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CLIMATIC EVALUATION OF MODELS THAT PREDICT HOURLY DIRECT IRRADIANCE FROM HOURLY GLOBAL IRRADIANCE: PROSPECTS FOR PERFORMANCE IMPROVEMENTS

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Abstract—This paper presents a comprehensive evaluation of recent models designed to predict direct from global irradiance on a short time step basis. Three models are selected for the present evaluation. These were proposed by Erbs *et al.*, Skartveit and Olseth, and Maxwell. Model validation is performed against a large array of experimental data: A total of over 60,000 global and direct data points from 14 sites in Europe and the United States. Environments range from humid oceanic to desertic, including humid continental, high altitude, subtropical, and polluted. It is found that specific models are better adapted to certain climatic types than others. However, each model is found to have a "generic" insolation-dependent error pattern across all climates. This error pattern may be deterministically corrected and yield substantial performance improvement without additional input data.

1. INTRODUCTION

Short time step irradiance reaching the earth's surface is a useful and sometimes indispensable design component for solar energy/daylighting applications. For instance, the best anisotropic diffuse irradiance algorithm to compute energy on a tilted surface is of no use if the direct component impinging on that surface is not known with some precision.

It is likely that, in the foreseeable future, direct irradiance, as a climatological quantity, will become increasingly available in many locations thanks to the development of new low cost/low maintenance instrumentation[1] and to the gradual improvement of networks worldwide[2,3]. For the time being, however, the climatological direct irradiance data available in many cases (e.g.,[4,5]) are extrapolated from global horizontal irradiance measurements often extrapolated themselves from other meteorological parameters. In the United States, the SOLMET-derived[4] Typical Meteorological Year (TMY) data[6] which is considered as the highest quality climatological radiation data available for design purposes, consists entirely of modeled direct irradiance.

The global-to-direct conversion models that were used in the U.S. for SOLMET/TMY[7] data generation have been questioned by some[8,9] and recently led the Solar Energy Research Institute to the development of a new algorithm in their effort for improving the accuracy of the national data base[8,10]. Independently, the preparation of a daylight availability data base for New York State and of a national data base in Switzerland prompted the need for this evaluation. Having acquired, through several cooperative research efforts, high-quality global and direct irradiance data for a wide range of climatic environments, the authors are in a key position to make this comprehensive global-to-direct algorithm evaluation.

2. METHODOLOGY

2.1 *Selected algorithms*

Three algorithms are selected. They were formulated respectively by Erbs, Klein and Duffie[11], Skartveit and Olseth[12], and Maxwell[8]. They will be respectively referred to as EK&D, S&O, and Maxwell models from here on. Note that the two former models were developed to estimate hourly diffuse rather than hourly direct radiation.

The EK&D model was selected because it had been found to be the most accurate of such models by the International Energy Agency (IEA) after a comprehensive evaluation against 15 data sets from North America, Europe and Australia[13]. This model is comparable in essence to the well known Orgill & Hollands model[14], which was found to perform almost as accurately by the IEA.

The two other algorithms are posterior to the IEA evaluation. The S&O model has been found to outperform the EK&D model in some European locations[5] while the Maxwell model was found to perform well in the United States[8]. The EK&D and S&O models are primarily of a statistical nature and were derived from experimental data sets (other statistically derived models include those developed by Boes[15], Spencer[16], and Iqbal[17] they were not evaluated by the IEA). The Maxwell model is termed as "quasi-physical" as it combines a physical clear sky model with experimental fits for other conditions.

Input to all models consists of global irradiance and solar zenith angle, Z. However, Z is not an active variable in the EK&D model, but it is limited to the calculation of the clearness index, Kt.

Each algorithm is detailed below.

EK&D model. The normal incidence direct irradiance, I, is obtained from global irradiance, G, and the solar zenith angle, Z, through:

$$I = G\,(1 - \psi)/\cos Z, \qquad (1)$$

where ψ is a function of the clearness index, Kt (ratio of horizontal global to horizontal extraterrestrial irradiance), given below:

If $Kt \leqq 0.22$: $\psi = 1 - 0.09\,Kt$,
If $0.22 < Kt < 0.8$: $\psi = 0.9511 - 0.1604\,Kt + 4.388\,Kt^2 - 16.638\,Kt^3 + 12.336\,Kt^4$,
If $Kt \geqq 0.8$: $\psi = 0.165$,

S&O model.

