Verification of surface solar radiation fluxes predicted by ALADIN

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Abstract - Solar radiation output fluxes predicted by ALADIN were verified using observed data from three station of Hungarian Meteorological Service. Period of June - August 2001 was selected for the study. Differences between observed and forecasted values were analysed separately for all cases and cloudless cases. It was found that ALADIN estimates daily totals essentially correctly but standard deviations of model data series are considerably lower than those of true data series and the model cannot produce sufficiently low daily totals like those occurring in reality. For cloudless cases, using aerosol optical depth to represent radiation transmission condition of the atmosphere, it was found that ALADIN overestimates atmospheric radiation transmission for cases of high turbidity and underestimates it for very clear conditions. It means that radiation transmission scale of the atmosphere produced by the model is more narrow than that of true atmosphere.

1. Introduction

For any user who intends to use solar radiation outputs from ALADIN it is important to know their reliability. It seems that in Hungary the interest for global radiation forecasts of ALADIN increases so it was high time carrying out verification of them. The aim of the study that is shown in this paper was to determine deviations between predicted and observed values as well as to analyse them: to try to understand reasons of them more deeply that means finding of possible insufficiencies in background physics produced by ALADIN. Based on the results to make suitable improvements in the model would be possible if interest would arise. Observed data and forecasted parameters used for the study, the method for verification and its results separately for all cases and cloudless cases with conclusions are shown in the paper.

2. Solar radiation parameters and data used for the study, as well as radiometers from which data come

Parameters that are used for the study were global, direct and diffuse radiation. The observed data came from the solar radiation observatory of Hungarian Meteorological Service which is a WMO Regional Centre for Solar Radiation for Region VI, as well as it is a station of BSRN. Direct radiation (marked with DIR in the figures) is measured by pyrheliometer Eppley NIP affixed on a sun tracker SCI-TEC, global radiation (GL in the figures) is measured by pyranometer Kipp-Zonen CM11 and diffuse radiation (DIF in the figures) that is the scattered component of solar irradiance reaching the Earth's surface is measured by also pyranometer Kipp-Zonen CM11 affixed on the same sun tracker using shading disks. The pyrheliometer is regularly calibrated to our absolute cavity pyrheliometer HF 19476 which is the regional standard for WMO Region VI and thus represents World Radiometric Reference (which means the reference radiometric scale) for the region. Previous comparison of HF 19476 to the World Standard Group was carried out in 2000 at the last International Pyrheliometer Comparison in Davos, Switzerland. All our instruments are in well-calibrated condition.

Using serial lines detectors are connected to a data acquisitor PC in Budapest or to automatic weather stations MILOS at the countryside observatories. Data base consists of both one minute and ten minute averages that are calculated from the individual measurements (samplings) which are made by the detectors. Six individual measurements are carried out in each minute.

Concerning observed data the direct solar radiation that is measured by pyrheliometer is the irradiance from the solar disc that insolates a surface perpendicular to the direction of the Sun. Direct solar radiation that was needed for the investigation is the vertically incident component that is equal to difference of global and diffuse radiation. So it was calculated as difference of observed global and diffuse irradiance.

The study was carried out for the daily total for subsequent day and for the day after subsequent day. Predicted data used were the 24 hour and 48 hour cumulative surface fluxes from ALADIN. Daily totals for the day after subsequent day were calculated, evidently, as the differences of 48 and 24 hour cumulative fluxes. Forecasts released at 0 h were used in each case and characteristics of deviations of daily totals predicted by ALADIN from the observed daily totals were analysed. ALADIN predicts vertical component of direct radiation (that is incident on a horizontal surface) and diffuse radiation so forecasted global radiation values were calculated from them. Global radiation is simply the sum of vertically incident direct radiation and diffuse radiation. The study was carried out for

- Budapest-Lõrinc (φ : 47°25'45'', λ : 19°10'56'')

and for two countryside stations:

- Sármellék (φ : 46°41'15'', λ : 17° 09' 42'')
- Nagyiván (φ : 47°21'01'', λ : 20° 54' 33'')

In addition to Budapest this two countryside stations seemed to be most representative in respect of solar radiation, among the global radiation measuring sites of the Hungarian Meteorological Service. Direct and diffuse radiation measurements are in progress solely Budapest consequently only global radiation was studied for Nagyiván and Sármellék. So forecasted daily totals below were verified:

– direct radiation for the subsequent day (Budapest)
– diffuse radiation for the subsequent day (Budapest)
– global radiation for the subsequent day (Budapest, Sármellék, Nagyiván)
– direct radiation for the day after subsequent day (Budapest)
– diffuse radiation for the day after subsequent day (Budapest)
– global radiation for the day after subsequent day (Budapest, Sármellék, Nagyiván)

The investigation was made for the period of June-August 2001 that means 92 days.

Solar radiation outputs of ALADIN depend on the following parameters: solar zenith angle, N2, O2, total water vapour content, CO2, O3, water in both liquid and ice state (clouds), 3d cloudiness, aerosols. Concerning the considerably changing physical parameters, in reality solar radiation flux reaching the Earth's surface is affected mostly by cloudiness, total water vapour content and aerosols (obviously besides solar zenith angle that is determined by celestial mechanical parameters). Ozone, for example, has no effect on wide energy range radiation but on narrow spectral ranges only.

The factor that most considerably influences solar irradiance reaching the Earth's surface is undoubtedly the cloudiness. Among the radiation parameters direct radiation is which is affected by it most dramatically: cloudiness can make direct value equal to zero if each photon is absorbed in the clouds. It can occur frequently in case of thick clouds. Consequently the deviation of amount of forecasted cloudiness from that appearing in reality is of principal importance in respect of prediction. Also it is of crucial importance that whether forecasted cloudiness arrives when the real cloudiness does or on the contrary: whether cloudiness does not arrive at given place in the model when real cloudiness does.

Daily average cloudiness values were calculated as arithmetic mean of hourly cloudiness values without any weighting for Budapest. The resulted 'daily total cloudiness' is a draft parameter but in this first study it was considered sufficient. Satellite images were used for consideration of cloudiness for both countryside stations since no human observer is employed in those sites so cloud coverage values were not available.

