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First Validation Against A Global Experiment

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MODELLING MOISTURE CONDITIONS OF NORWAY SPRUCE (*PICEA ABIES*): FIRST VALIDATION AGAINST A GLOBAL EXPERIMENT

Niklewski, Jonas[1]; Emmerich, Lukas[2]; Sand Austigard, Mari[3], Batista, Djeison Cesar[4]; Boivin, Gabrielle[5]; Cai, Lili[6]; Creemers, Jos[7]; Humar, Miha[8]; Hundhausen, Ulrich[9]; Ibáñez, Marcela[10]; Kartal, Nami[11]; Meincken, Martina[12]; Möller, Antonia[13]; Singh, Tripti[14]; Wong, Daniel[15]; Brischke, Christian[16]

1: Building and Environmental Technology
Lund University
jonas.niklewski@kstr.lth.se

2: Wald und Holz NRW
Centre of Forest and Wood-Based Industries
lukas.emmerich@wald-und-holz.nrw.de,

3: Mycoteam AS
msa@mycoteam.no,

4: Federal University of Espírito Santo
Department of Forest and Wood Sciences
djeison.batista@ufes.br,

5: FPInnovations (Quebec),
gabrielle.boivin@fpinnovations.ca

6: Department of Forest, Rangeland and Fire Sciences
University of Idaho
lcai@uidaho.edu,

7: SHR Timber Research
j.creemers@shr.nl

8: Biotechnical Faculty
University of Ljubljana
miha.humar@bf.uni-lj.si,

9: NTI (Norwegian Institute of Wood Technology)
uhun@treteknisk.no,

10: Instituto Superior de Estudios Forestales, Cenur Noreste
Universidad de la República
claudia.ibanez@pedeciba.edu.uy,

11: Faculty of Forestry
Istanbul University-Cerrahpaşa
snkartal@iuc.edu.tr

12: Department of Forest and Wood Science
Stellenbosch University
mmein@sun.ac.za

13: Wood Biology and Wood Products
University of Goettingen

a.moeller03@stud.uni-goettingen.de

14: National Centre for Timber Durability & Design Life
University of the Sunshine Coast
tsingh1@usc.edu.au,

15: FPInnovations (Vancouver)
daniel.wong@fpinnovations.ca,

16: Thünen-Institute of Wood Research
christian.brischke@thuenen.de

ABSTRACT
Wood used in outdoor construction is consistently subjected to wetting by precipitation. High levels of moisture content, especially if sustained over long periods, promote fungal decay and structural degradation. Predicting temporal variation of moisture content in wood exposed to rain is essential for durability assessment, and simple fit-for-purpose numerical approaches have been developed for this purpose. While these models do not fully describe the complex dynamics of free water transport, they have been shown to capture the relevant features for durability assessment. Extensive validation is however necessary to assess their applicability, robustness and limitations. This study evaluates a numerical model for moisture content prediction of Norway spruce (*Picea abies*) boards by comparing its outputs to measurements from 12 locations around the world, all using the same parameter settings. Overall, the model aligned with observed trends and demonstrated robustness across diverse climates, though some discrepancies likely stemmed from weather data inconsistencies and inherent simplifications. The results confirm its reliability for durability-related moisture assessments and suggest refinements to further enhance performance.

KEYWORDS: Wood, moisture conditions, durability, model, experiment, gravimetric

1. INTRODUCTION

Wood used in outdoor construction is continuously exposed to fluctuating moisture conditions due to cycles of wetting and drying. These variations in moisture content influence the long-term durability of wood, particularly when high moisture levels are sustained for extended periods, as they can accelerate fungal decay and structural deterioration [1]. As the use of wood in sustainable construction increases, the ability to predict durability issues becomes increasingly important for ensuring the longevity of timber structures. Reliable moisture modelling is therefore essential for making informed decisions regarding the design, maintenance, and preservation of wood in outdoor environments.

Decay hazard maps are used to predict and visualize the risk of wood deterioration due to fungal decay across different geographic regions. These maps integrate climatic variables such as temperature, relative humidity, and precipitation to estimate conditions that favour fungal growth and wood decomposition. This can be done by directly describing the decay hazard as a function of weather variables, see e.g. [2], or to calculate wood moisture content as an intermediate variable, see e.g. [3]. A robust moisture model should maintain consistency across different climate types and therefore need to be validated against a diverse set of data. For practical purposes, it is advantageous that the model relies solely on widely available weather data, including relative humidity, temperature, and precipitation.