$$I = G\,(1 - \Phi)/\cos z, \qquad (2)$$

where Φ is a function of Kt and the solar elevation angle h in degrees. This function is detailed below:

If $Kt < K_0$

$$\Phi = 1$$

where

$$K_0 = 0.2$$

If $K_0 \leqq Kt \leqq \alpha K_1$:

$$\Phi = 1 - (1 - d_1)(a\sqrt{K} + (1 - a)K^2)$$

where

$$\alpha = 1.09$$
$$K_1 = 0.87 - 0.56 \exp(-0.06\,h)$$
$$d_1 = 0.15 + 0.43 \exp(-0.06\,h)$$
$$a = 0.27$$
$$K = 0.5(1 + \sin[\pi(a'/b' - 0.5)])$$

where

$$a' = Kt - K_0$$
$$b' = K_1 - K_0$$

If $Kt > \alpha K_1$:

$$\Phi = 1 - (\alpha K_1(1 - \xi)/Kt)$$

where

$$\xi = 1 - (1 - d_1)(a\sqrt{K'} + (1 - a)K'^2)$$

where

$$K' = 0.5(1 + \sin[\pi(a''/b' - 0.5)]$$

where

$$a'' = \alpha K_1 - K_0.$$

Note that this model's authors indicate that some of the constants may have to be adjusted for conditions deviating from their validation domain. This task is not undertaken here.

Maxwell model.

$$I = I_0\,\{Knc - [A + B \exp(m\,C)]\} \qquad (3)$$

where Knc is a function of the air mass, m, given by:

$$Knc = 0.866 - 0.122\,m + 0.0121\,m^2 - 0.000653\,m^3 + 0.000014\,m^4,$$

and where A, B, and C are functions of the clearness index given below:

if $Kt \leqq 0.6$: $A = 0.512 - 1.560\,Kt + 2.286\,Kt^2 - 2.222\,Kt^3$
$B = 0.370 + 0.962\,Kt$
$C = -0.280 + 0.932\,Kt - 2.048\,Kt^2$

if $Kt > 0.6$: $A = -5.743 + 21.77\,Kt - 27.49\,Kt^2 + 11.56\,Kt^3$
$B = 41.40 - 118.5\,Kt + 66.05\,Kt^2 + 31.90\,Kt^3$
$C = -47.01 + 184.2\,Kt - 222.0\,Kt^2 + 73.81\,Kt^3$.

Note that the SERI report[8] describing this model contains a typographical error in eqn (3) for the term, Knc. This was discovered during the course of this work and accounted for in this analysis.

2.2 *Model evaluation methodology—Experimental data*

Two statistical quantities, model root mean square error (RMSE) and mean bias error (MBE) against actual direct irradiance measurements, constitute the main evaluation tools of this paper. Much attention is devoted to the observation of MBE and RMSE variations with insolation conditions and site climatic/environmental features. Insolation conditions are described here by Kt and Z, as these constitute the only two quantities available to the models. Model performance is also characterized in a more qualitative fashion through observation of trends in scatter plots.

Benchmark experimental data consist of 14 sets acquired through recent research and cooperation projects and covering a wide range of climatic environments. All data sets were prepared with class I instrumentation for both direct and global irradiance. Data are known, in each case, to have been recorded with care and subjected to stringent quality control. Each data set and corresponding environmental features are briefly described in Table 1.

Note that some of the U.S. data sets, obtained with mobile stations that were periodically relocated [23,24], only span a 6-month period. Although this may be too short for fully delineating a site's climatology, these solstice-to-solstice research data sets are believed to be long enough to assess the prevailing relationship between solar radiation components at a given site. In fact, results obtained with the six-month data sets are fully consistent with the longer sets.