In cloudless cases solar radiation reaching the Earth's surface is affected by aerosol content and total water vapour content. Unfortunately, running of the model afterwards for parameters that have not been operationally output previously would have taken too much time so those parameters were not considered in this first study. It means that values of forecasted cloudiness and other influencing parameters were not available for the study but despite this fact useful conclusions for reasons of the differences are made based on the results. Study of 'goodness' of influencing parameters would be a next step of the investigation in the framework of which the parameters needed for the study would come to be computed during the operational model running.

3. *Results for all cases*

Predicted and observed data series are shown on *Fig. 1 - 5* for 24 hour forecasts for direct, diffuse and global radiation for Budapest, as well as for global in case of both countryside station. To save pages, the same parameters for 48 hour forecasts are shown for two countryside stations only (*Fig. 6 - 7*). It can be seen that variability of observed data series is considerably higher than that of predicted series. It is not unexpected actually since models usually smooth fluctuations. They are able to predict extrema with less reliability. Standard deviation of data series are shown in *Table 1*. It is conspicuous how lower the standard deviations of model data series are, as compared with those of observed series. In case of direct radiation, standard deviation of the predicted data series is 552.3, while it is 684.2 for the observed series. For diffuse radiation that is of considerably less variable parameter as a consequence of its nature, it is 184.2 and 286.1, respectively. Concerning global radiation, also it can be established based on the table values that differences of standard deviations and values of standard deviations themselves are very close to each other for all three stations. The differences are: 217.3, 201.8 and 248.2.

Fig. 1. **Observed and forecasted daily totals of direct radiation for 24 hour forecasts. Budapest, June - Aug 2001**

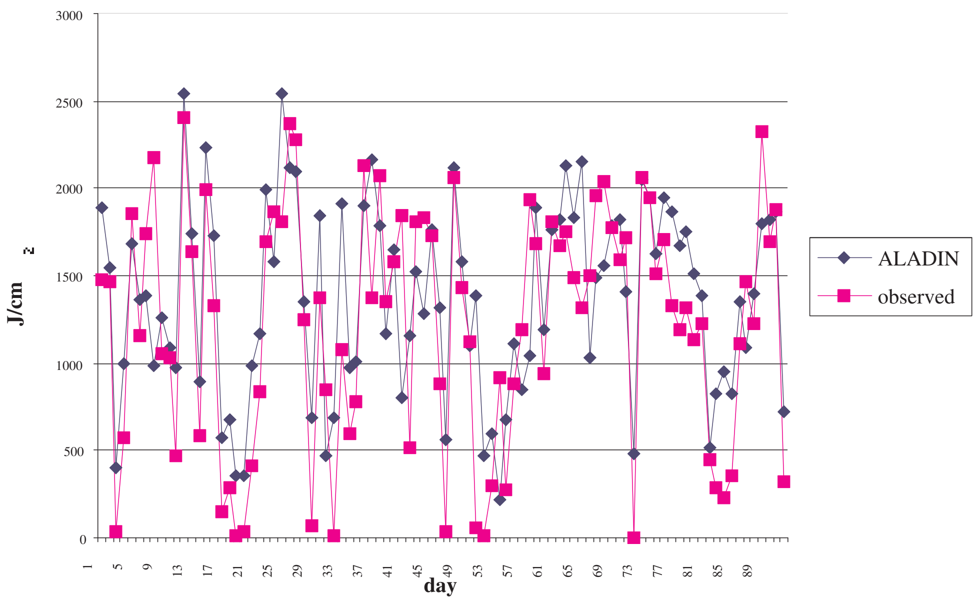


Fig. 2. **Observed and forecasted daily totals of diffuse radiation for 24 hour forecast. Budapest, June - Aug 2001**

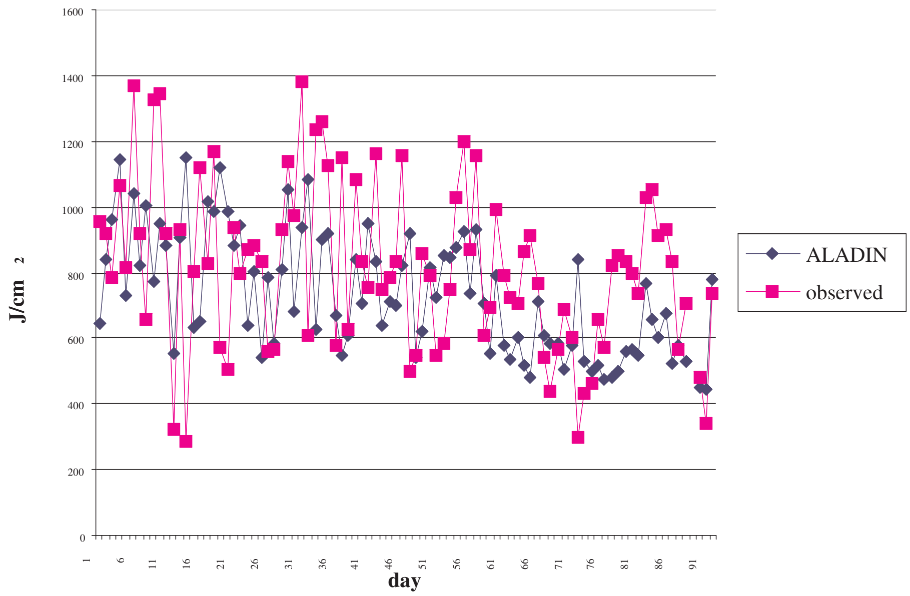


Fig. 3. **Observed and forecasted daily totals of global radiation for 24 hour forecasts. Budapest, June - Aug 2001**

