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A general model to predict individual exposure to solar UV by using ambient irradiance data.

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Abstract

Background. Excessive exposure to solar ultraviolet (UV) is the main cause of skin cancer. Specific prevention should be further developed to target overexposed or highly vulnerable populations. A better characterisation of of anatomical UV exposure patterns is however needed for specific prevention.

Objectives. To develop a regression model for predicting the UV exposure ratio (ER, ratio between the anatomical dose and the corresponding ground level dose) for each body site without requiring individual measurements.

Methods. A 3D numeric model (SimUVEx) was used to compute ER for various body sites and postures. A multiple fractional polynomial regression analysis was performed to identify predictors of ER. The regression model used simulation data and its performance was tested on an independent dataset.

Results. Two input variables were sufficient to explain ER: the cosine of the maximal daily solar zenith angle and the fraction of the sky visible from the body site. The regression model was in good agreement with the simulated data ER (R^2=0.988). Relative errors up to +20% and -10% were found in daily doses predictions, while an average relative error of only 2.4% (-0.03% to 5.4%) was found in yearly doses predictions.

Conclusions. The regression model predicts accurately ER and UV doses on the basis of readily available data such as global UV erythemal irradiance measured at ground surface stations or inferred from satellite information. It renders the development of exposure data on a wide temporal and geographical scale possible and opens broad perspectives for epidemiological studies and skin cancer prevention.

Introduction

Excessive exposure to solar ultraviolet (UV) radiation can cause erythema, pigment darkening, eye diseases and is responsible for 50 to 90% of all skin cancers [1, 2]. UV radiation has been classified as as "carcinogenic to humans" (Group 1) by IARC[3]. Epithelial skin cancer is the most common cancer among fair-skinned people with an annual burden of approximately 13 million new cases worldwide (10 million basal cell carcinomas (BCC) and 2.9 million squamous cell carcinomas (SCC)) [4]. Melanoma is less frequent (about 10% of skin cancers) but far more lethal than epithelial skin cancers. Skin cancer causes yearly circa 60 000 deaths worldwide, the majority of these being melanomas [4]. SCC is predominantly induced by chronic (cumulative) sun exposure, leaving outdoor workers and elderly people at greater risk [5-7]. Melanoma has been associated with intermittent sun exposure [8], whereas both cumulative and intermittent exposures appear to be responsible for BCC development [9, 10]. The steady rises in skin cancer rates over the past 50 years concur with the gradual increase in outdoor leisure activities, vacation in sunny areas, and changing clothing habits favouring exposure of larger skin surface [11, 12].

The increase in skin cancer incidence has heightened awareness towards UV exposure, and emphasised the need to further develop prevention. However, the scarcity of exposure data as well as the lack of understanding of the dose-response between UV exposure and skin cancer occurrence renders this development difficult. A better understanding of exposure patterns could help identify overexposed subpopulations and specific exposure situations that would benefit from tailored prevention strategies. Factors influencing anatomical exposure are numerous and generalizing dosimetric data for epidemiological purposes is currently unrealistic.

Anatomical exposure is strongly affected by environmental factors (altitude, sun elevation, total ozone column, meteorological conditions and albedo) as well as behavioural and host factors such as posture, orientation to the sun, skin complexion, clothing and other sun protective behaviours [13-15]. For a given individual, the anatomical distribution of UV exposure is highly heterogeneous, poorly correlated with ground irradiance, and depends on the time of exposure and orientation to the sun [16]. Exposure of different body sites for a given individual may typically range between 13 and 76% of the exposure to the vertex of the head [17].

In order to facilitate comparisons between measurements performed in different conditions (e.g. location, time), and thus generalize exposure data, the Exposure Ratio (ER) is a frequently used measure. Exposure ratio (also termed percent ambient exposure) is the ratio between the dose received by a specific body site and the corresponding dose received on a flat horizontal surface at ground level (integrating ambient irradiance over the same time period) [18]. The use of ER is convenient because it mostly depends on behavioural factors. In a recent review of ER for outdoors workers [19], the ranges of average values reported were 8-66% (arms and wrist), 11-85% (vertex of the head) and 11-70 % (shoulder). Furthermore, for some body sites (e.g. neck), ER beyond 100% have been measured for outdoor workers [20-22]. The high variability observed for the same body site reflects the importance of individual exposure conditions such as partial shading, period of the day and body posture. The importance of body posture can be illustrated by results obtained using a sitting and standing manikin, where ER ranges for the legs were of 0-75% and 14-39%, respectively [15].

Assuming that the influence of environmental factors on ER is minor, it can be used to assess exposure doses in numerous geographical locations. This approach is interesting because global UV erythemal irradiance (referred to hereafter as ambient irradiance) data is more readily and frequently available than anatomical exposure data. Average ambient irradiance can easily be measured in the field using stationary UV detectors and is also routinely measured at some meteorological stations.

The potential use of ER and ambient irradiance to expand the set of exposure data available opens interesting perspective in terms of exposure science research and epidemiology. Two current issues are (1) the limited number of measurements (typically between 10 and 100) and measurement periods (e.g. daily doses) on which ER have been established so far, and (2) the limited evidence available on the possible influence of environmental factors on ER. In this respect, the Solar Zenith Angle (SZA) has been shown to strongly influence the ER [23].

In this study, the use of ER as a generic tool to predict exposure levels in various exposure conditions is investigated. A recently developed 3D numeric model (SimUVEx) [24] was used to compute daily doses and ER for various body sites and body postures for the whole year 2012. Results were analyzed in order to (1) identify individual and environmental factors influencing ER, (2) construct a model to predict ER and, (3) assess the model performance and limits.

Material and methodS

Ground irradiance data

Ambient UV erythemal irradiance data measured at the MeteoSwiss Payerne station (46.815°N, 6.944°E, altitude 491m) were used. The Payerne facility is part of the Baseline Surface Radiation Network of the World Meteorological Organization, World Climate Research Program [25]. Ambient direct, diffuse, and reflected UV irradiance are measured concomitantly every minute at this facility using erythemally-weighted broadband UV radiometers (biometer 501A by Solar Light). These broadband radiometers undergo strict quality assurance procedures including regular calibrations traceable to the European Ultraviolet Calibration Center [26]. The calibration technique accounts for differences between the spectral response of the filter and the theoretical erythemal action spectrum [27, 28]. The overall uncertainty of the measurement is estimated at 10%.

Irradiance data collected for the entire year 2012 were used in this study (527 040 measurements, 1 measurement per minute). Data were checked for missing or aberrant values (e.g. maintenance of the measuring device). 5 061 (0.9%), 7 447 (1.4%) and 135 (<0.1%) missing or aberrant values were found for direct, diffuse and reflected measurements, respectively. Ground global irradiance was used to recalculate the missing/aberrant value when only one radiation component was missing. When several radiation components were missing, the diffuse/direct or diffuse/reflected ratios obtained from the closest day of similar meteorological conditions were used to reconstruct the data. Data were analysed using Stata/IC 12.1 (StataCorp LP, Texas, USA). Ground irradiance data for 2012 is available as supplementary material (see supplementary material Figure S1)

Modelling

Anatomical exposures were estimated through numeric simulation using the SimUVEx (Simulating UV Exposure, v1.0) model. The principles and a validation of the SimUVEx model in field conditions have been detailed previously [24]. Briefly, SimUVEx predicts the dose and anatomical distribution of UV exposure received on the basis of ground irradiation and morphological data. 3D computer graphics techniques are used to compute the interaction between a virtual manikin, depicted as a triangle mesh surface constituted of 4 000 meshes, and the incoming solar radiation. Five input parameters are required to model the ambient radiation: direct, diffuse and ground reflected irradiance (W/m^2), and sun position (defined by its azimuth and zenith angles). Direct, diffuse and reflected components are computed separately for each body site. The amount of solar UV energy received by each triangle is calculated, taking into account the three radiation components and shading from other body parts.