Numerical modelling approaches, particularly diffusion-based methods, have been widely applied to simulate moisture transport in wood. These models are commonly used to describe moisture movement in the hygroscopic range [4]. However, accurately representing moisture transport remains challenging, particularly when accounting for free water movement, e.g., during and after rainfall. Factors such as surface wetting dynamics, boundary conditions, and the complex behavior of free water introduce uncertainties in diffusion-based models. Despite these challenges, several studies have successfully modelled moisture transport in exposed wood under both controlled laboratory conditions [5,6] and outdoor environments [7,8]. More recently, advancements in multi-phase modelling approaches, where free water is explicitly represented, have shown promise in accurately capturing the underlying phenomena [9,10]. A persistent challenge, however, in applying numerical models to outdoor conditions is the limited amount of validation against real-world data. Without thorough validation across diverse climates and exposure conditions, models may fail to accurately capture key moisture dynamics, leading to misrepresentations of decay risk and uncertainty in durability assessments.

To address these challenges, this study evaluates the performance of a simple numerical model for predicting moisture content in wood by testing it against a dataset from a global joint trial. In this trial, wooden specimens were exposed outdoors at 17 different sites over a period of at least 3 months. During this period, gravimetric measurements were taken at regular intervals to monitor the average moisture content. The data set presents a unique opportunity for model validation, as it includes a large variety of different climates and local conditions. In addition, since the test is running for a relatively short period, any non-stationary effect related to wood aging [11] is minimized.

The objective of this study is to assess how well a single, simple model configuration can effectively represent moisture dynamics across diverse climates. Predictions are based solely on relative humidity, temperature, and precipitation, without consideration of other climate variables (like solar radiation) or local effects such as partial shading. By evaluating the model's performance across a geographically diverse dataset, this study provides insight into its potential and limitations. Furthermore, the findings contribute to ongoing efforts to refine moisture prediction models, ultimately supporting the development of more durable and resilient timber structures in outdoor environments.

2. METHOD

2.1. Numerical model

The numerical model is based on Fick's second law of diffusion. With wood moisture concentration, c (kg/m^3) as the potential, the rate of change can be described as follows:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial c}{\partial x}\right) \quad (1)$$

Where c (kg/m^3) is the moisture concentration, D (m^2/s) is the effective diffusion coefficient and x (m) is the depth dimension. Equation 1 governs the transport of moisture inside of the wooden element. The diffusion coefficient, shown in Figure 1, is temperature dependent and was determined experimentally for Norway spruce by Koponen [12,13] during water soaking. It is implemented at 20° as a piecewise function with temperature compensation according to [7].

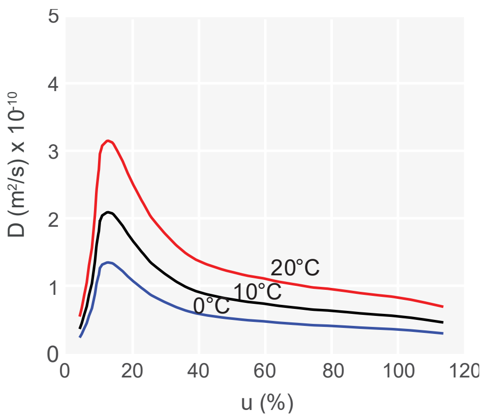

Figure 1. Diffusion coefficient at 0°C, 10°C and 20°C.

Since wood is a hygroscopic material, the surface tends towards an equilibrium condition with the ambient air. The function relating the wood moisture content, u_{eq} (kg/kg), to the relative humidity of the air, ϕ (-) is the sorption isotherm. Note that moisture content and concentration are related via the dry density, $c_{eq} = \rho u_{eq}$. The following sorption isotherm from [8] is used in the present study:

$$u_{eq} = \frac{\phi}{1.78 + 0.116\phi - 9.62 \cdot 10^{-4}\phi^2} \tag{2}$$

The rate at which moisture transfers between the air and the wood surface, q (kg/m^{2}s) can be modelled with any relevant potential, such as partial vapour pressure or moisture concentration. These potentials are related via the sorption isotherm which is non-linear. As such, the choice of potential affects the flux. In the present study, moisture concentration, c, was used as potential. This is a very common choice of potential in wood science, and the effect of the choice is discussed in section 3. The boundary flux is then given by:

