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HIGH LATITUDE GLOBAL AND DIFFUSE RADIATION ESTIMATED FROM HELIOSAT

by

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1. INTRODUCTION

Images taken by geostationary satellites are a valuable source to retrieve solar irradiance data with an almost continuous spatial coverage (Beyer et al., 1996). With increasing latitude, however, the accuracy of such retrievals declines due to the fact that geostationary satellites see the earth's surface at an increasingly unfavourable angle. This limitation is not shared by the sun-synchronous polar orbiting satellites, but the retrieval of solar irradiance from these satellites is hampered by their incomplete temporal coverage (Karlsson, 1994, 1996).

The present note compares some high latitude hourly ground observations with global radiation estimated from the geostationary satellite Meteosat. In addition to looking at the mean bias deviations, our note focuses on how well frequency distributions of hourly global irradiance at the surface are reproduced by corresponding data retrieved from Meteosat data.

2. DATA

2.1 Meteosat/Heliosat data

The Heliosat procedure is described by Beyer et al. (1996). A measure of cloud cover is inferred from pixel counts in the VIS-channel (0.5 - 0.9 μm), and this measure is subsequently used to estimate surface global irradiance as a fraction of the irradiance under clear sky conditions. This procedure is carried out with one clear sky model, viz. Heliosat Version 2n (Hammer 1996). For each of our ground stations, global radiation data for 3 X 5 pixels centred around the ground pixel of the station, were estimated by the Heliosat procedure from Meteosat image acquisition each half hour for the period March 27. - October 26. 1995 (Hammer 1997). Based on these global radiation data horizontal diffuse radiation is estimated by the Skartveit & Olseth diffuse fraction model (1987).

2.2 Ground truth data

Hourly global radiation measured by CM11 pyranometers are available from the nine stations (Table 1) plotted in Fig. 1. For three of the stations hourly horizontal diffuse radiation, measured by CM11 pyranometers with shading disk at Bergen and Gävle, and with shading ring at Ås, are available. For Ås the diffuse radiation is corrected according to the method of Littlefair. The difference with respect to time schedule of the various observations was approximately resolved as follows: For stations run according to GMT, the ground observation for e. g. the hour 11⁰⁰ - 12⁰⁰ GMT is compared to a weighted average of Heliosat estimates at 10⁵⁴, 11²⁴, and 11⁵⁴ GMT (with weights 0.25, 0.5, and 0.25). For Bergen, which is run according to Local Apparent Time (5°19'E), the ground observation for e. g. the hour 11³⁰ - 12³⁰ LAT is compared to the average of Heliosat estimates at 11²⁴ and 11⁵⁴ GMT. Note that the impact of the remaining minor time shifts is substantially reduced by comparing averages and distributions of actual global / clear sky global irradiation rather than comparing individual pairs of corresponding hourly irradiances (see below).

3. RESULTS

3.1 The clear sky index

The clearness index for a given period is most commonly obtained by dividing the actual global irradiation H (observed or satellite-derived) by the extraterrestrial global irradiation H_{ex} . In the present

note, we instead choose to divide by an "average" cloud-free irradiation H_0 , and thus obtain the clear sky index k :

$$k = H/H_0. \quad (1)$$

Here H may be an observed irradiation or an irradiation derived from Meteosat data by the Heliosat Version 2n.

Fig. 2 compares two different models of clear sky irradiance. There is a nice agreement between Heliosat Version 2n and the McMaster (Davies & McKay 1989) model. The slight phase shift in seasonal variation between McMaster and Heliosat Version 2n is due the fact that McMaster accounts for the seasonal variation in atmospheric water vapor/turbidity while Heliosat Version 2n implies a constant Linke turbidity factor = 3. Note that the $V2n / McMaster$ ratio varies in a stepwise manner due to the fact that the input data to McMaster are monthly averages, which varies stepwise from one month to the next.

Fig. 3 compares hourly irradiances observed during cloudless days at Bergen (1451 hrs during 1965 - 1996) and corresponding values obtained from three different models i) - iii): i) the Heliosat model Version 2n with Linke turbidity = 3.0, ii) the McMaster model with estimated climatological averages of water vapor and turbidity, iii) the McMaster model with water vapor and turbidity approximately halved and all-wave single scattering albedo reduced from 0.75 to 0.35. It is seen that all these three models nicely reproduce the observed global irradiances from Bergen. The Heliosat 2n model even reproduces the average observed diffuse (shading disk) and beam (global - diffuse) irradiances, while water vapor, turbidity and single scattering albedo need to be reduced below climatological averages to make the McMaster model reproduce the observed splitting of global irradiance into its diffuse and beam components. Moreover, this overall pattern seen in Fig. 3 is even seen within each of five solar elevation intervals (Fig. 4).