Implementation

Daily exposures doses were computed for the entire year 2012 (366 days). The exposure scenario considered an adult male, performing an outdoor activity between 8 am and 5 pm without shading and protective clothing. Although arbitrary and not realistic for several anatomical sites, this hypothesis allows comparison between simulation results at different time periods of the year. To account for the dynamic body orientation (due to walking or turning), the manikin was rotated between each simulation step. We used a simulation step of 1 minute and a step rotation of 24° corresponding to four full rotations per hour. Five body postures were considered: seated, kneeling, standing bowing, standing erect arms down, and standing erect arms up (see supplementary material, Figure S2). Overall, 1830 (366 days x 5 postures) simulation runs were conducted.

Exposures ratios ER [%] were computed using the simulated daily anatomical doses [J/m2] and the measured time-integrated UV erythemal global irradiance obtained from MeteoSwiss (diffuse + direct irradiance) [J/m2] during the same time period. Results were analyzed for seasonal trends as well as body posture and body site factors. ER was estimated by a multivariable fractional polynomial regression model, applying a backward selection algorithm (in-built Stata function “mfp”).

Results

Daily ER

Daily ER computed over the year 2012 are shown in Figure 1. The influence of body site and body posture on ER in identical environmental conditions is highlighted in Figures 1a and 1b, respectively. Average ER ranges from 89% for the top of shoulders, an unshaded, horizontally-oriented surface to 43% for the face, a vertically-oriented surface. An average ER of 65% was found for the back of the neck, which orientation is intermediate and which is partially shaded from the head. ER for the face varies with body posture, ranging from 50% for a standing posture to 20% for a bowing posture. Overall, both body site and body posture strongly influence the ER.

Figure 1 about here

Interestingly, ER varies over the year, indicating that environmental factors plays a significant, although less important, role than individual factors. Three patterns of variations can be identified: (1) extreme values for some winter days, which can be attributed to snowy episodes, (2) daily variability brought by the weather changes (cloudiness), which affects the diffuse to direct irradiance ratio, and (3) an inverse bell-shaped decrease during the summer period, which is inversely related to the SZA (the higher the SZA, the lower vertically-oriented body parts (e.g. the face) will receive direct sun irradiance).

Modelling ER

The regression model used simulations results for three body postures: kneeling, standing bowing, and standing erect arms down. Eight body sites were considered in the model: face, skull, forearm (external), upper arm (external), back of the neck, top of shoulders, upper back and belly (see supplementary material, Figure S3). The first seven were chosen for their relevance as they are often left uncovered and have various orientations. The belly was added as a contrast, in order to include a less exposed body site into the model. Days with snow-covered ground were not considered.

Several parameters related to direct or diffuse exposure and possible shading from other body parts were investigated in the polynomial regression model: surface [cm^2], zenith angle [°], and vertical angle [°] of the body site, shading (scoring), curvature (scoring), cos SZA [-], fraction of sky visible from the body site [%]. Two input variables were sufficient to explain ER: the cosine of the maximal daily SZA and the fraction of sky visible from the body site. The resulting regression model is given in equation 1.

Equation 1: regression model predicting exposure ratio for various body sites and body postures

$$ER = -3.396 * lnVis_{cent} + 10.714 * Vis_{cent} - 9.199 * cosSZA^3{}_{cent} + 56.991$$

Where:

ER: Exposure ratio [%]

Vis: Visible part of the sky from the body site surface [%]

cosSZA: cosine of the maximal solar zenith angle (daily maximal) [-]

x_{cent}: refers to the centred value of variable x, with:

$$lnVis_{cent} = ln(Vis/10) - 1.758$$

$$Vis_{cent} = Vis/10 - 5.800$$

$$cosSZA^3{}_{cent} = cosSZA^3 - 0.315$$

The *Vis* parameter is largely predominant in the regression model. This parameter affects the exposure to direct and diffuse radiation by taking into account shading from other body parts and the body orientation. A *Vis* value close to 100% means that the body part is oriented upward, mostly horizontal and unshaded, and will thus be highly exposed to both direct and diffuse radiation. Estimating its value requires some practice and may be difficult for an inexperienced user. Conveniently, this parameter is computed in the SimUVEx model and is available for a large number of body postures and body sites. For each vertex of the 3D manikin, the surface of the half-sphere, representing the surrounding sky visible from the vertex is calculated [24]. Typical *Vis* values are provided as supplementary material (see supplementary material, Table S1).

Figure 2 about here

Figure 3 about here

The regression results obtained for three body postures show that the fitted curve adequately predicts the average ER value and follows the inverse bell shaped pattern of the computed value (Figure 2). Results were similar for the other body sites (results not shown).

An overview of the regression results obtained for the 8 body sites and 3 body postures considered in the model fitting (n=8515) is shown in Figure 3a. Despite the daily variability, the agreement between the predicted and computed ER was high (R^2=0.988). The model performance was tested with independent data (data not used to fit the model) using two additional body postures: seated and standing erect arms up (n=5672). Results are illustrated in Figure 3b. Although slightly decreased (R^2=0.972), the overall agreement remained high. Similar results were found when testing the model for additional body parts (results not shown).

Predicting exposure dose with modelled ER

Predicted exposure doses were computed using the ER model and the available ground irradiance data. The predicted doses were then compared to the doses computed with the SimUVEx model. The relative error observed between the simulation and the ER model approaches for face exposure is illustrated in Figure 4. Unsurprisingly, the variability during the summer season led to a substantial relative error in the daily doses estimates (between +20% and -10%). Before mid-spring and after mid-autumn, the relative error is markedly decreased, ranging between +10% and -5%.

The performance of the model to predict short-time ER is limited by the daily weather variability. To assess chronic UV exposure doses, one needs to predict accurately the annual dose or the seasonal dose (e.g. for a seasonal worker) related to a specific outdoor activity. Relative errors between the predicted and the computed UV dose for selected body sites and different time periods are summarized in Table 1. The average relative error for the annual dose prediction was 2.4% (-0.03% to 5.4 %). Relative errors for seasonal doses predictions were of the same order of magnitude. Average relative errors of 1.7% (-0.7% to 2.7%), 2.9% (-2.1% to 6.1%), 1.6% (0.3% to 4.7%) and 2.5% (-0.09% to 7.7%) were found in spring, summer, autumn and winter, respectively.

