation was below 250 W m^{-2}.
- Wind speed data followed the same trends but LWF values were lower because of the height difference between the sensor poles (4.5 m for LWF vs. 10 m for MeteoSwiss). The differences were mostly less than 2 m/s.
- Wind direction data showed the greatest deviations, higher than 20° for 50% of the data; 60–88% of these cases occurred when wind speed was less than 1 m/s. The differing heights of sensor poles explained the remaining variations.

Several previous analyses have shown that the LWF meteorological data, while only automatically checked and not yet validated as described above, are already of high quality (e.g., von Arx et al. 2012, 2013a, Büker et al. 2012, Ferrez et al. 2011, Renaud and Rebetez 2009, Renaud et al. 2011; Schaub et al. 2007).

Air temperature during the 2003 summer heatwave showed significant correlations between the absolute value of temperature and the leaf area index (LAI), a trend that was stronger with higher temperatures (Renaud and Rebetez 2009). Daily maximum temperatures were up to 5.2 K cooler on average under the canopy during the main part of the heatwave (Renaud and Rebetez 2009). During the 2003 hot summer, the impact on daily maximum temperature was stronger in deciduous and mixed forests, especially those with beech (*Fagus sylvatica*) as the dominant tree species, compared to coniferous forests (Renaud and Rebetez 2009). For minimum temperature, the impact was higher in coniferous forests. South-oriented slopes showed greater differences for daily maximum temperature whereas north-oriented slopes showed greater differences for daily minimum temperatures (Renaud and Rebetez 2009). Influences of altitude and orientation as well as of the forest cover were shown on extremely high maximum and extremely low minimum temperatures depended on the effect of forest cover: for higher sites, maxima were less variable and less correlated with the open-field data (Ferrez et al. 2011). Southerly orientations increased the correlation for minima and so reduced the sheltering effect during cold periods (Ferrez et al. 2011). Slope steepness had a complex impact on the distributions of extremes and on their correlation with open-field data (Ferrez et al. 2011).

Clear impacts of the forest canopy were found on relative humidity, maximum and daily mean photosynthetically active radiation (PAR), and wind speed (Renaud et al. 2011). The forest influence on PAR and maximum temperature was shown to be mostly determined by the tree species, whereas the influence on minimum temperature was affected by both tree species and slope orientation (Renaud et al. 2011). Furthermore, the impact of the forest canopy on humidity depended on the soil moisture and consequently soil type (Renaud et al. 2011; von Arx et al. 2013b). Finally, wind speed was most impacted by topography and slope orientation (Renaud et al. 2011). The general moderating effect of canopy on below-canopy microclimate was confirmed through an average decrease in daily maximum air temperature of 1.8 K and an increase in daily minimum relative humidity of up to 12.4%, with an overall average increase of 5.1% (Von Arx et al. 2012). Broad-leaved and non-pine coniferous forests moderated the daytime microclimate about twice as much as pine forests, while at nighttime, considerably less cooling and lower relative humidity compared to the open area were recorded at the pine forest sites (Von Arx et al. 2012). The moderation of temperature and relative humidity was greater at lower altitudes than that at higher altitudes and strongest during the growing season, particularly in summer and it depended in a complex way on the general weather situation (Von Arx et al. 2012). Analyses of air temperature and vapor pressure deficit (VPD) together with additional data such as soil matrix potential and LAI highlighted the strong impact of soil moisture and seasonality on the moderating capacity of the forest cover and suggested a threshold canopy density, probably linked to site-specific water availability, below which the moderating capacity of forest ecosystems drops considerably or disappears (Von Arx et al. 2013b).

The LWF meteorological data were used for the modeling of soil water fluxes (Graf Pannatier et al. 2011) and drought stress (Graf Pannatier et al. 2012; von Arx et al. 2013b) at selected LWF sites with the CoupModel (Jansson and Karlberg 2004). Missing temperature, relative humidity, global radiation, and wind data were estimated using correlations between cleaned LWF data (open-field and under canopy) and data from nearby MeteoSwiss stations. For precipitation, the volume of bi-weekly precipitation sampled for deposition measurements and the daily distribution from a nearby meteorological station during the same period were used to estimate the gaps, particularly in case of winter precipitation. The good fit between measurements (e.g., throughfall, soil moisture) and results from CoupModel reflects the good quality of this database's measurements. In a parallel study applying CoupModel to calculate a drought index, Walthert et al. (2013) used the LWF meteorological data to validate modeled meteorological data.

The automatically checked LWF precipitation data have been used to fill gaps in the precipitation volume of the bulk and throughfall sampling used to determine atmospheric deposition particularly in case of overflow of the collectors (Thimonier et al. 2005; Waldner et al. 2007; Thimonier et al. 2010a, b; Waldner et al. 2014).

To determine ozone flux to forest trees, Büker et al. (2012) applied the Penman-Monteith energy balance method in the DO3SE soil moisture module to drive water cycling through the soil-plant-atmosphere system and empirical data describing stomatal conductance relationships with pre-dawn leaf water status to estimate the biological control of transpiration. These methods were evaluated against field data, including LWF meteorological data.

Schaub et al. (2007) aimed at establishing whether UNECE/ICP-Forests monitoring data (i) provide the variables necessary to apply the ozone flux-based modeling methods and (ii) meet the quality criteria necessary to apply the flux-based critical level concept. Application of this model has been possible using environmental data collected from the UNECE/ICP-Forests monitoring network in Switzerland and Italy for 2000–2002. Hourly wind speed, hourly photosynthetic photon flux density (PPFD), hourly and daily air temperature, hourly relative humidity, and daily precipitation were input parameters required for stomatal ozone flux modeling according to the UNECE Mapping Manual (CLRTAP 2004). For the Swiss sites, the test for data completeness resulted into five out of a possible total of six possible *F. sylvatica* L. plots being identified as suitable for ozone flux-based modeling.

Previous results using the LWF meteorological data show that these data have already contributed to a better understanding of the complex processes involved in forest resilience to climate change. The dataset presented here is now available for further analyses of the climate under the canopy as a contribution to an improved understanding of forest ecosystem functioning.

This dataset is unique because it offers comparisons of meteorological parameters both under the forest cover and at a parallel station in the open-field of similar topography less than 2 km away. The dataset allows a better understanding of the impact of different forest ecosystems on below-canopy weather parameters. This understanding is crucial when attempting to determine the potential impact of warmer temperatures and altered precipitation regimes on forest ecosystems. Many prognoses are based on process models that require accurate data for calibration. This dataset allows distinctions between the impacts of the forest type, altitude, topography, weather types, and moisture conditions. In the context of climate change, it will provide important clues to the understanding of the future evolution of different types of mid-latitude forests at different elevations and may be essential for validation of respective climate-effects models.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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