The diffuse irradiances in Fig. 4 are measured with shading disk, while the beam irradiances are obtained as global - diffuse. During 1991 - 1996 beam irradiances are even measured with Eppley Normal Incidence Pyrheliometer (NIP). Measured global irradiances, beam irradiances either measured by NIP or as (global - shading disk diffuse), and diffuse irradiances either measured with shading disk or as (global - NIP) are plotted against values modelled by McMaster with estimated climatological water vapor and turbidity as input (Fig. 5) and even against solar elevation (Fig. 6). Moreover, irradiances recorded within 2.5 years after the eruption of Mt. Pinatubo are identified. The pattern is the same when diffuse and beam are estimated from global and NIP as it is when the estimate is based on global and shading disk. For beam, the average ratio observed / McMaster is 1.13-1.15 during the "non Pinatubo" part of the 6 year period 1991 - 1996, while the ratio is 0.98 - 1.01 during the "Pinatubo" part of that period. For the whole 1965 - 1996 period, the corresponding average ratio (1.07) is intermediate between the two above ratios. Moreover, some 60% of the "Pinatubo" decrease in beam irradiance is compensated by increased diffuse irradiance. Thus, a some 4% reduction in global irradiance makes the average cloudless diffuse / global ratio increase from 0.14-0.15 during the "non Pinatubo" part of the 6 year period to 0.21-0.23 during the "Pinatubo" part of the period.

In summary, the Heliosat Version 2n model with Linke turbidity = 3.0 and the McMaster model with estimated climatological input data yields nearly the same cloud free global irradiances, and these model estimates agree nicely with observed values at Bergen. The splitting of cloud free global irradiance into its beam and diffuse components differ, however, somewhat between these two models. Moreover, observed cloudless diffuse / global ratios are highly sensitive to atmospheric composition.

In this work all clear sky indices refer to the Heliosat Version 2n model (Kasten/Dumortier model).

3.2 Frequency distributions

Observed hourly clear sky indices at 9 northern stations are plotted against their Heliosat Version 2n counterparts for snow free conditions (Fig. 7) and for not entirely snow free conditions (4 stations, Fig. 8). For snow free conditions, the average obs / satellite ratio ranges from 0.95 to 1.00 among the 9 stations, while it for not snow free conditions ranges from 1.05 to 1.09 among 4 stations. This probably indicates that the Heliosat model tend to interpret ground snow cover as cloud cover and thus underestimate the global irradiance for scenes with snow cover and partial or no cloud cover.

Frequency distributions of hourly clear sky indices (ground truth and satellite derived) at the 9 northern stations were formed for hours with solar elevation within several intervals. For solar elevations $\geq 20^\circ$, the satellite derived distributions (Figs. 9-10) reasonably well reproduce the characteristic bimodal pattern of the distribution observed at the surface, which is characteristic of this climatic region (Skartveit & Olseth, 1992).

For solar elevation $> 10^\circ$ we form (1) the distribution of hourly clear sky indices k observed at the ground and (2) the corresponding distribution of Heliosat Version 2n cloud indices n . We next plot "percentile match curves" as follows: the lowest k against the highest n , the second lowest k against the second highest n , ..., the highest k against the lowest n . During the snow-free period, these curves vary only moderately between the 9 stations (Fig. 11), and for the central 95% of the distributions they are close to the following straight line:

$$k = 1 - n, \quad (2)$$

applied in Heliosat Version 2n. During the not entirely snowfree periods, a significant number of high clear sky indices is not reproduced by Heliosat Version 2n (Fig. 12), most probably because Heliosat tend to interpret cloud free scenes with snow as partly cloud covered scenes.

Fig. 13 indicates that for high cloud indices, Heliosat Version 2n tends to overestimate ground truth clearness index for high solar elevations and underestimate ground truth for low solar elevations. For low cloud indices (nearly cloud free) the ground truth / Heliosat 2n ratio appears to be close to unity and more independent of solar elevation.

Fig. 14 demonstrates that the above "percentile match" curves are in fact close to the average of linear regression lines between k and n calculated with (1) k as dependent variable and n as independent variable, and with (2) n as dependent variable and k as independent variable.

3.3 Overall and daily clear sky indices

Fig. 15 shows satellite derived overall clear sky indices at each of the 9 stations, plotted versus their surface observed counterparts. The spatial variation of ground observations is reasonably well reproduced by the Heliosat Version 2n data, both within solar elevation intervals and for all solar elevations collectively. The observed clear sky index for all snow-free data (9 stations) is 0.632, while the satellite-derived counterpart is 0.649 (Table 1). The individual average clear sky indices for the 9 stations range from 0.568 to 0.713 for surface observed data, and from 0.583 to 0.733 for satellite-derived data. The root-mean-square-deviation (surface vs satellite) of these individual averages is 0.021, which is some 14.5% of the inter-station range observed at the surface. For the possibly snow-affected data (4 stations) the overall mean bias deviations and the root-mean-square-deviation is a factor of about 1.5 larger than for the snow-free data (Table 1).