Figure 4 about here

Table 1 about here

Influence of snow cover

As ER is computed considering down-welling irradiance (diffuse + direct) but not upwelling (reflected) irradiance, its use is inadequate during snow-covered ground episodes. Snow-covered days (ground reflection > 5% of the total irradiance, n=28) were thus removed from the regression and assessment process. To quantify the bias brought by this simplification, the ER model was applied to datasets including and excluding snowy days. As shown in Table 2, although the inclusion of snowy days slightly increased the average relative error from 2.4% (-0.03% to 5.4 %) to 2.7% (-2.3% to 5.3%), the overall performance of the prediction remained unchanged.

Table 2 about here

Discussion

The combined use of ER and ground irradiance data to predict individual exposure has been initiated previously [29]. This approach is here further developed and generalized, taking into account ER variations due to both environmental and postural factors. The regression model developed in this study allows predicting ER and relies only on a generic postural and anatomical parameter (the percentage of the sky visible from a body site surface in a given body posture) and an environmental parameter (the maximal solar zenith angle). Cumulative (seasonal or annual) exposures to solar UV of anatomical sites can be calculated using predicted ER and ground UV irradiance without requiring time-consuming and costly individual exposure measurements.

Accuracy of the model

The regression model predicted chronic exposures (seasonal, annual) fairly accurately. It should be pointed out that the error inherent to the regression model was small (on average, 2.4% in annual UV dose) comparatively to other approaches. A symmetric mean absolute percentage error (sMAPE) of 13% was found between the field measurements and the SimUVEx model [24], while the standard deviation for spore film dosimeters ranges between 5 and 20% [30, 31] and uncertainties of 7 to 10% were reported for. polysulphone and polyphenylene oxide dosimeters [32, 33].

The daily variability evidenced in ER is a functional limit of the model. Variability is greater in summer when the difference in ER between cloudy and clear-sky conditions is higher (e.g. daily relative errors up to 20%). Daily weather changes (cloudiness) affect the diffuse to direct irradiance ratio and limit the performance of the model to predict exposure dose over short time periods. This variability has however little impact on dose estimates based on longer time periods, such as annual or seasonal doses predictions. Inclusion of a "cloudiness" parameter in the model could, in the future, expand its capability to predict accurately acute exposures situations. In addition, the inclusion of such a parameter may account for cases where the performance of the model could be changed, especially when the cloud cover situation is markedly different than that of Switzerland. For example in regions with little cloudiness in summer (e.g., Mediterranean region, North Africa), Figure 1 will most likely be populated with points at the bottom of the inverse bell-shaped curved described at the beginning of the results section, and this could result in a different fit.

The model is also inadequate to predict exposure in snow covered environments. In such environment, UV reflection is substantial as snow reflects up to 80% of the incoming radiation [34, 35]. The use of ER is inappropriate as it refers to ambient measurements of down-welling radiation which largely neglects the albedo component. The regression model should therefore not be applied to predict exposure near water or other highly reflective surfaces. Interestingly, the influence of snowy episodes on otherwise uncovered grounds bears only a negligible influence on the yearly doses estimates. This can be understood by considering that snowy episodes at Payerne are restricted to the winter season when the ambient UV irradiance is low.

Consistency between the model and field-based ER

The predicted ER were consistent with previous field-based reports, with the highest values (80-100%) for upper horizontally-oriented body parts and average values (20-50%) for vertically-oriented body parts (e.g. face). Quantitative comparisons are however difficult because the range of ER values reported in the literature is extremely wide [19], while the range of predicted ER values is noticeably narrower.

It should be kept in mind that the model predicts ER assuming an unprotected skin, with no shading and a continuous exposure. In real-life situations, outdoor workers (gardeners, building workers, farmers, golfers) may be exposed intermittently to UV (e.g. performing an indoor activity) and be shaded or partially shaded from surrounding elements (e.g. trees). This can be illustrated using specific examples. Measured ER of 36-87% for back and 19-60% for arms were reported in vineyard workers [19], an occupation highly exposed (repetitive task, with little or no shade). According to equation 1 and depending on the body posture and time of year, our modelled ER falls within a range of 30-87% for upper back and 44-64% for forearm, which concurs well with

Siani's observations. ER of 8% (male) and 15% (female) for forehead were measured in full time farmers, an occupation involving tasks in shaded areas (e.g. driving a tractor, activities in stables, barns, etc.) [36]. The modelled ER falls within a range of 15-55% for the face, which overestimates exposure of farmers. If relevant, ER prediction should therefore be weighted taking into account the time spent in the shade or the use of skin protection such as clothing.

Availability of irradiance data

Information on ground UV ambient irradiance can be obtained from several sources. Ground surface measurements using broadband radiometers provide the most precise information locally. However such data are relatively scarce and limited in time. At the European level, 12 ground stations monitoring UV irradiance throughout Europe were selected and used as part of the COST Action 726 "Long term changes and climatology of UV radiation over Europe" (http://www.cost726.org/). The European UV database EDUCE hosted by the Finnish Meteorological Institute hosts spectral UV data submitted from about 30 sites (http://ozone2.fmi.fi/uvdb/). In the U.S., the Department of Agriculture operates a network that included up to 20 stations [37]. In other parts of the world, UV ground monitoring appears scarcer.

Two sources provide spatially and temporally extended information on ground UV radiation levels in Europe: a) a European dataset of reconstructed UV irradiance resulting from the effort of COST Action 726 [38]; and b) satellite datasets, which are global like the Tropospheric Emission Monitoring Internet Service (TEMIS) that uses observations from nadir-viewing satellite instruments such as GOME, SCIAMACHY [39] or the Solar radiation Data (SoDa) and Eurosun databases that use surface solar irradiance derived from the Meteosat satellite's images.

Perspectives

The developed ER model will find direct applications in epidemiological studies which have been, up to now, limited in the definition of exposure. The main limitation in epidemiological studies was the impossibility to account for clothing and anatomical site when estimating the actual erythemal UV dose received. The ER model will be easily applicable in studies on workers or beachgoers as requiring only the few following information that can be made available in questionnaires: place of work or of exposure, posture, clothes, days and hours of exposure. Linking this information with erythemal UV resources, such as satellite data, with zenith angle data, and with the ER model, researchers will be able to estimate site-specific erythemal doses received at an individual level. Such information will be particularly important when investigating the best prevention strategies for overexposed or highly vulnerable populations.

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REFERENCES

[1] Lucas R. Solar Ultraviolet Radiation: Assessing the environmental burden of disease at national and local levels. Geneva: WHO, World Health Organization; 2010.

[2] Sklar LR, Almutawa F, Lim HW, Hamzavi I. Effects of ultraviolet radiation, visible light, and infrared radiation on erythema and pigmentation: a review. Photochemical & Photobiological Sciences. 2013;12(1):54-64.

[3] El Ghissassi F, Baan R, Straif K, Grosse Y, Secretan B, Bouvard V, et al. A review of human carcinogens. Part D: radiation. The Lancet Oncology. 2009;10(8):751-2.

[4] Lucas RM, McMichael AJ, Armstrong BK, Smith WT. Estimating the global disease burden due to ultraviolet radiation exposure. International Journal of Epidemiology. 2008 June 1, 2008;37(3):654-67.