Table 1. Description of experimental sites and data sets

Site	Climate/Environment Main Features	Data Set Span and Frequency
Geneva, Switzerland [19]	Temperate maritime, with central Europe continental influence. Persistent nebulosity enhanced by "blocking position at foot-hill of the Alps.	1 yr. hourly data
Cabauw, Netherlands [20]	Northern Europe temperate maritime	1 yr. hourly data
Trappes, France [21]	Temperate maritime with high incidence of intermediate skies	3 yr. hourly data
Carpentras, France [21]	Mediterranean	3 yr. hourly data
Albany, NY, USA [22,23]	Humid continental	3 yr. hourly data 2 yr. 15 min. data
New York, NY, USA [23]	Humid continental with maritime influence plus large City's anthropogenic environment	1 yr. 15 min. data
Farmingdale, NY, USA [23]	Same as above but without city's environment	1 yr. 15 min. data
Oswego, NY, USA [23]	Humid continental, Great Lakes basin	6 mo. 15 min. data
Glens Falls, NY, USA [23]	Humid continental, Adirondack Mountains	6 mo. 15 min. data
Phoenix, AZ, USA [24]	Arid, low elevation	6 mo. hourly data
Albuquerque, NM, USA [24]	Arid, High elevation (1800 m)	1 yr. hourly data
Los Angeles, CA, USA [24]	Arid and maritime influence plus high frequency of anthropogenic smog events	6 mo. hourly data
C. Canaveral, FL, USA [24]	Subtropical, low latitude, maritime	6 mo. hourly data

2.3 *Determination of possible modeling improvements*

The margin for possible model performance improvement is evaluated here by deriving a site-independent "correcting function" for each model from the entire pool of data, that is, a total of 60,000 points. Each correcting function is obtained by simply fitting the observed resultant bias pattern for all sites. The functions depend solely on Kt and Z, that is, the same input as the models themselves.

Models with and without correcting function are then compared. The resulting improvement is a conservative measure of the possibility for performance amelioration.

It is stressed that this paper's objective is not to deliver new improved models, but to provide, in a systematic fashion, prospects for global-to-direct conversion improvement. The rudimentary analytical fits that compose the correction functions, although they do improve model performance, are not to be considered as ultimate upgrades to already complex models. This is further discussed in the next section.

3. RESULTS

3.1 *Model evaluation*

Overall performance. Each model's overall RMSEs and MBEs for the 14 sites, sorted by clearness index and solar zenith angle are presented in Table 2. The Table also reports the number of validation data points and the mean beam irradiance in each $Kt-Z$ bin.

Table 2. Overall performance of selected algorithms as a function of insolation conditions and solar zenith angle

Zenith Angle Range	0.00–0.20	0.20–0.45	0.45–0.70	0.70–	ALL	0.00–0.20	0.20–0.45	0.45–0.70	0.70–	ALL
	Number of Occurences					Mean Direct (W/m2)				
0-35	1101	1329	2018	3170	7618	1	40	366	793	434
35-50	1862	2248	3547	3576	11233	2	39	426	807	399
50-65	3423	3810	6687	3043	16963	2	40	508	829	358
65-75	3795	4351	6070	983	15199	1	46	518	780	271
75-85	2515	3989	3124	42	9670	2	93	440	544	183
0-85	12696	15727	21446	10814	60683	2	55	474	805	326
Maxwell Model	MBE (W/m2)					RMSE (W/m2)				
0-35	1	1	-5	-22	-10	6	48	105	95	84
35-50	-2	7	20	17	13	32	47	103	98	84
50-65	-2	13	44	40	27	19	51	117	107	90
65-75	-1	18	52	69	30	10	61	122	134	91
75-85	-2	11	51	146	21	10	70	127	179	86
0-85	-1	12	38	17	20	17	59	117	104	88
S&O Model	MBE (W/m2)					RMSE (W/m2)				
0-35	-1	-1	14	-30	-9	5	47	105	96	85
35-50	-2	1	-6	-46	-17	32	47	101	107	87
50-65	-2	2	-33	-59	-24	19	49	115	120	92
65-75	-1	1	-37	-10	-16	10	55	117	156	89
75-85	-2	-8	6	315	-1	10	70	145	331	97
0-85	-2	-1	-20	-40	-15	17	56	118	115	90
EK&D Model	MBE (W/m2)					RMSE (W/m2)				
0-35	0	5	86	24	34	5	48	137	97	96
35-50	-1	7	53	3	19	32	48	115	96	88
50-65	0	3	-8	-16	5	19	48	111	106	86
65-75	1	-5	-65	42	-24	10	56	130	149	96
75-85	0	-45	-111	302	-53	10	92	167	338	114
0-85	0	-10	-20	8	-8	17	64	129	107	95

Overall, the Maxwell model performs best in RMSE terms, followed by the S&O and the EK&D models. Looking more in detail at the results, one notices that the Maxwell's edge comes from a better handling of clear conditions, whereas the S&O model is slightly ahead for intermediate sky conditions.