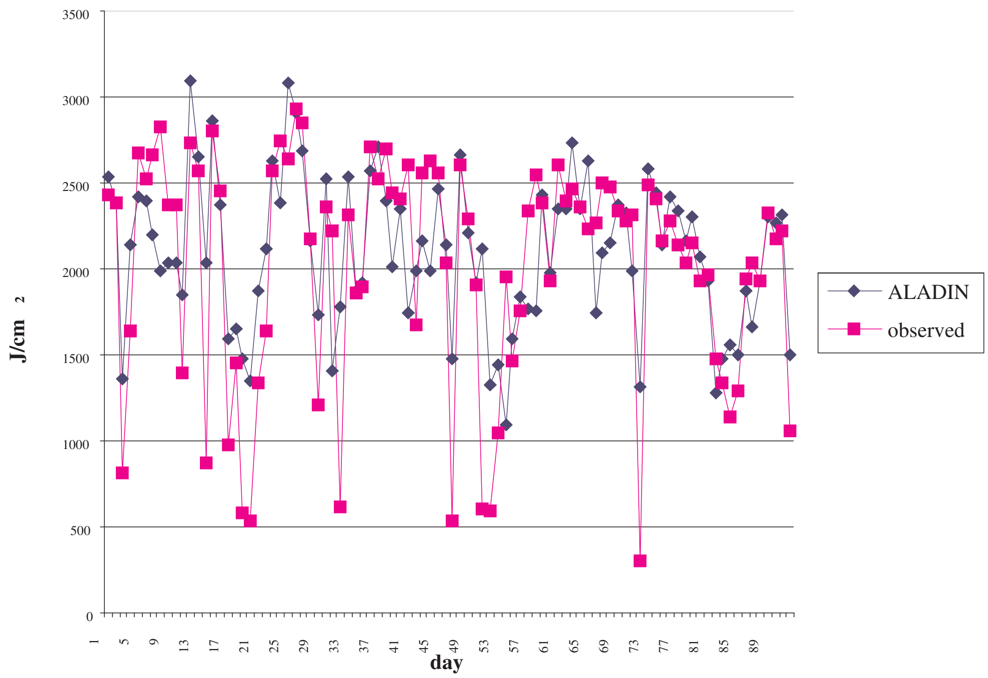


Fig. 4. **Observed and forecasted daily totals of global radiation for 42 hour forecasts. Nagyiván, June - Aug 2001**

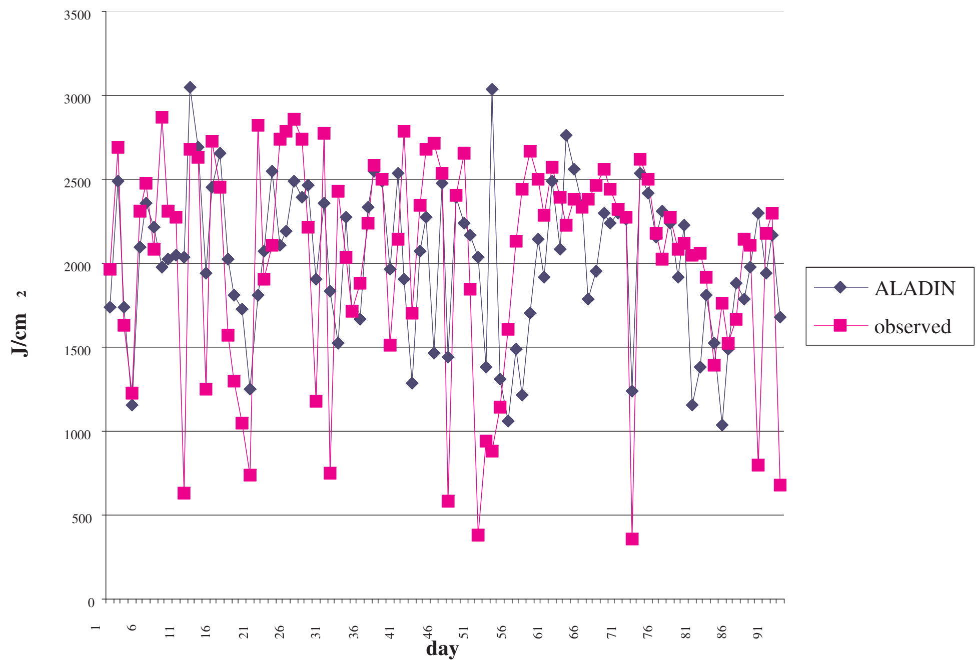


Fig. 5. **Observed and forecasted daily totals of global radiation for 24 hour forecasts. Sármellék, June - Aug 2001**

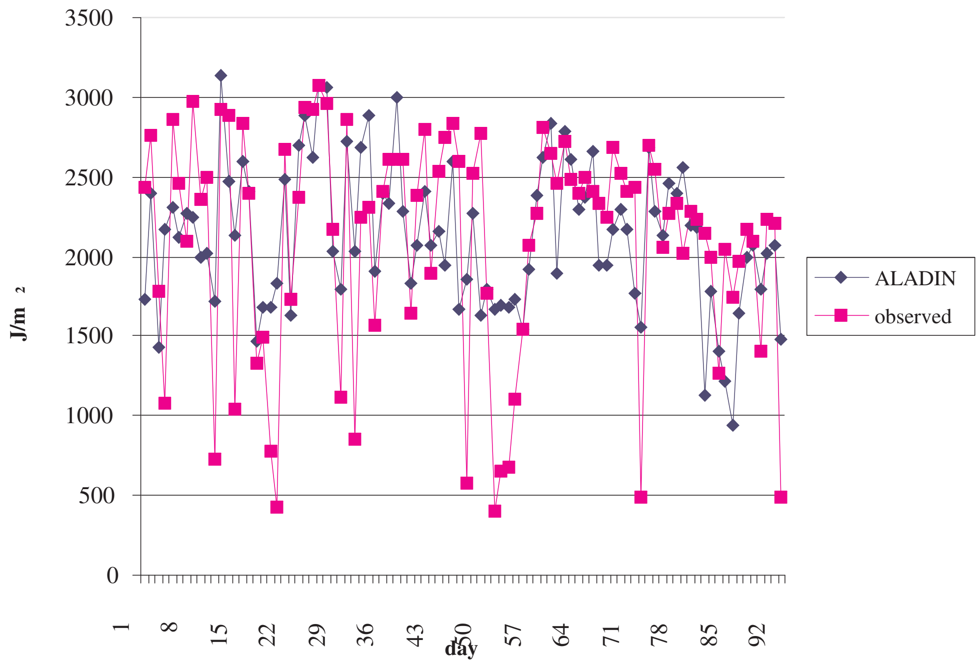


Fig. 6. **Observed and forecasted daily totals of global radiation for 48 hour forecasts. Nagyiván, June - Aug 2001**