[5] Armstrong BK, Kricker A. The epidemiology of UV induced skin cancer. J Photochem Photobiol B. 2001;63(1-3):8-18.

[6] Levi F, Te VC, Randimbison L, Erler G, La Vecchia C. Trends in skin cancer incidence in Vaud: an update, 1976-1998. European Journal of Cancer Prevention. 2001;10:371-3.

[7] Schmitt J, Seidler A, Diepgen TL, Bauer A. Occupational ultraviolet light exposure increases the risk for the development of cutaneous squamous cell carcinoma: a systematic review and meta-analysis. British Journal of Dermatology. 2011;164(2):291-307.

[8] Elwood JM, Jopson J. Melanoma and sun exposure: an overview of published studies. Int J Cancer. 1997;73:198-203.

[9] Kricker A, Armstrong BK, English DR. Does intermittent sun exposure cause basal cell carcinoma? a case-control study in Western Australia. International Journal of Cancer. 1995;60(4):489-94.

[10] Bauer A, Diepgen TL, Schmitt J. Is occupational solar ultraviolet irradiation a relevant risk factor for basal cell carcinoma? A systematic review and meta-analysis of the epidemiological literature. British Journal of Dermatology. 2011;165(3):612-25.

[11] Erdmann F, Lortet-Tieulent J, Schüz J, Zeeb H, Greinert R, Breitbart EW, et al. International trends in the incidence of malignant melanoma 1953–2008—are recent generations at higher or lower risk? International Journal of Cancer. 2013;132(2):385-400.

[12] Bulliard JL, R.G. P, Levi F. Epidemiology of epithelial skin cancers. Rev Med Suisse. 2009;5:882-8.

[13] Hill D, White V, Marks R, Theobald T, Borland R, Roy C. Melanoma prevention: behavioral and nonbehavioral factors in sunburn among an Australian urban population. Preventive Medicine. 1992;21(5):654-69.

[14] Autier P, Boniol M, Doré J-F. Sunscreen use and increased duration of intentional sun exposure: Still a burning issue. International Journal of Cancer. 2007;121(1):1-5.

[15] Parisi AV, Kimlin MG, Lester R, Turnbull D. Lower body anatomical distribution of solar ultraviolet radiation on the human form in standing and sitting postures. J Photochem Photobiol B. 2003;69(1):1-6.

[16] Parisi AV, Kimlin MG, Wong JC, Fleming RA. The effects of body size and orientation on ultraviolet radiation exposure. Photodermatol Photoimmunol Photomed. 1996;12:66-72.

[17] Wright C, Diab R, Martincigh B. Anatomical distribution of ultraviolet solar radiation. South Afr J Sci. 2004;100(9-10):498-500.

[18] Rosenthal FSW, Sheila K.; Munoz, Beatriz; Emmett, Edward A.; Strickland, Paul T.; Taylor, Hugh R. Ocular and Facial Skin Exposure to Ultraviolet Radiation in Sunlight: A Personal Exposure Model With Application to a Worker Population. Health Physics. 1991;61(1):10.

[19] Siani AM, Casale GR, Sisto R, Colosimo A, Lang CA, Kimlin MG. Occupational Exposures to Solar Ultraviolet Radiation of Vineyard Workers in Tuscany (Italy). Photochemistry and Photobiology. 2011;87(4):925-34.

[20] Gies P, Wright J. Measured solar ultraviolet radiation exposures of outdoor workers in Queensland in the building and construction industry. Photochem Photobiol. 2003;78(4):342-8.

[21] Milon A, Sottas PE, Bulliard JL, Vernez D. Effective exposure to solar UV in building workers: influence of local and individual factors. Journal of Exposure Science and Environmental Epidemiology. 2007;17:58-68.

[22] Siani AM, Casale GR, Diemoz H, Agnesod G, Kimlin MG, Lang CA, et al. Personal UV exposure in high albedo alpine sites. Atmos Chem Phys. 2008;8:3749-60.

[23] Downs N, Parisi A. Measurements of the anatomical distribution of erythemal ultraviolet: a study comparing exposure distribution to the site incidence of solar keratoses, basal cell carcinoma and squamous cell carcinoma. Photochemical & Photobiological Sciences. 2009;8(8):1195-201.

[24] Vernez D, Milon A, Francioli L, Bulliard JL, Vuilleumier L, Moccozet L. A Numeric Model to Simulate Solar Individual Ultraviolet Exposure. Photochemistry and Photobiology. 2011;87:721-8.

[25] Ohmura A, Dutton EG, Forgan B, co-authors. Baseline Surface Radiation Network (BSRN): New precision radiometry for climate research. BullAmMeteorolSoc. 1998;79(10):2115-36.

[26] Hülsen G, Gröbner J. Characterization and calibration of ultraviolet broadband radiometers measuring erythemally weighted irradiance. ApplOpt. 2007;46:5877-86.

[27] Erythema Reference Action Spectrum and Standard Erythema Dose. *CIECommission Internationale de l'Eclairage* Vienna, Austria: CIE Central Bureau 1998.

[28] Webb AR, Slaper H, Koepke P, Schmalwieser AW. Know Your Standard: Clarifying the CIE Erythema Action Spectrum. Photochemistry and Photobiology. 2011;87(2):483-6.

[29] Wright C, G. C, Ncongwane K. Ambient solar UV radiation and seasonal trends in potential sunburn risk among schoolchildren in South Africa. South African Journal of Child Health. 2011;5(2):35-8.

[30] Moehrle M, Korn M, Garbe C. Bacillus subtilis spore film dosimeters in personal dosimetry for occupational solar ultraviolet exposure. Int Arch Occup Environ Health. 2000;73:575-80.

[31] Furusawa Y, Quintern LE, Holtschmidt H, Koepke P, Saito M. Determination of erythema-effective solar radiation in Japan and Germany with a spore monolayer film optimised for the detection of UVB and UVA - results of a field campaign. Appl Microbiol Biotechnol. 1998;50:597-603.

[32] Casale GR, Siani AM, Diémoz H, Kimlin MG, Colosimo A. Applicability of the Polysulphone Horizontal Calibration to Differently Inclined Dosimeters. Photochemistry and Photobiology. 2012;88(1):207-14.

[33] Schouten PW, Parisi AV, Turnbull DJ. Usage of the Polyphenylene Oxide Dosimeter to Measure Annual Solar Erythemal Exposures. Photochemistry and Photobiology. 2010;86(3):706-10.

[34] Renaud A, Staehelin J, Frohlich C, Philipona R, Heimo A. Influence of snow and clouds on erythemal UV radiation : Analysis of Swiss measurements and comparison with models. Washington, DC, ETATS-UNIS: American Geophysical Union 2000.

[35] Philipona R, Schilling A, Schmucki D. Albedo-enhanced Maximum UV Irradiance—Measured on Surfaces Oriented Normal to the Sun¶. Photochemistry and Photobiology. 2001;73(4):366-9.

[36] Schmalwieser AW, Cabaj A, Schauberger G, Rohn H, Maier B, Maier H. Facial Solar UV Exposure of Austrian Farmers During Occupation. Photochemistry and Photobiology. 2010;86(6):1404-13.