$$q = k_c(c_s - c_{eq}) \tag{3}$$

where k_c (m/s) is the mass transfer coefficient, c_{eq} (kg/m^3) is the equilibrium moisture concentration of the ambient air, which is obtained from the sorption isotherm, c_s (kg/m^3) is the moisture concentration on the surface and ρ (kg/m^3) is the dry wood dry density. Note that a positive flux ($c_{eq} < c_s$) means that water vapour is leaving the material. The mass transfer coefficient and dry density are set to $1.4{\times}10^{-7}$ m/s and 350 kg/m^3, respectively [7]. It can be noted, however, that the choice of dry density has no effect on the resulting (relative) moisture content when concentration is used as potential in both equation (1) and (3).

Moisture absorption into wood is a slow process, particularly in species like Norway spruce with low permeability. Even mild rain intensity will saturate the wooden surface almost immediately [14]. The amount of absorbed water therefore depends on the duration of wetting rather than the volume of rain that strikes the surface. Moisture absorption during precipitation is therefore considered by increasing the surface moisture content to a maximum value for the duration of the rain event. The duration of the rain event is a parameter which is highly uncertain and not easily estimated from weather data. Here, we assume that any hour when more than 2 mm of precipitation is recorded corresponds to a full hour of wetting. For lower values, the time of wetting is calculated with a linear relationship. For instance, a value of 1 mm recorded in an hour corresponds to 30 minutes of wetting. Values below 0.2 mm are neglected.

The maximum moisture content, u_f, which is assigned to the surface during wetting has previously been used as a calibration parameter to reproduce transient moisture gradients obtained in laboratory experiments with spruce sapwood subject to one or several cycles of spray, see Niklewski et al. [7]. The effect of a rain event can be seen as a temporary disturbance on the surface that spreads through the wood core, with the deeper regions experiencing this effect later and in a weaker form as it gradually fades. A larger maximum moisture content, u_f, will amplify this response. In the present study, simulations were run with two different values, namely 60% and 120%, and the resulting moisture variation is presented as upper and lower bounds.

It should be noted that the shape of the diffusion coefficient is highly uncertain in the over hygroscopic range, and the boundary conditions applied during wetting are to some extent calibrated. Nevertheless, this set of parameters has previously been shown to reproduce accurate moisture gradients during cyclic wetting, given that the depth of liquid water penetration is limited. Depending on the choice of u_f, the model gives a liquid absorption coefficient of about 2-4 kg/m^{2}s$^{0.5}$ which is a reasonable range for spruce. For a more rigorous motivation of parameters and calibration, the reader is referred to Niklewski and Fredriksson (2018) and Niklewski et al. (2016).

2.2. Experimental data

To advance the understanding of wood moisture performance under diverse climatic conditions, an international joint field trial was conducted, involving 17 research groups across 14 countries [15]. The primary objective was to evaluate the correlation between laboratory-derived moisture indicators and real-world exposure data, ultimately supporting the integration of moisture performance into durability classifications.

Wood specimens of varying species and configurations were exposed at 17 outdoor test sites representing a wide range of climatic conditions. The configurations included small stakes (100x10x5 mm^3) and boards (150x50x25 mm^3) with and without a slit through the top face to expose end-grain. In the present study, only the small stakes and boards of spruce without slits were included. The boards were sealed on all short faces, including end-grain, but the stakes were left unsealed. These are shown in Figure 2. Moisture content was monitored over a 12-week period at each location by weighing at least two times per week. The date was recorded, but the time-of-day is unknown.

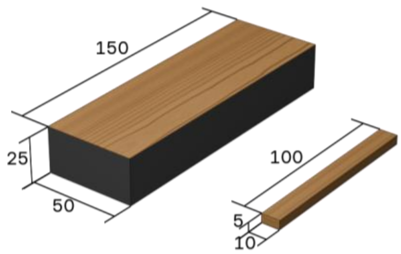

Figure 2. The two different specimens that were included in the present study: board (left) and stake (right). Note that the board has sealed short edges (black), whereas the small specimen is unsealed.

2.3. Weather data

Most participants originally provided daily values of relative humidity, temperature, and precipitation for the full test period. However, the numerical model requires hourly weather data. This is particularly critical when modelling the stakes which experienced significant subdaily fluctuations. Therefore, only sites where hourly data of sufficient quality could be retrospectively obtained were included in the present study.