Close analysis of mean bias error reveals a distinct behavior for each model. The Maxwell tends to overestimate, particularly for intermediate conditions; however, it handles the clear sky extremes (high and low solar zenith angles) better than the others. The EK&D model features an interesting shift in error sign between high and low solar zenith angles. This is a direct consequence of the fact that this model, simpler than the two others, does not incorporate solar zenith angle as an active variable; it does, however, perform substantially better than the two others for mid-range solar zenith angles. The S&O model has a pronounced tendency to underestimate, increasingly with clearness; its performance for low direct beam events is good.

Another indirectly related point of interest in Table 2 is the fact that *Kt* exhibits a noticeable dependency with solar zenith angle (Note for instance the low number of high *Kt* events at high zenith angles and, correspondingly, the larger number of observations for lower *Kts*. Note also that this effect may be enhanced by quality control elimination of many high solar zenith angle data points). The use of another, zenith angle-independent, variable instead of *Kt* should be considered for better delineation of insolation conditions—note that the S&O model attempts to go in this direction by featuring zenith-dependent *Kt* boundaries, whereas the others do not.

Site dependency evaluation. Model RMSE as a function of location and insolation conditions have been plotted in Fig. 1 for 10 representative locations or groups of locations. Mean bias errors have been plotted in Fig. 2.

The observations made above, that is, better performance of the Maxwell model for high *Kt* conditions and small edge of S&O model for low *Kt* con-

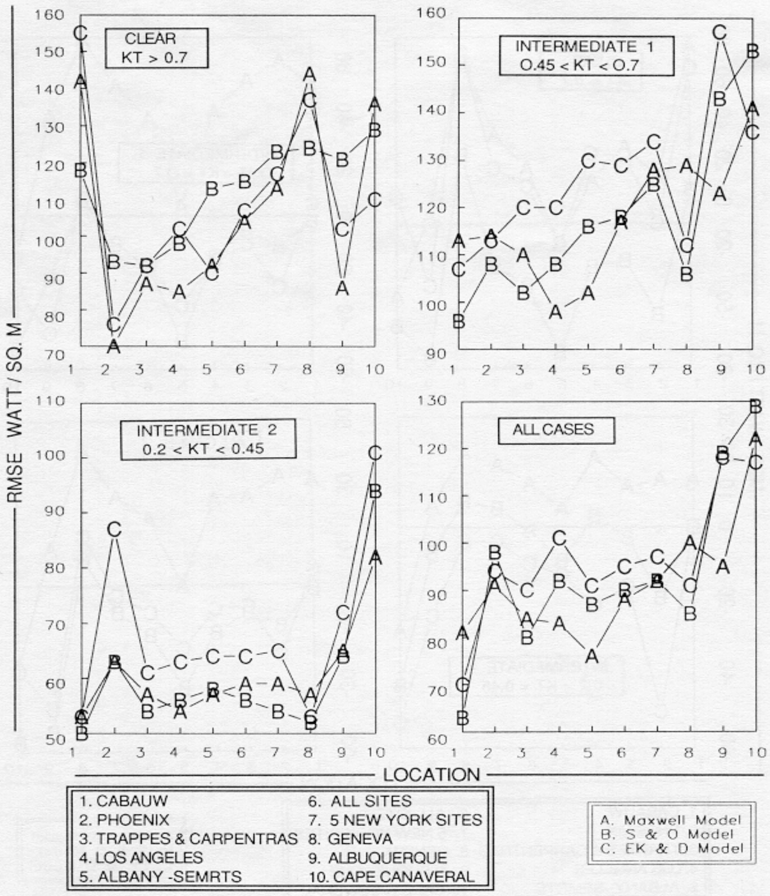

Fig. 1. Variations of model RMSE as a function of location and insolation conditions for each algorithm.

ditions, are quite apparent through these figures. However, some additional site-specific features are worth noting.

The poor clear-condition performance of all models, but particularly EK&D and Maxwell's, for the two north European locations shown (Cabauw and Geneva) is most interesting, and is indicative of higher than average beam attenuation at a given clearness level (likely causes: high turbidity, persistence of thin nebulosity). Note that the better overall performance in Cabauw is caused only by a much larger incidence of overcast events at this site.

No model is found to perform adequately for the Florida site, where results are noticeably distinct from elsewhere. Interestingly, differences with other sites peak for low Kt conditions.