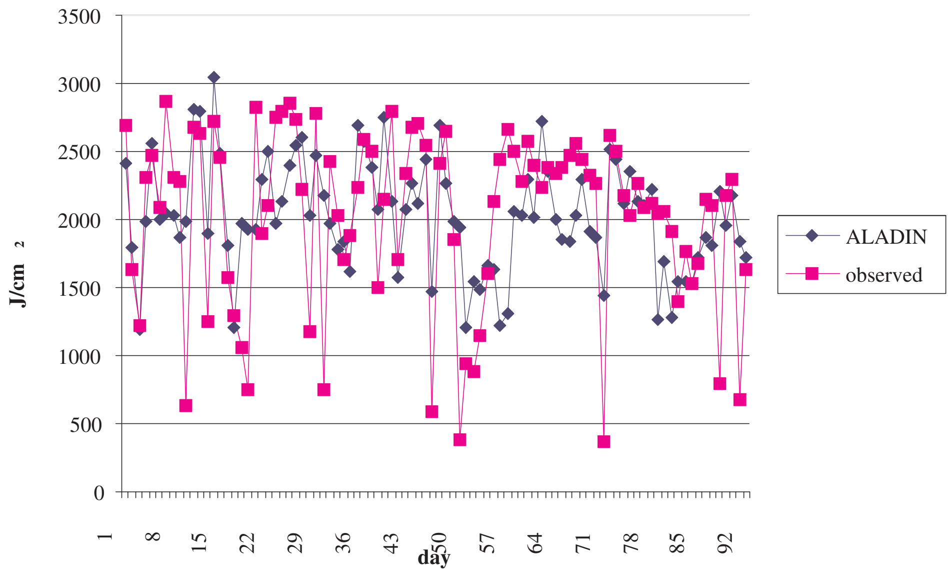
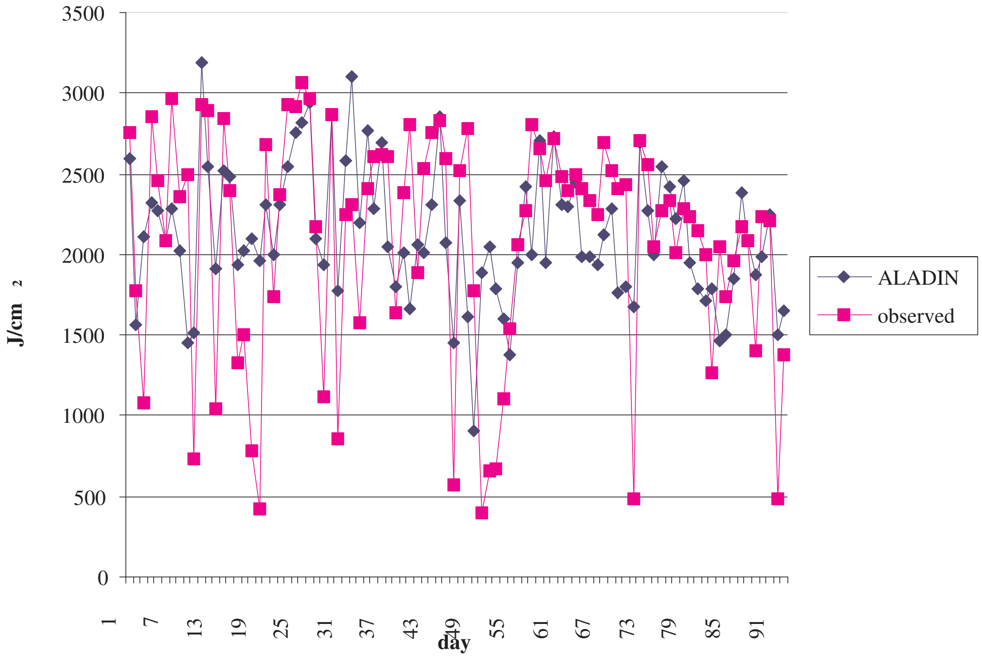


Fig. 7 **. Observed and forecasted daily totals of global radiation for 48 hour forecasts. Sármellék, June - Aug 2001**



It is the most conspicuous from the figures that values of minima in observed data series are considerably low as compared with those occurring in model data series, mainly for direct and global radiation. On days when sky was covered by clouds almost throughout the day, daily totals of direct component hardly differed from zero as expected but in the same time such cases did not occur in the model. ALADIN considerably overestimated the irradiance reaching the surface for those days. Two cases are to be supposed: (1) ALADIN estimates cloud coverage erroneously on those days but it is not probable that it would have been mistaken for the most cloud-covered days right in each case. (2) ALADIN clouds are not so effective radiation absorbers like the real clouds and they thus, when were present, could not cause radiation decrease of such magnitude like the real clouds did. It can be checked in case when, maybe in a possible next experiment, cloud coverage will be calculated with higher temporal resolution in model running.

Table 1. Standard deviation of data series

	ALA	OBS
Budapest – Direct	552.3	684.2
– Diffuse	184.2	286.1
– Global	435.9	653.2
Nagyiván – Global	444.2	644.0
Sármellék – Global	457.1	705.3

Table 2. Overestimation - underestimation

24 h	Budapest	Nagyiván	Sármellék
Direct	67 - 25	-	-
Diffuse	31 - 61	-	-
Global	55 - 37	37 - 55	40 - 52
48 h	Budapest	Nagyiván	Sármellék
Direct	64 - 28	-	-
Diffuse	35 - 57	-	-
Global	47 - 45	39 - 53	40 - 52

Number of overestimations and underestimations are shown in *Table 2*. It can be established undoubtedly that the model considerably overestimated direct radiation (67 – 25 for the 24 hour forecasts, 64 – 28 for the 48 hour forecasts), underestimated diffuse component (31 – 61 and 35 – 57, respectively), which was probably caused also by the non- sufficient radiation transfer effectiveness of ALADIN clouds. It can mean that in addition to that ALADIN clouds are not suitably effective, they did not scatter radiation in such a degree like true clouds do.