Hourly data was sourced from a variety of different sources, and not necessarily from the same weather station that was used to capture the original daily data. In most cases, hourly data could be obtained from one or several nearby public or private weather stations. In some cases, only relative humidity and/or temperature were available at the site. In these cases, if a public nearby weather station was also available, all data was obtained from that station for consistency. For all locations where data was missing either partially or completely, we additionally sourced hourly data from ERA5-Land [16]. This data is available globally and describes average values over an area of approximately 9 km horizontal resolution.

The quality of the hourly weather data was assessed by cross-referencing against the original daily data submitted by the participants. If the values aligned reasonably well, then the hourly data was considered reliable. In one case, the variation in temperature and relative humidity aligned well but there was a systematic difference in the absolute level. In this case, the hourly data was corrected to align with the original data on a daily scale while preserving the subdaily variations.

The relative humidity and temperature from the ERA5-Land were in many cases reasonably consistent with the original daily measurements. The reliability of the precipitation data, however, was often questionable. This was expected, as ERA5-Land represents the average climate over a larger area rather than a specific site. Since precipitation can be very localized, several sites had an inflated number of days with low- to moderate precipitation. For this reason, only two examples of locations where all data was sourced from ERA5-Land were included (Tacuarembó and Stellenbosch) here.

Figure 3. Locations of sites, including Stellenbosch (1), Brasilia (2), Jerônimo Monteiro (3), Quebec City (4), Vancouver (5), Beijing (6), Göttingen (7), Bogor (8), Wageningen (9), Oslo (10), Ljubljana (11), Brisbane (12), Istanbul (13), Sea Ranch (14), Bangalore (15), Tacuarembó (16), Moscow, US (17). Red markers indicate sites which were included in this specific study.

2.4. Numerical considerations

All numerical simulations were conducted as one-dimensional to simplify the modelling process and reduce computational effort. In these simulations, one boundary (upper face) was exposed to water, while the other (bottom face) was sheltered from precipitation but exposed to ambient air. The element depth was set to 25 mm for the boards and 5 mm for the stakes.

For the board with sealed short edges, the one-dimensional model is entirely valid, as moisture transport occurs only in one direction. However, in the short stakes, moisture can be absorbed through the short edges and, more significantly, through the end-grain. End-grain absorption cannot be accurately captured using a simple diffusion-based model of this type. Consequently, the simulated moisture content will be underestimated, making any comparison with experimental data qualitative rather than quantitative.

Numerically, the model is simple and robust. To ensure accuracy, sensitivity analyses were conducted to confirm that the model was unaffected by mesh resolution and numerical tolerance. A maximum time step of 2 minutes was used to prevent the model from overshooting rain events.

3. RESULTS AND DISCUSSION

The results from all twelve locations are summarized in Figure 4. The data is structured into three rows and divided into two parts (a and b), each containing six locations. In each part, the first two rows show the simulated (red) and measured (black) moisture content for the small stakes and boards, respectively. The third row presents the weather data for the same period, which was used as model input.

The simulation generally captures the moisture variations of the boards. However, in two cases (Jerônimo Monteiro and Wageningen) and during shorter periods at other locations (e.g., the final month at Vancouver), the model reproduces the overall trend but fails to match the absolute values. Notably, in these two cases, a similar discrepancy appears in the small stakes, where the measured moisture content is significantly lower than expected. This discrepancy could arise from a model limitation in reproducing the equilibrium moisture content, potentially related to the sorption isotherm. However, a more likely explanation, given that the model seems to fit well in other cases, is a systematic difference between the relative humidity used as input and the actual relative humidity near the exposed wood surface. Several factors could contribute to this, such as differences in conditions between the weather station and the micro-climate at the wood surface or sensor drift in the relative humidity measurements.

A reason for the former would be the impact of sunlight heating the surface, which could locally reduce the relative humidity (assuming a constant vapor content).