Larger than average errors found in Albuquerque are probably traceable to this site's altitude. None of the models account for this parameter upon which Kt does depend. Noticeably better performance is observed at the other, low altitude, arid site, Phoenix, AZ.

There is an interesting difference between model performance against SEMRTS data from Albany (#5) and the group of five New York State locations (#7) which includes more recent measurements from Albany. The main difference between the two sets is the time step, (respectively, hourly and 15 min.). Assigning a mid-point zenith angle for an hourly value tends to underestimate mid-point global more than it does direct. This phenomenon which increases rapidly with the size of the time step may account for the reversed bias tendency between the two data sets.

Although instrumentation calibration and operation differences may be the cause of part of the differences observed from site to site, it is felt that the overall picture emerging from this analysis is a sound one, indeed because of the number of sites, the variety of climates and data collecting procedures involved.

Qualitative remarks. Modeled beam irradiance has been plotted in Fig. 3 against measured values for each model and for three sites with markedly distinct climatic environments and noticeable model performance differences. The sites are Geneva, where S&O model is ahead, Phoenix, where Maxwell is ahead,

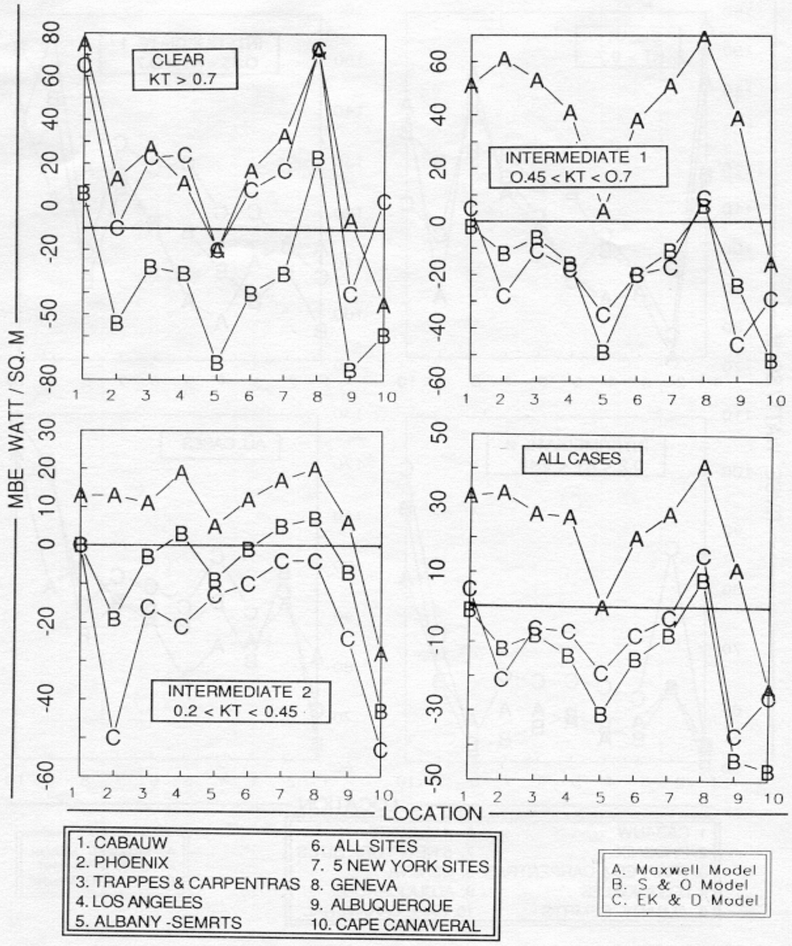

Fig. 2. Variations of model MBE as a function of location and insolation conditions for each algorithm.

and Farmingdale, where results lie half-way between the two previous cases.

It is important to point out that the x-axis in Fig. 3 is measured direct beam, *not* Kt. Indeed, many high Kt events correspond to medium and sometimes low direct beam values, particularly for places with frequent intermediate conditions like Geneva. This has to be kept in mind when contrasting results in Fig. 3 with those in Table 2 and Figs. 1 and 2.