[37] Bigelow DS, Slusser JR, Beaubien AF, Gibson JH. The USDA Ultraviolet Radiation Monitoring Program. Bulletin of the American Meteorological Society. 1998 1998/04/01;79(4):601-15.

[38] Koepke P, Backer HD, Bais A, Curylo A, Eerme K, Feister U, et al. Modelling solar UV radiation in the past: comparison of algorithms and input

data. In: Slusser JR, Schäfer K, Comerón A, eds. *Remote Sensing of Clouds and the Atmosphere XI* 2006.

[39] van Weele M, van der A R, J., v. Geffen J, Roebeling R. Space-based surface UV monitoring for Europe using SCIAMACHY and MSG. SPIE 5979, Remote Sensing of Clouds and the Atmosphere X; 2005; Bruges, Belgium: SPIE; 2005. p. 59791K-K-8.

Supplementary information is available at www.nature.com/jes

Figure legends

Figure 1. Computed daily ER [%] over the year 2012 for (a) the same body posture (standing arms down) and 3 body sites; (b) for the face in 3 body postures

Figure 2. Computed and fitted daily ER [%] over the year 2012 for the face in 3 body postures

Figure 3. Computed and fitted daily ER [%] for (a) data used to fit the model (3 body postures) (b) independent data (2 additional body postures).

Figure 4. Relative error [%], between the computed daily UV dose and the daily UV dose predicted by the ER model (Face, standing erect arms down)

Tables

Body site	Relative error of the predicted dose average [%] (min – max)				
	yearly dose	Spring (March 1st – May 31st)	Summer (June 1st – August 31st)	Autumn (Sept. 1st – Nov. 30th)	Winter (Dec. 1st – Feb. 28th)
face	2.20 (1.81 - 3.04)	1.48 (0.44 - 2.21)	4.25 (3.09 - 5.22)	1.62 (0.48 - 4.71)	1.10 (0.49 - 2.37)
skull	2.01 (1.78 - 2.33)	1.93 (1.57 - 2.32)	2.60 (2.26 - 3.10)	1.20 (0.89 - 1.53)	2.38 (1.62 - 3.29)
forearm (external)	1.29 (-0.03 - 2.35)	1.10 (-0.65 - 2.37)	1.16 (-2.08 - 5.32)	1.07 (0.46 - 1.70)	2.02 (0.60 - 3.09)
upper arm (external)	2.11 (1.51 - 2.62)	2.14 (1.53 - 2.87)	3.34 (0.44 - 6.06)	1.06 (0.27 - 1.61)	1.76 (0.19 - 2.81)
back of the neck	2.56 (2.20 - 2.87)	2.39 (1.74 - 2.74)	2.56 (0.21 - 5.51)	1.78 (0.96 - 2.86)	3.69 (1.48 - 6.50)
top of shoulders	4.46 (1.43 -	1.43 (0.98 -	-0.28 (-1.71 -	3.53 (1.85 -	5.55 (1.35 -

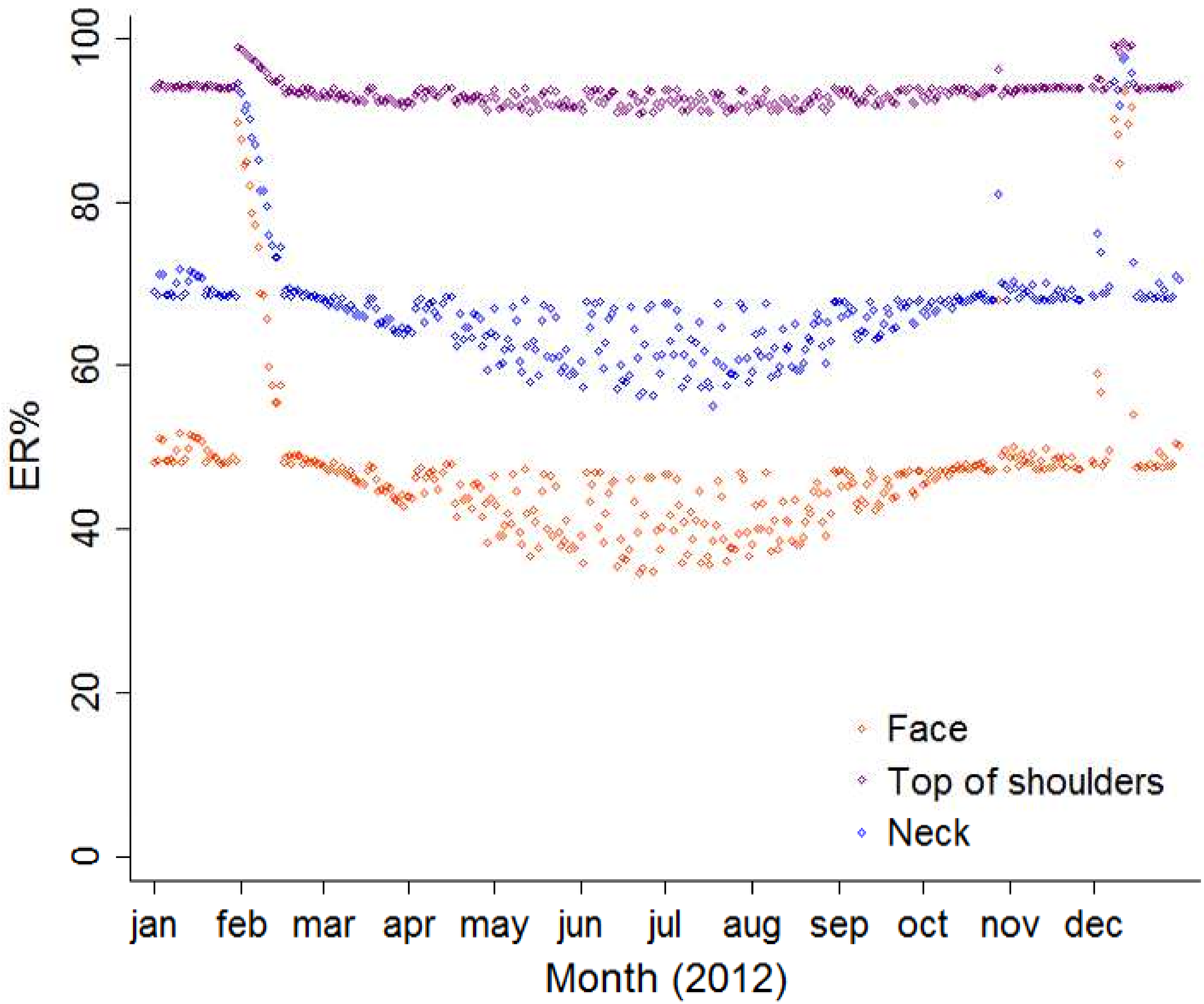
	5.31)	1.66)	2.90)	4.06)	7.69)
upper back	2.22 (1.93 - 2.52)	1.75 (1.49 - 1.96)	4.23 (-0.42 - 7.52)	0.92 (0.37 - 2.61)	1.25 (-0.09 - 4.43)
belly	2.24 (1.25 - 2.77)	1.35 (-3.62 - 2.80)	3.67 (-3.70 - 6.43)	2.01 (0.25 - 7.97)	2.11 (0.47 - 7.42)