Also simulated monthly totals of global radiation were calculated for the three months used for the study from the forecasted values and they were compared with monthly totals calculated from observed values. Results are summarized in *Table 3* where percentage deviations that were calculated in the way as follows are also shown : *DEV (%) = ((GALA – GOBS)/GOBS))*100*

One can establish that there is no considerable difference between simulated and true monthly totals. Deviation higher than 5 % occurred in one case only (8.14 % at 24 hour forecast for Budapest) among the nine deviation values. It is to be noted that on the one hand it was expected since errors for longer period considerably decrease effect of each other, on the other the users mainly do not need forecasts for monthly averages but for subsequent days so those relatively good agreements cannot considered too useful.

Table 3. Monthly totals of global radiation (J /cm2)

June	ALA	OBS	DEV (%)
Budapest	66 502	61 502	8.14
Nagyiván	63 793	62 980	1.29
Sármellék	66 798	64 942	2.86
July	ALA	OBS	DEV (%)
Budapest	62 002	62 311	-0.50
Nagyiván	60 382	61 768	-2.24
Sármellék	66 554	63 356	5.05
August	ALA	OBS	DEV (%)
Budapest	64 135	62 397	2.79
Nagyiván	61 748	61 501	0.40
Sármellék	62 219	62 844	-0.99

Also frequency distributions of differences between observed and predicted daily totals were studied. Differences for direct, diffuse and global radiation are marked with DIF_DIR, DIF_DIF and DIF_GL, respectively, in the figures. To save pages, differences for 24 hour forecasts are shown here for Budapest only. Intervals with a width of 200 J/cm2 were selected in the way that differences higher than 1000 J/cm2 were collected into one group. In *Fig. 8 – 13* percentage case numbers are shown. It can also be seen that overestimations dominate the figure for direct and global radiation and underestimations rather dominate it for diffuse radiation. Also it is clear from the figures that number of higher overestimations is larger in cases of 48 hour forecasts.

Using satellite images each day was explored to find out if higher differences occurred systematically. It was found what expected actually: higher differences occurred in cases when sky was almost completely covered by clouds above the given surface point and above its surroundings but in the same time smaller 'holes' or thinner cloud parts appeared in the cloudiness. The model obviously is able to predict those kind of phenomena in the least.