The most important fact shown by these plots is that what differentiates performance at one site from another's appears to be the relative frequency of intermediate events at that site—the performance of each model for very clear conditions is remarkably site-independent; however, intermediate events are very few in Phoenix and very common in Geneva. The physical basis for the Maxwell model is apparent through a good interpretation of the clearest cases, which, for each site, are positioned about the 1 : 1 line, however this model's handling of all other events is less satisfactory. On the other hand, the S&O model statistical origins are apparent through a well positioned overall bias, but achieved at the cost of a marked negative departure for the clearest events, apparent at all sites. This behavior is also apparent, to a lesser extent, in the case of the EK&D model, although the main problem for this model lies in the absence of the zenith angle as an active input variable; this is apparent here through the characteristic shape of its dispersion pattern.

Based on this discussion it is likely that a model, combining a correct physical interpretation of the clearest events with an adequate handling of intermediate conditions, could be developed and yield a much more acceptable level of performance; a better delineation of intermediate events particularly for high Kt's is a necessity. The following section reinforces this statement in a quantitative fashion.

3.2 *Modeling improvement evaluation*

Rudimentary model correcting functions, CF, are derived by fitting analytical formulations to the bias patterns observed in Table 2. Again, the primary purpose of these functions is not to recommend the use of an empirical correction, but to provide a conservative measure of the room for model perform-

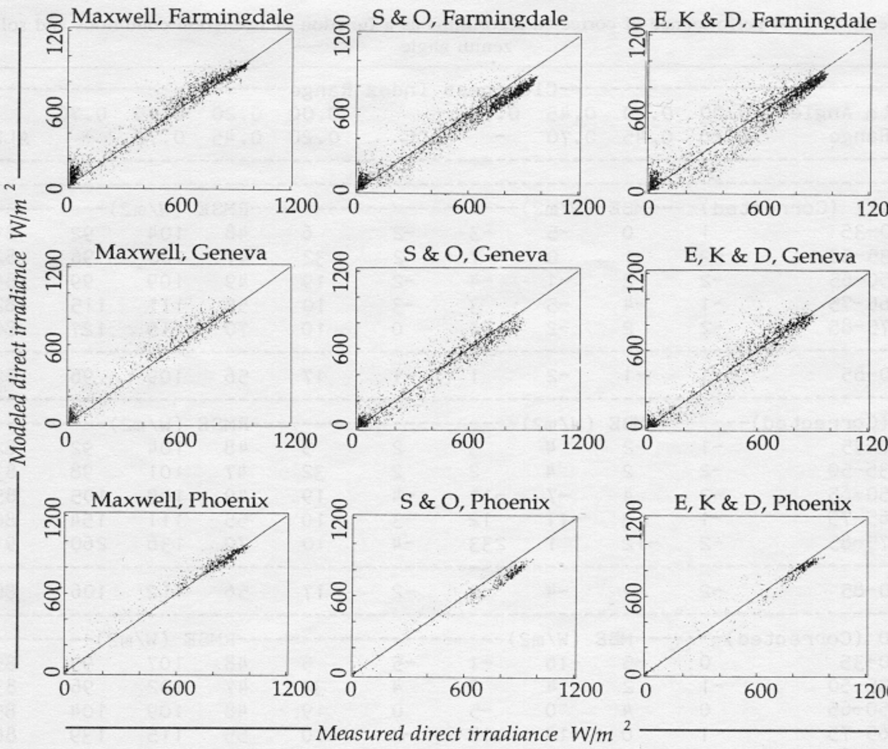

Fig. 3. Measured vs. predicted direct irradiance for each algorithm at three selected sites.

ance improvement without requiring more input information.

This is given here as an example for the Maxwell model.

If $Kt > 0.7$ then $CF = 1 - 0.00124\,(100\,Z^{1.2} - 60)$
Else If $Kt > 0.45$ then $CF = 1 - 0.00211$
$[75\,(\sin Z)^2 + 10\sin(2\,Z) - 25]$
Else $CF = 1 - 0.0182\,[25\,\{\sin(1.1\,Z)\}^4 - 0.125/H]$
where $H = [\pi/2 - \min(Z, 1.4)]^3$

Model performance with correcting function may be assessed in terms of overall RMSE and MBE in Table 3 and in terms of site-dependent RMSE in Fig. 4 and MBE in Fig. 5, where Maxwell models with and without correction are compared.

Performance improvement, through this simple *and yet incomplete procedure*, is notable for all insolation conditions for each model. Results in Fig. 4 demonstrate that the improvement spans all sites: this preliminary correction yields notable ameliorations in some cases but results only in minor performance deterioration for this model. General improvement is also found for the other models with, at worst, marginal performance deterioration in a few sites. Note that all models perform very similarly at all sites after correction.