Table 1. Relative error [%] between the computed daily UV dose and the daily UV dose predicted by the ER model for selected body sites and seasons

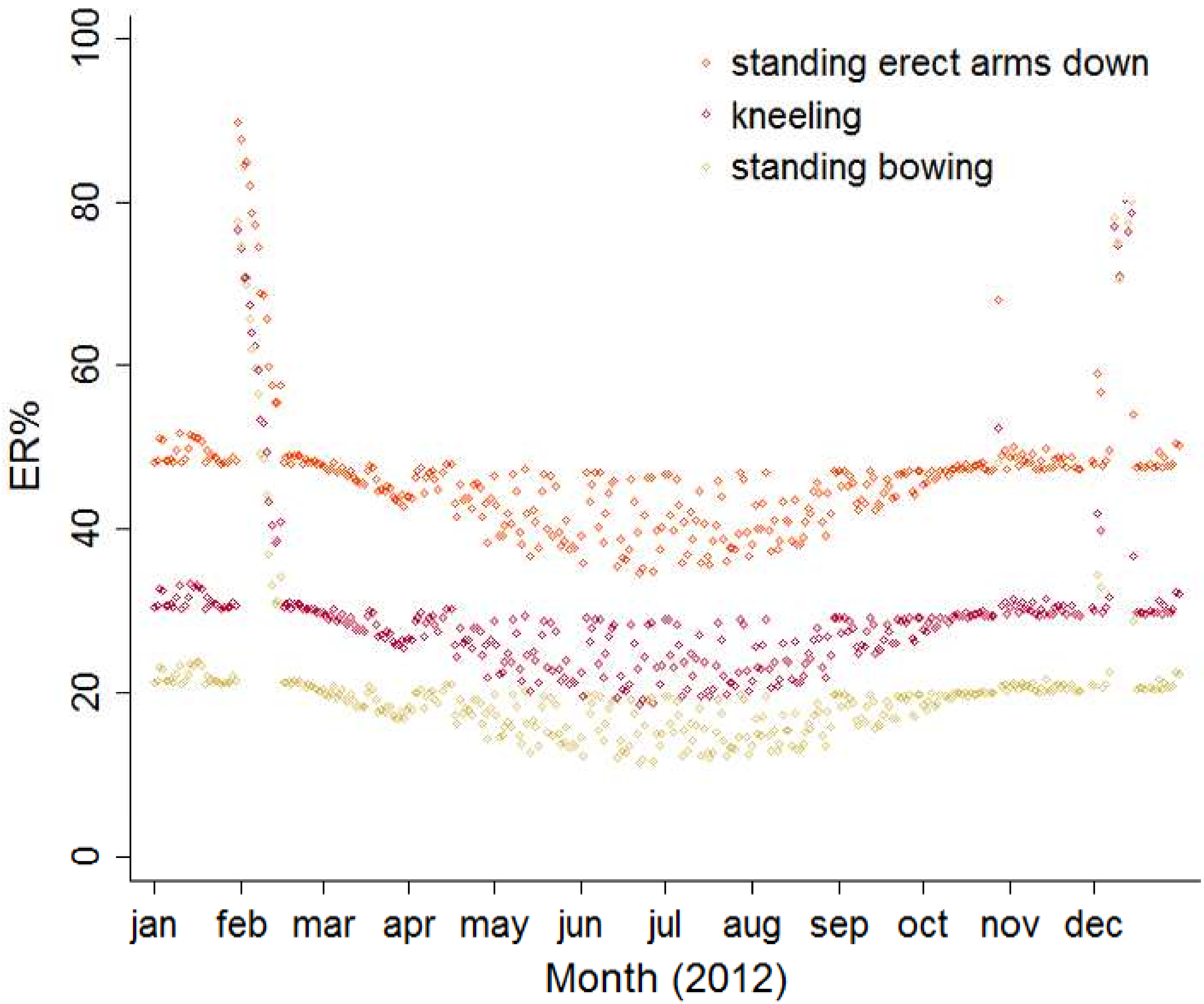
Body site	Relative error of the predicted dose average [%] (min – max)	
	yearly dose (excluding snow-covered days)	yearly dose (including snow-covered days)
face	2.20 (1.81 - 3.04)	1.19 (-0.08 - 2.54)
skull	2.01 (1.78 - 2.33)	3.14 (2.45 - 3.91)
forearm (external)	1.29 (-0.03 - 2.35)	2.10 (0.89 - 2.67)

upper arm (external)	2.11 (1.51 - 2.62)	2.87 (1.91 - 3.72)
back of the neck	2.56 (2.20 - 2.87)	4.19 (3.41 - 5.16)
top of shoulders	4.46 (1.43 - 5.31)	4.54 (1.83 - 5.31)
upper back	2.22 (1.93 - 2.52)	2.26 (0.96 - 4.79)
belly	2.24 (1.25 - 2.77)	1.67 (-2.27 - 3.40)

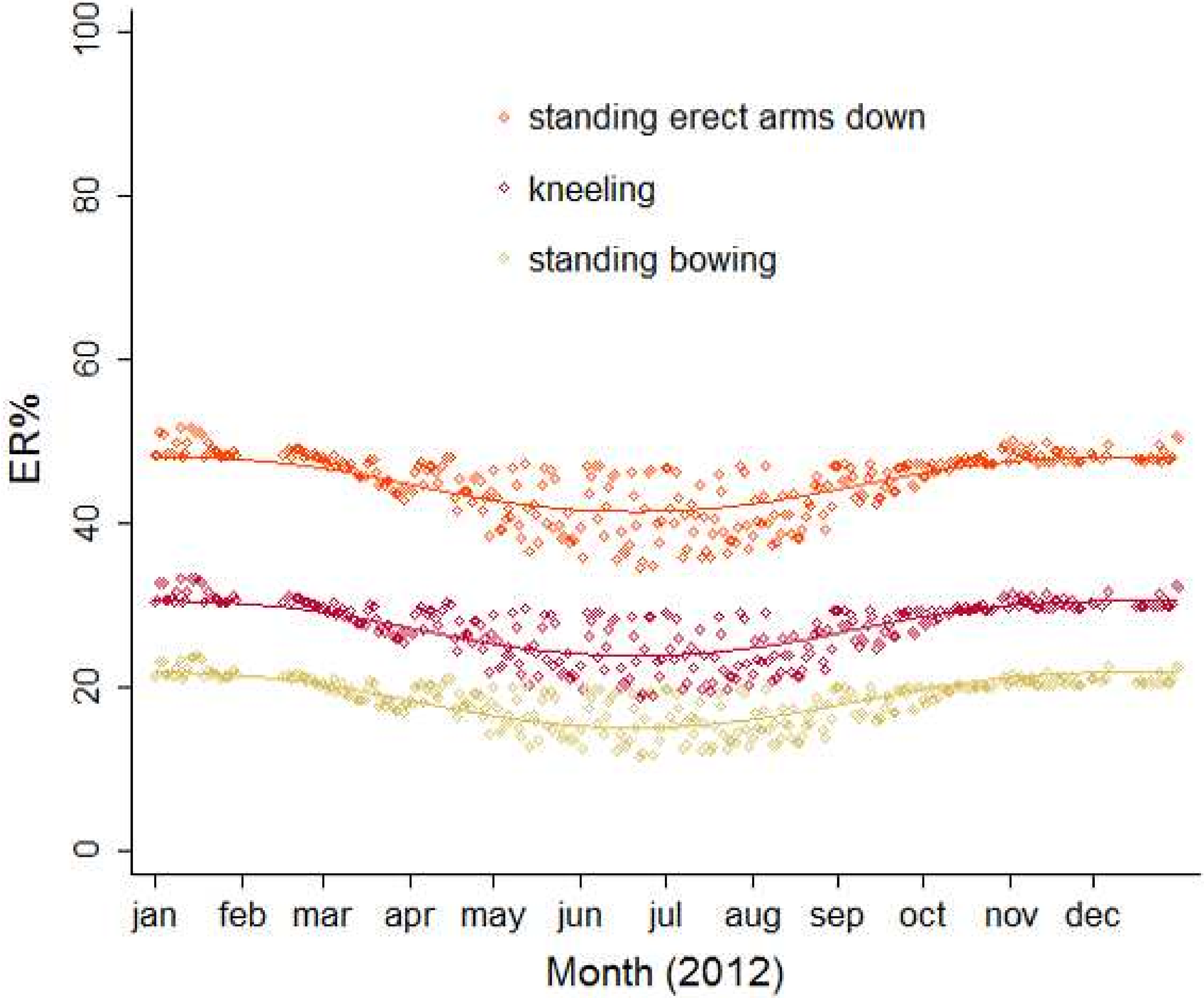
Table 2. Relative error [%] between the computed daily UV dose and the daily UV dose predicted by the ER model, including and excluding snow-covered days