Fig. 8. **Frequency distribution of DIF_DIR (24 hour forecasts for Budapest)**

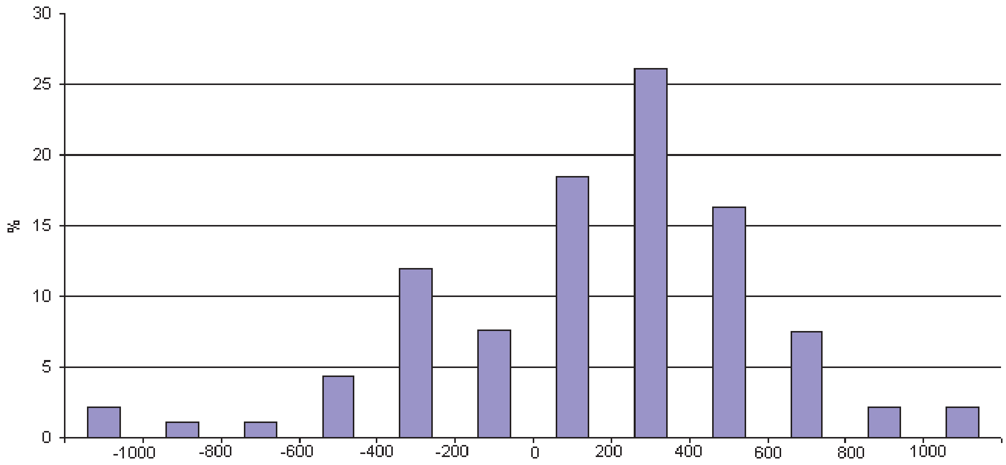


Fig. 9. **Frequency distribution of DIF_DIF (24 hour forecasts, Budapest)**

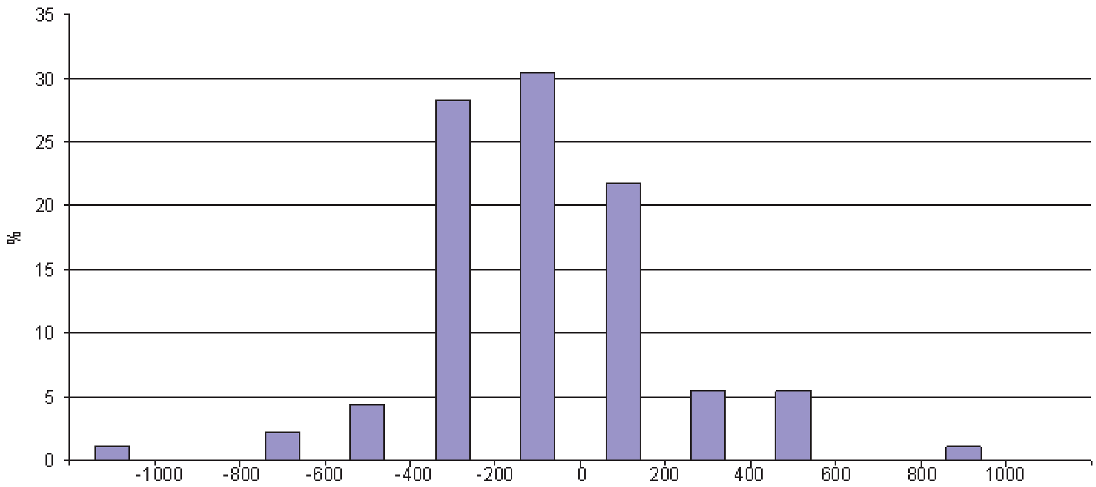


Fig. 10. **Frequency distribution of DIF_GL (24 hour forecasts for Budapest)**

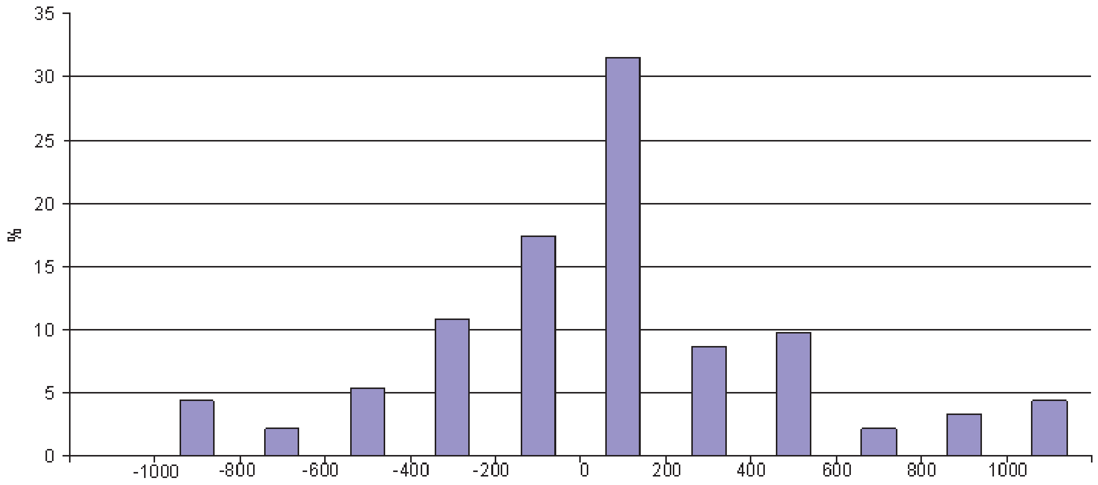


Fig. 11. **Frequency distribution of DIF_DIR (48 hour forecasts for Budapest)**

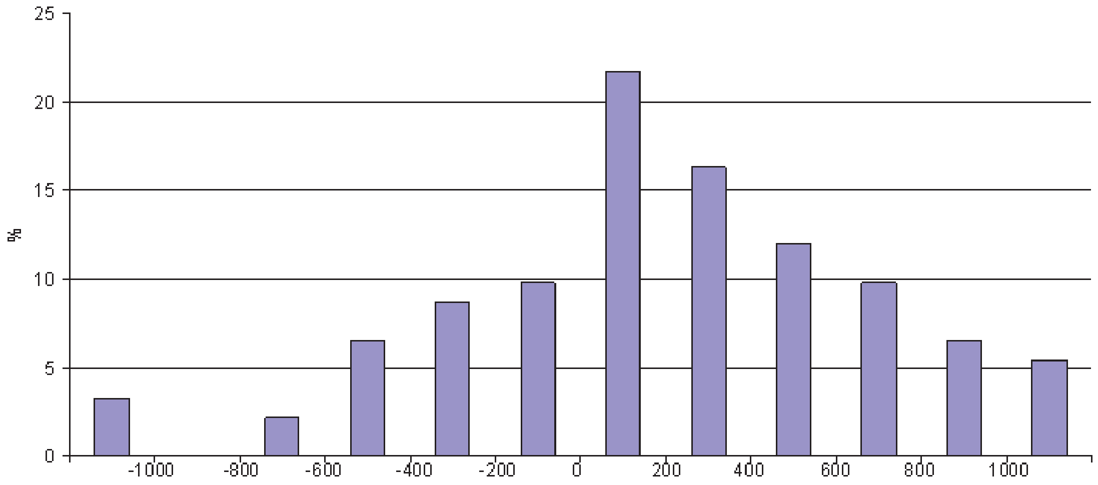


Fig. 12. **Frequency distribution of DIF_DIF (48 hour forecasts for Budapest)**

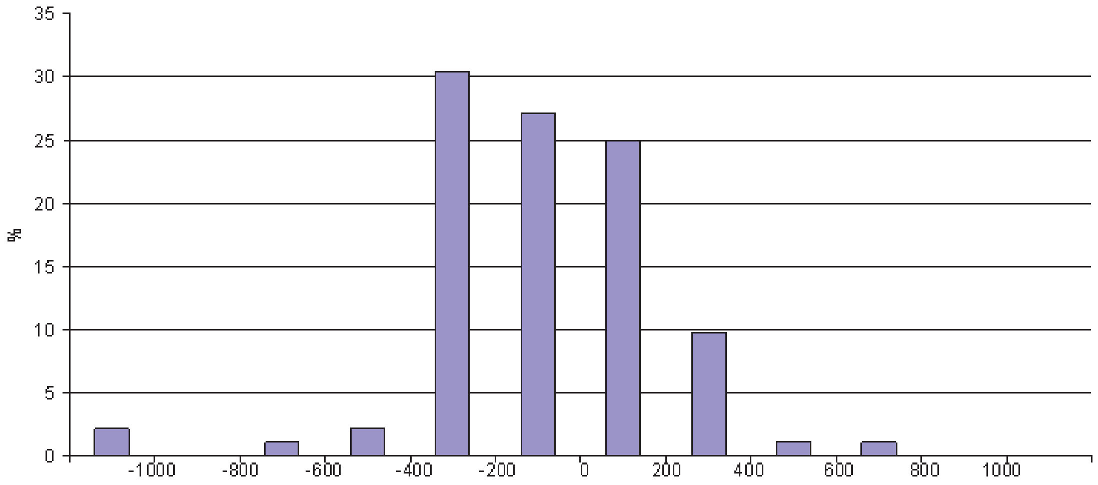
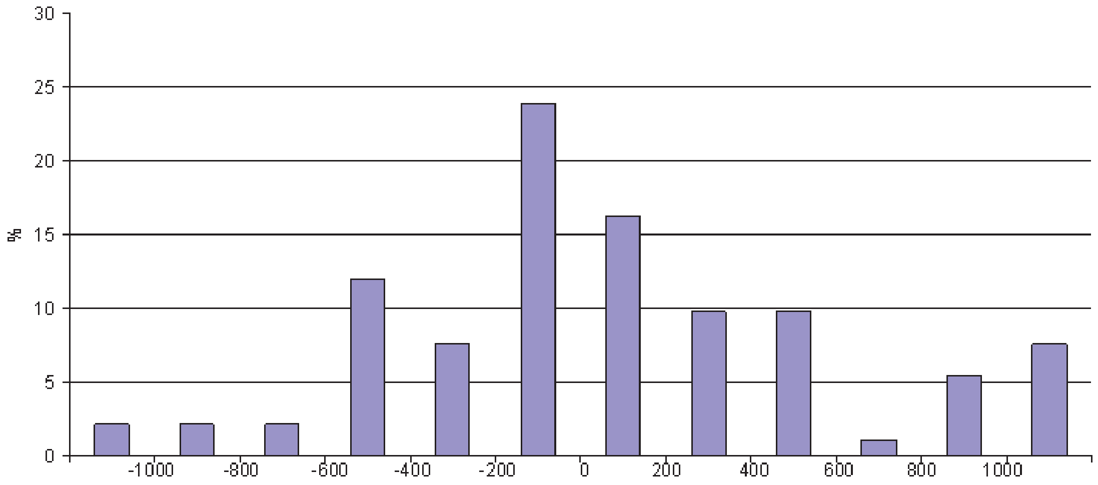