Although the argument may be advanced that the correction, derived from the same data used for validation, yields, in fact, a dependent test, this may be refuted on two grounds: First and foremost, the "dependent" pool of data is very large and spans a complete spectrum of climatic conditions. Second, one of the tests, that of Cabauw, is "truly" independent and reinforces the first point: this site was not included in the derivation of correcting functions.

Attention should rather be focused on the fact that hourly global-to-direct conversion can be noticeably improved from current levels, without using additional input data. It is believed that the improvement obtained here with very crude corrections can be enhanced by (i) starting from a simple physical model and refining the present fitting procedure to include all data points instead of the 10-point fit presented here, (ii) accounting for the zenith angle-dependent nature of Kt as an insolation condition describer, (iii) including site's altitude and, possibly, a simple climatic index in the model structure, (iv) researching a better means of differentiating, based on the available information, between events which are physically clear (i.e., cloudless sky) and those which may be labeled as intermediate at equivalent high Kt levels—using the daily data structure as an indicator of the presence of light clouds is a possibility which has already shown some potential for the determination of the one-minute structure of hourly data[18].

4. CONCLUSIONS

Three global-to-direct (diffuse) conversion models, considered to be among the best available to date have been evaluated against 14 high quality data sets cov-

Table 3. Overall performance of corrected algorithms as a function of insolation conditions and solar zenith angle

Zenith Angle Range	MBE 0.00–0.20	MBE 0.20–0.45	MBE 0.45–0.70	MBE 0.70–	MBE ALL	RMSE 0.00–0.20	RMSE 0.20–0.45	RMSE 0.45–0.70	RMSE 0.70–	RMSE ALL
Maxwell (Corrected) — MBE (W/m2) / RMSE (W/m2)										
0–35	1	0	−5	−3	−2	6	48	104	92	83
35–50	−2	1	0	7	2	32	47	100	96	82
50–65	−2	−2	−1	−4	−2	19	49	109	99	84
65–75	−1	−4	−5	3	−3	10	55	111	115	82
75–85	−2	2	−2	74	0	10	70	115	127	80
0–85	−1	−1	−2	1	−1	17	56	109	98	82
S&O (Corrected) — MBE (W/m2) / RMSE (W/m2)										
0–35	−1	−2	4	3	2	5	48	104	92	82
35–50	−2	2	4	2	2	32	47	101	98	83
50–65	−2	4	−7	−11	−4	19	49	109	105	85
65–75	−1	3	−11	12	−3	10	55	111	154	86
75–85	−2	−12	1	233	−4	10	70	136	260	91
0–85	−2	−1	−4	0	−2	17	56	112	106	86
EK&D (Corrected) — MBE (W/m2) / RMSE (W/m2)										
0–35	0	−5	−16	−1	−5	5	48	107	95	85
35–50	−1	2	4	7	4	32	47	102	96	83
50–65	0	4	0	−5	0	19	48	109	104	85
65–75	1	0	−14	18	−4	10	55	115	139	86
75–85	1	−34	−44	126	−28	10	83	143	188	98
0–85	0	−8	−11	3	−5	17	61	115	103	87