Qualitative evaluation of the stake results suggests that the model generally captures the duration of moisture absorption but tends to underestimate peak moisture content. This is an expected consequence of the one-dimensional simplification, which does not account for end-grain capillary effects and lateral moisture transport. However, the measured values from Göttingen and Istanbul stand out, likely due to the combination of high precipitation and elevated relative humidity at this location. Under high relative humidity, evaporation slows down because the vapor pressure gradient between the ambient air and the wood surface is minimal. However, the model, which relies on moisture concentration (Equation 3), does not fully account for this effect. To explore this discrepancy, the surface flux was modified from a concentration-based approach to one driven by vapor pressure.

$$q = k_p(p_s - p_a) \tag{4}$$

where k_p (kg/m^{2}sPa) is the mass transfer coefficient while p_s (Pa) and p_a (Pa) are the vapour pressures at the wood surface and the ambient air, respectively. Assuming that the air and wood temperature are equal, the vapour concentration and corresponding vapour pressure at the wood surface can be obtained from the sorption isotherm. In the following comparison, a mass transfer coefficient of 30×10^{-9} kg/m^{2}sPa was used.

Figure 5 shows the results from Istanbul and Göttingen, with boundary conditions according to equation 3 (red) and 4 (blue), respectively. The results demonstrate that the choice of boundary condition has a great impact on the effect of precipitation during periods with high relative humidity. This is explained by the large difference in drying potential at high surface moisture contents. The comparison should be made with some caution, considering that the simplified simulation of the stakes *should* underestimate the moisture content. For the other locations, the choice of boundary condition was less critical.

Overall, the results confirm the reliability of the numerical model for durability applications. While discrepancies exist, it should be emphasized that the same parameter settings were used across all sites, despite possible differences in local conditions. In addition, hourly weather data were obtained from many different sources and likely vary in quality. Finally, several weather variables were omitted, such as wind and solar radiance. Given the uncertainty and simplicity of the model, the results were deemed satisfactory.

Future efforts should concentrate on developing a method to bias-correct hourly data (e.g., ERA5-Land) against the original daily data. This would allow inclusion of the five remaining locations that were excluded in the current dataset. Completing the full dataset with reliable hourly weather data will also enable the dataset to serve as a benchmark for comparing different models of wood moisture prediction. Finally, although the simplicity of the present approach was deliberate, incorporating additional weather variables could help clarify their significance and improve model performance.