Fig. 13. **Frequency distribution of DIF_GL (48 hour forecasts for Budapest)**



4. Results for cloudless cases

Two main factors affect solar radiation flux reaching the Earth's surface in case of wider energy range radiation: total water vapour content and total aerosol content of the air column. There was no possibility to compute them with the model afterwards since running the model again for 92 days would have taken up very much time. Despite it a study was still invented to find out how ALADIN would be able to estimate surface solar radiation fluxes in cloudless cases or in other words: how it would be able to estimate atmospheric radiation transmission. Days, among the 92 days, that were completely or 'almost' completely cloudless were selected. Term 'almost' means that values of a parameter called daily average cloud coverage were determined which, for lack of a better, was the arithmetical mean of hourly cloud coverage values. Those days were involved in the study when daily mean of cloud coverage values were not higher than 2 octa. Additional filtering was not reasonable to apply since, based on the hourly values of given days, it was clear that daily averages lower than 2 octa occurred on days solely when almost no any cloud appeared throughout the day. If sufficient number of days would have not remain or no effect would have been found, a filtering technique for selecting suitable cases would have been to apply: to examine whether the few octa cloudiness covered the solar disc or did not. But this filtering was not needed due to that 24 days were found that met the criteria given by us.

To represent radiation transmission condition of the atmosphere aerosol optical depth was selected. Aerosol optical depth values are available from our database of spectral solar radiation measurements carried out regularly with spectroradiometer LI-1800 that has a suitably designed tube to measure spectral intensity of direct radiation so it can be operated as spectrophotometer (in our practice it is used as spectrophotometer continuously).

The aim of the study was to obtain any information on reliability of ALADIN surface solar radiation forecasts concerning different atmospheric radiation transmission conditions. It is very important since considerable radiation extinction can in many cases occur even when sky is cloudless.

Aerosol optical depth values are available for Budapest-Lõrinc Observatory for each recorded solar spectra for the 10 standard wavelengths. Aerosol optical depth characterizes total columnal aerosol content of the atmosphere and can be calculated in the way as follows :

$$\tau_A(\lambda) = \frac{1}{M} \ln \frac{I_0(\lambda)}{I(\lambda) S} \left(\frac{P}{P_0} \tau_R(\lambda) + \tau_0(\lambda)\right)$$

where:

$\tau_A(\lambda)$: aerosol optical depth

$I_0(\lambda)$: extra-terrestrial irradiance at mean Sun-Earth distance

$I(\lambda)$: irradiance at the point of observation

S : correction factor for Sun-Earth distance

M : relative optical air mass (depends on solar elevation)

$\tau_R(\lambda)$: optical depth due to Rayleigh scattering of air molecules

$\tau_0(\lambda)$: optical depth due to ozone absorption: $\tau_0(\lambda)=a_0(\lambda)\,\eta$

where: $a_0(\lambda)$: absorption coefficient for ozone: η: total columnal ozone content

P, P_0 : current pressure and standard pressure at sea level

To determine aerosol optical depth those wavelengths are used where either no considerable gaseous absorption appears or solely ozone has absorption. At wavelengths where ozone absorbs, the ozone optical depth can be calculated and considered at the aerosol optical depth calculation based on our ozone measurements. Standard wavelengths are as follows (in nm): 368, 380, 412, 450, 500, 610, 675, 778, 862, 1024.

To use only one wavelength is practically sufficient to characterize quantitatively a given aerosol transmission condition of the atmosphere (several wavelengths are needed when, due to availability of both some aerosol model and aerosol size distribution, aerosol concentration would be intended to determine). In according to agreement the optical depth values calculated for 500 nm (τ500) are generally used so also they were used for our studies, namely their daily averages.

Relationship between daily average aerosol optical depth and difference of observed and predicted solar irradiances (DIF_DIR, DIF_DIF and DIF_GL in the figures) was studied for all three radiation parameters. Results are shown in *Fig 14 – 16.* Aerosol optical depth for 500 nm is represented on horizontal axis and differences between observed and forecasted irradiances (IALA - IOBS) are represented on vertical axis in each figure.

Results for direct irradiance is shown in *Fig 14.* Based on our five year long aerosol optical depth data series it is known that average value for Budapest-Lõrinc Observatory is approximately 0.3 for 500 nm. It is clear from *Fig. 14* that for the most part overestimations are found for values of τ500 lower than 0.3 and underestimations are found for τ500 values higher than 0.3. It means that the model underestimates direct irradiance reaching the surface in cases when atmospheric radiation transmission is high, namely when very small amount of pollutant is present and overestimates it in cases when atmosphere is considerably polluted. Based on it one can conclude that atmospheric radiation conditions predicted by the model are generally approach average conditions due to that the model draftly handles parameters influencing radiation transmission, namely its variability is lower than that of corresponding true parameters. The model predicts more polluted atmosphere compared with reality in very clear cases close to Rayleigh atmosphere. These findings are confirmed by results of the same study made for diffuse irradiance (*Fig. 15*). Pollutants and water vapour intensively scatters radiation consequently diffuse (scattered) irradiance observed at Earth's surface increases as larger amount of them is present in the atmosphere. It can be seen in Fig. 15 that in case of diffuse irradiance inverse effect was found as compared to that found for direct component: the model overestimates diffuse irradiance in cases of high transmission (τ500 < 0.3), namely it forecasts more polluted conditions than the true state of atmosphere and in the same time it underestimates in cases of lower transmission, namely it forecasts lower pollution than that appearing in true atmosphere. The same effect lies behind this phenomena like in case of direct fluxes so the explanation is the same: the model tends to produce such physical conditions of atmosphere that result in more average atmospheric transmission than those occurring in reality.