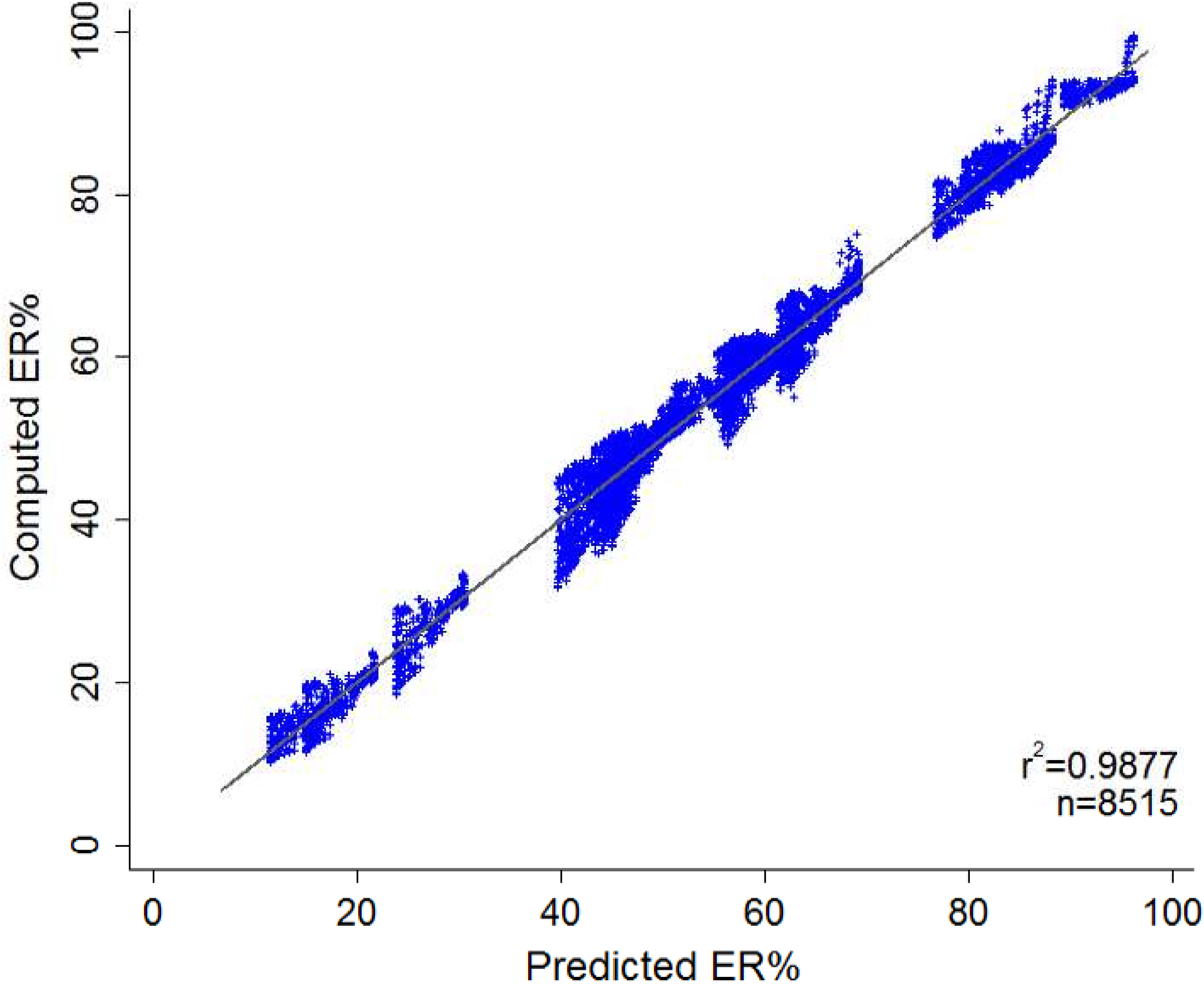


100
80
60
40
20
0
ER%
jan
feb
mar
apr
may
jun
jul
aug
sep
oct
nov
dec
Month (2012)
Face
Top of shoulders
Neck