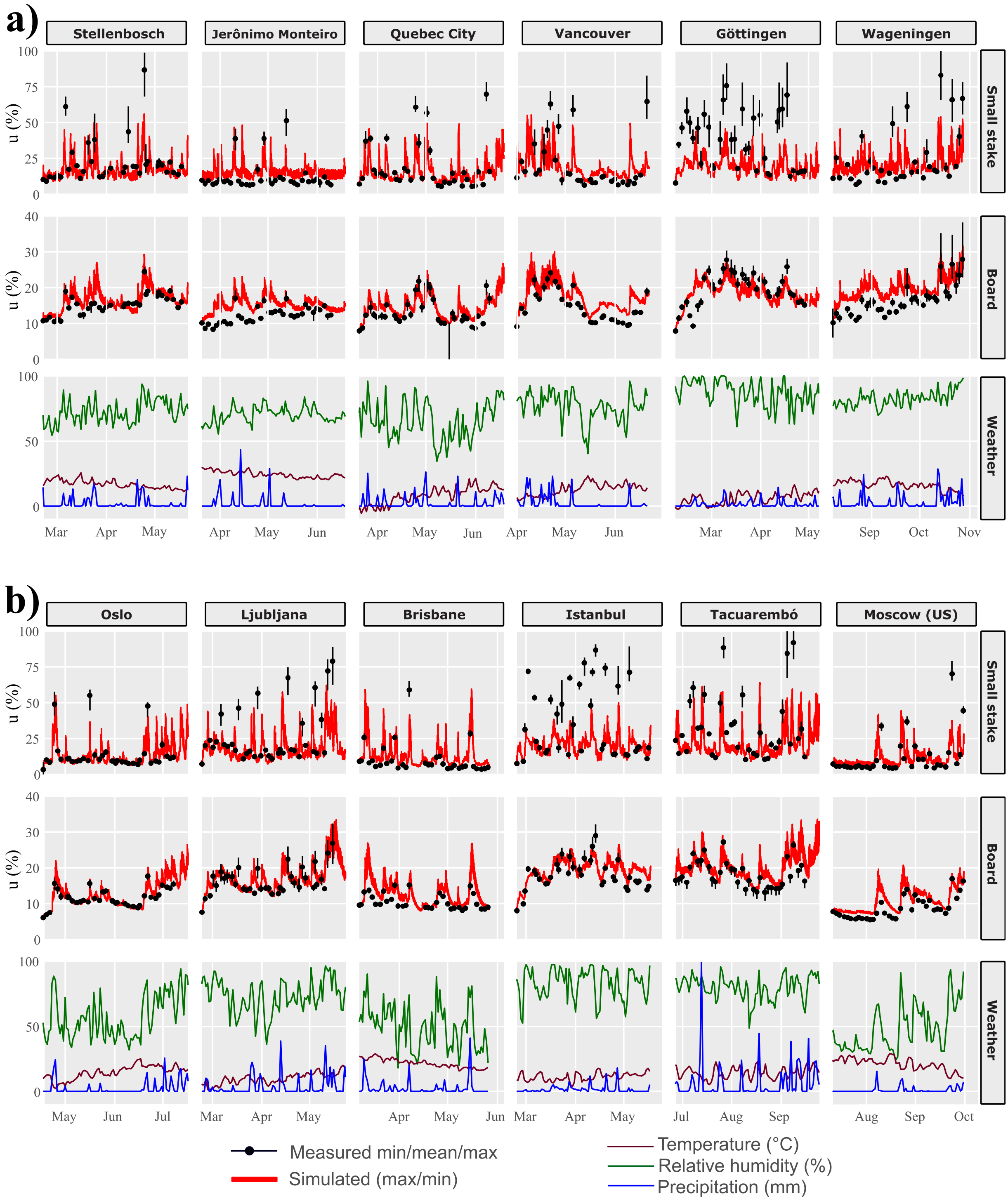

Figure 4. Measurements (black) and simulated (red) moisture variation over about 3 months in 12 different locations in small stakes and boards, together with daily weather data.

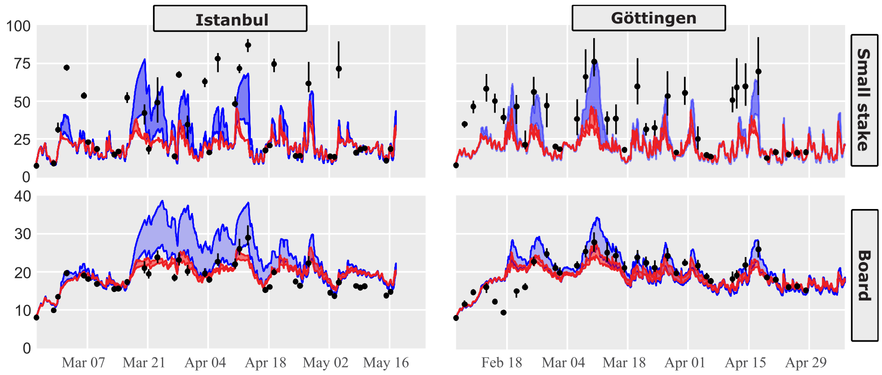

Figure 5. Comparison between measurements from Istanbul (left) and Göttingen (right) for the small stakes (top) and the boards (bottom), and simulations using two different boundary conditions.

CONCLUSIONS

The study compared gravimetric measurements of moisture content in Norway spruce (*Picea abies*) from 12 different locations against numerical simulations. The specimens included both boards with sealed edges and smaller stakes with unsealed edges. Based on the results, the following conclusions can be drawn

- The model was able to describe the general variations and features of the measurements in the boards. In most cases, the model was able to capture the absolute variation with a reasonable degree of accuracy.
- The moisture content in the boards generally followed the variations in relative humidity, with small peaks during rain events. The effect of rain was, in general, slightly overestimated.
- The stakes were subject to significant daily fluctuations from both relative humidity and precipitation. The model was able to capture the timing and duration of wetting after rain events, but the amplitude was generally underestimated because of model limitations.
- At two locations with high relative humidity, the effect of potential at the boundary (vapour or concentration), became evident.

This study presented the first attempt at modelling the global dataset. Further attempts should focus on (1) improving the hourly weather data by bias-correction against the original daily data, (2) expand the analysis to all 17 sites, (3) investigate whether including additional variables, such as solar radiation, can reduce systematic errors, (4) perform two-dimensional modelling of the stakes to account for lateral transport. Building on the current qualitative comparison, future work will incorporate statistical goodness-of-fit analyses to quantitatively assess and rank the performance of different models.

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