Those mentioned above are valid for global radiation also (see Fig. 16) but the effect is relatively less evident due to the fact that global irradiance is the sum of the previous two parameters so the effect in question decreases.

Fig. 14. Values of DIF_DIR at different aerosol optical depths

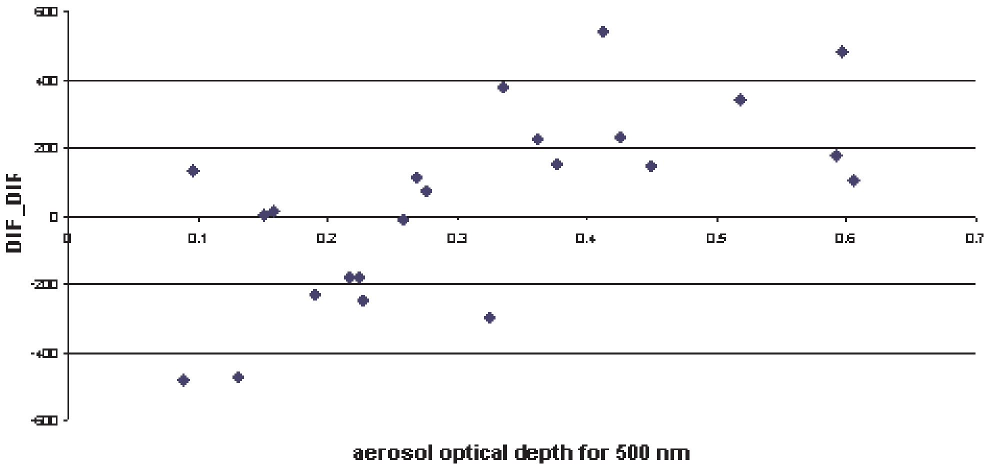


Fig. 15. Values of DIF_DIF at different aerosol optical depths

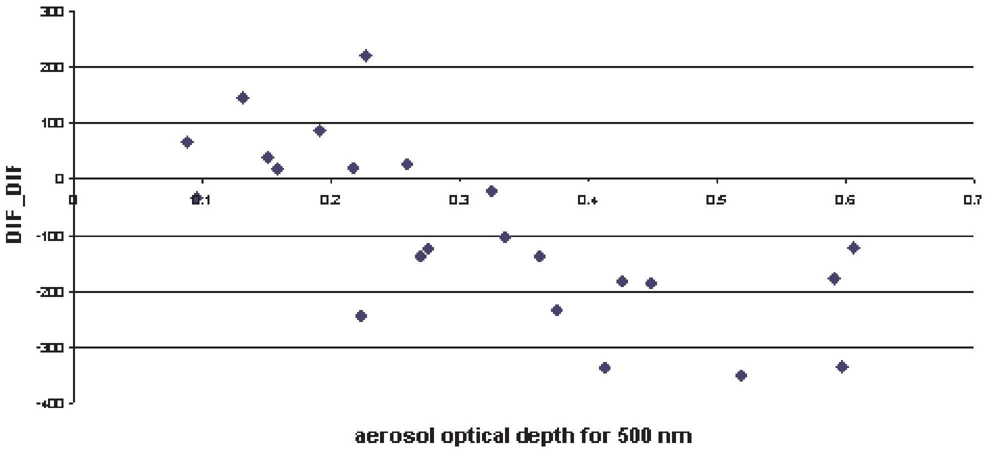
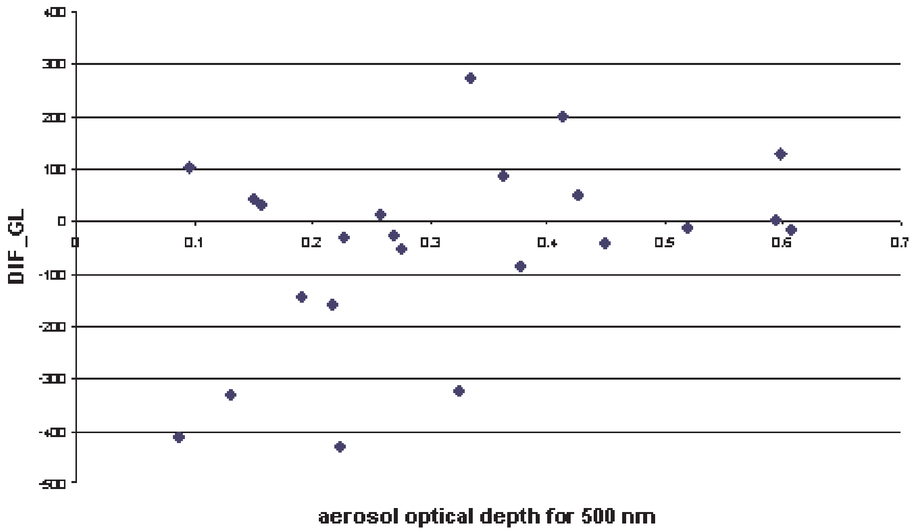


Fig. 16. **Values of DIF_GL at different aerosol optical depths**



5. Conclusions

Based on results discussed above one can conclude those as follows:

(i) It is to be established, based on deviations of predicted values from observed irradiances, that ALADIN, essentially, estimates solar irradiances reaching the Earth's surface with good accuracy.

(ii) Analysing observed and forecasted data series it was found that ALADIN predicts far more less number of very low value of daily totals than the case number occurring in reality and those low values are considerably higher than the corresponding true values (which are in some cases very close to zero). Since the probability of that the model made a mistake in forecasting the cloudiness always just on days in question, as reason it is more probable that ALADIN clouds are less effective radiation absorbers than true clouds.

(iii) Forecasted data series are characterized by considerably lower standard deviations than observed series. It means that the model cannot suitably reproduce variability of daily totals of irradiances.

(iv) In cloudless or 'almost' cloudless cases (cloud coverage < 2 octa for daily averages) differences of observed and predicted daily totals for direct and global irradiances increases with increasing aerosol optical depth while inverse dependence was found for diffuse component. It means that in cases of extremely high transmissions (low turbidity) the model predicted lower transmission and when the transmission was extremely weak (high turbidity) it forecasted higher transmission. It means that parameterization of aerosols and total water vapour is not sufficiently fine in the model, namely the resulted radiation transmission scale of the model is not sufficiently wide.

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