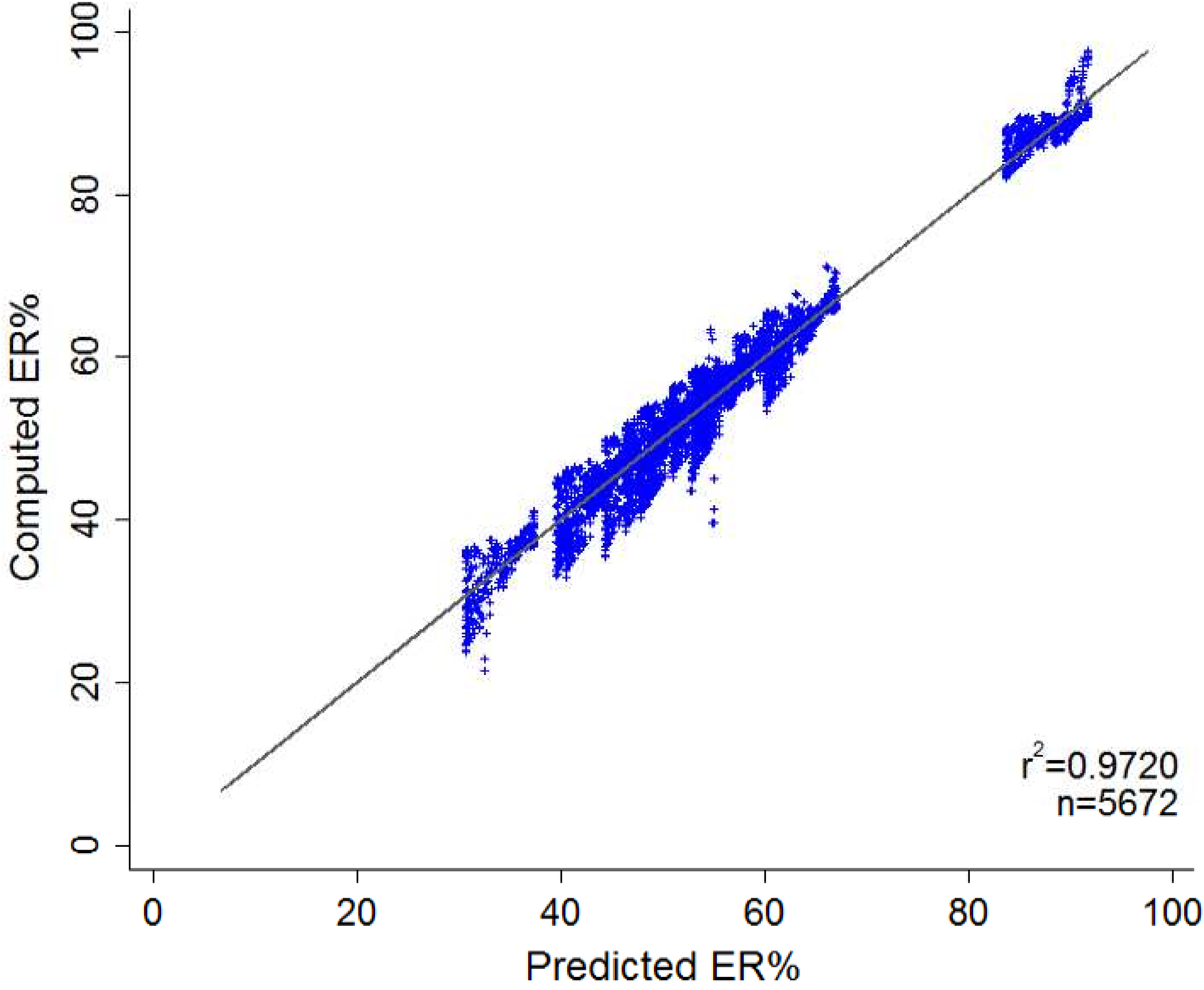


standing erect arms down
kneeling
standing bowing
ER%
100
80
60
40
20
0
jan
feb
mar
apr
may
jun
jul
aug
sep
oct
nov
dec
Month (2012)

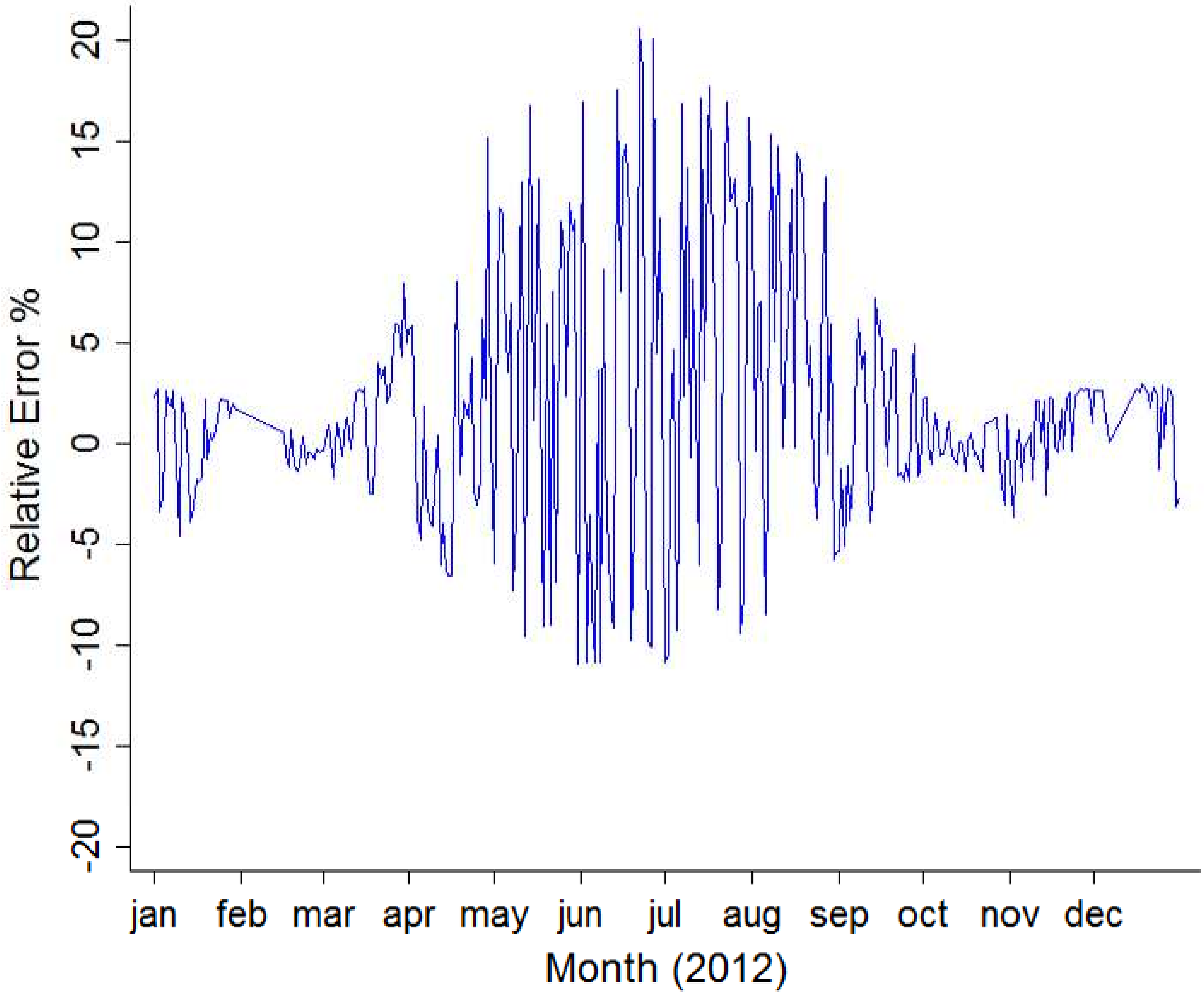

standing erect arms down
kneeling
standing bowing
ER%
0
20
40
60
80
100
jan
feb
mar
apr
may
jun
jul
aug
sep
oct
nov
dec
Month (2012)



Computed ER%
Predicted ER%
0
20
40
60
80
100
0
20
40
60
80
100
r^2=0.9877
n=8515



Computed ER%
Predicted ER%
0
20
40
60
80
100
0
20
40
60
80
100
r^2=0.9720
n=5672



Relative Error %
20
15
10
5
0
-5
-10
-15
-20
jan
feb
mar
apr
may
jun
jul
aug
sep
oct
nov
dec
Month (2012)