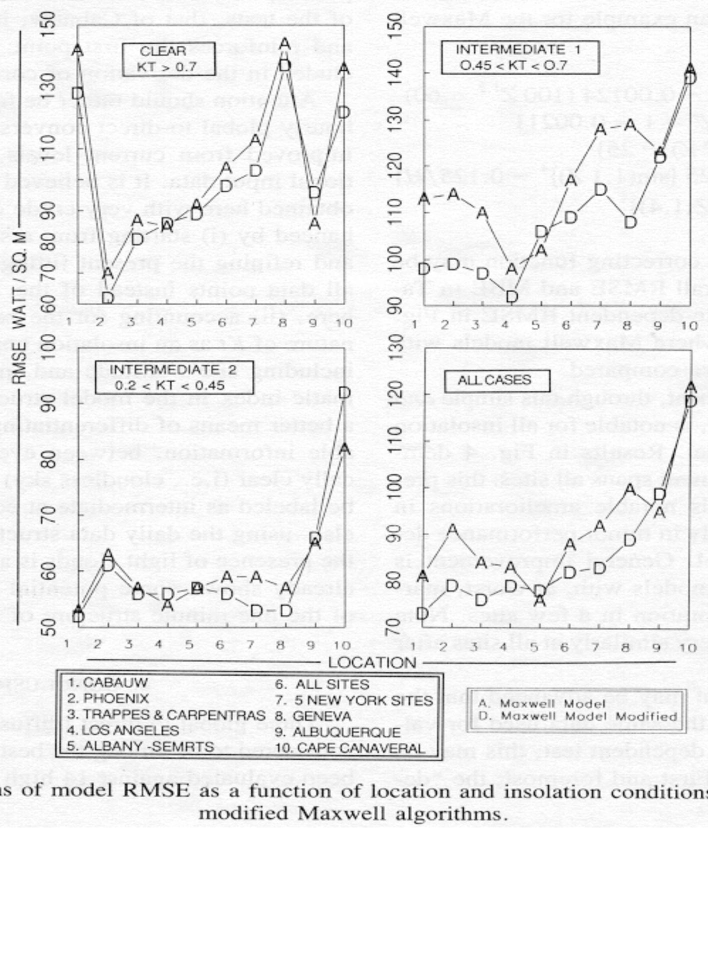

Fig. 4. Variations of model RMSE as a function of location and insolation conditions for original and modified Maxwell algorithms.

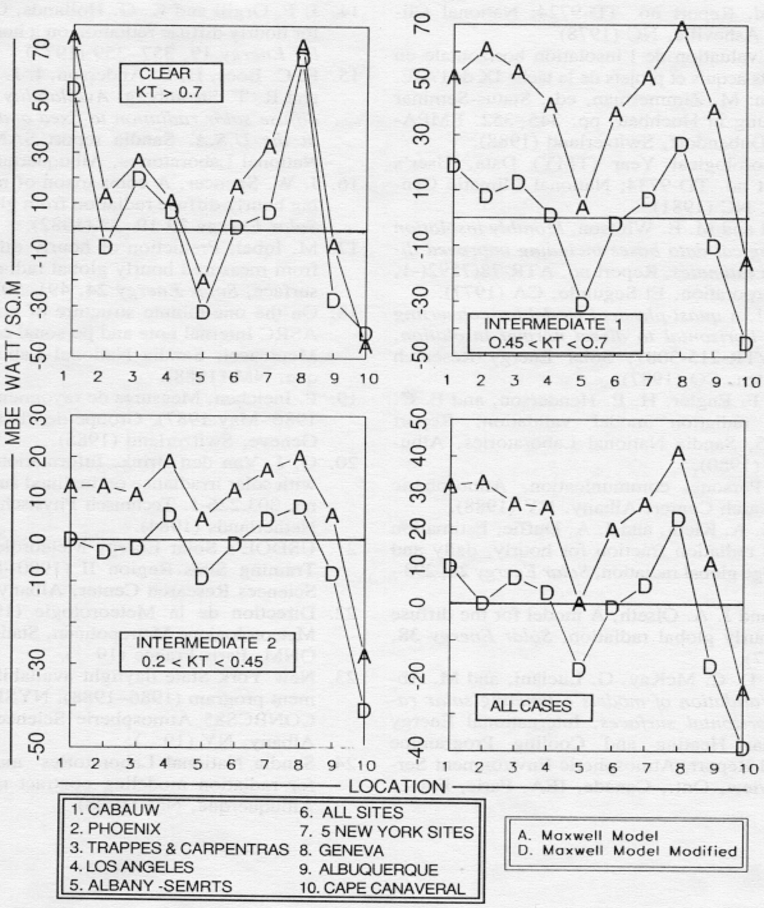

Fig. 5. Variations of model MBE as a function of location and insolation conditions for original and modified Maxwell algorithms.

ering markedly distinct climates and environments in western Europe and North America.

This study shows that the algorithm proposed by Maxwell[8] performs better overall than those proposed by Skartveit and Olseth[12] and Erbs *et al.*[13], in this order. The first model has an advantage for clear sky conditions, and consequently performs better at the sites were these prevail. The second performs better for intermediate conditions and, correspondingly, for the sites with fewer clear skies. The third model, which does not use the solar zenith angle as an active variable, is the best performer for mid-range solar zenith angles.

More importantly, this study demonstrates that there is ample room for model performance improvement at each site considered, using a single site-independent model. This conclusion was achieved by evaluating rudimentary site-independent corrections to the models, based on their resultant bias. It is therefore believed that global-to-direct conversion, crucial today for many applications, can be enhanced beyond the level of current proposals.

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