Observed daily clear sky indices and daily irradiances at all 9 stations are plotted against

indices/irradiations retrieved from Meteosat data by Heliosat Version 2n both for snow free periods and for not snow free periods (Fig. 16). A reasonable conformity between surface and satellite derived daily indices is seen. For 1186 snow free days the average ground truth / Heliosat irradiation ratio is 0.96, while the ratio is 1.03 for 137 not entirely snow free days.

3.4 Diffuse irradiance

Frequency distributions of hourly diffuse clear sky indices (ground truth and satellite derived) at the 3 northern stations with diffuse data were formed for hours with solar elevation within several intervals. A reasonable ground truth versus satellite agreement is seen (Fig. 17), but the Heliosat Version 2n data covers a somewhat more narrow range than do the ground truth data. Moreover, the Heliosat data shows a much more pronounced bimodal distribution pattern which is not seen in the ground truth data.

Observed (ground truth) daily diffuse irradiances are plotted against their counterparts derived from Heliosat Version 2n for the three northern stations with diffuse data (Fig. 18). For 410 snow free days the average ground truth / Heliosat ratio is 1.01, while the ratio is 0.92 for 14 not entirely snow free days.

3.5 The model of Ineichen (1997)

Observed hourly global clear sky indices at Geneva are plotted against corresponding values modelled from Heliosat Version 2n and from the model proposed by Ineichen (1997). The summer (June - Sep) average ground truth / model ratio is 0.85 for Heliosat Version 2n and 0.94 for the Ineichen model, while the winter (Dec - March) average ratio is 0.95 and 1.03, probably again indicating that the winter Heliosat values tend to be too low since some snow cover are interpreted as clouds.

Frequency distributions (Fig. 20) of hourly clear sky indices at Geneva reveal that Heliosat Version 2n indices during summer cover a somewhat wider range than do the ground truth indices, while the opposite is true for the Ineichen indices. During winter, however, both models fail to reproduce the highest ground truth indices. Moreover, it is noteworthy that the “percentile match curves” for some reason are markedly less linear at Geneva (Fig. 20) than they are at the above 9 northern stations (Fig. 11).

Frequency distributions of observed (ground truth) hourly clear sky indices at the 9 northern stations are plotted (Fig. 21) along with corresponding distribution derived from Meteosat data by the Ineichen model. It is seen that the clear sky mode is moved towards a too low clear sky index value, and the ground truth versus satellite agreement is thus not as accurate as the corresponding agreement seen for the Heliosat Version 2n model in Fig. 9.

Frequency distributions of hourly diffuse clear sky indices (ground truth and Ineichen model) at 3 northern stations are plotted in Fig. 22. In much the same way as with the Heliosat Version 2n model (Fig. 17), the satellite derived (Ineichen) diffuse indices cover a somewhat more narrow range than do the ground truth indices. In addition, contrary to the Heliosat diffuse indices in Fig. 17, the satellite derived (Ineichen) diffuse indices in Fig. 22 tend to be on the average somewhat lower than the ground truth indices.

4. CONCLUDING REMARKS

The Heliosat Version 2n model with Linke turbidity = 3.0 and the McMaster model with estimated

climatological water vapor and turbidity as input yields nearly identical cloud free global irradiances, and these modelled values agree nicely with observed cloud free irradiances at Bergen. The splitting of cloud free global irradiance into its beam and diffuse components differs, however, somewhat between the two models. Moreover, observed cloudless diffuse / global ratios are highly sensitive to atmospheric composition.

During the 245 days period March 27. - November 26. 1995, hourly observations of global irradiance at 9 high latitude ground stations show approximately the same frequency distribution as do corresponding data derived from Meteosat data by the Heliosat Version 2n model.

The Heliosat Version 2n data reasonably well reproduce the day to day variation in clear sky index, and even the spatial variation observed between 9 high latitude ground stations.

The occurrence of snow cover reduces the agreement between surface observations and satellite derived data.

The hourly diffuse irradiances derived from Heliosat Version 2n vary over a somewhat more narrow range than do the corresponding observed (ground truth) values at three northern stations, and they even show a bimodal distribution pattern which is not seen with the ground truth data. The average diffuse irradiance and the day to day variation of diffuse irradiation is nicely reproduced by the Heliosat Version 2n model.

For the northern stations the agreement between ground truth (global and diffuse) and data derived from Meteosat by the Ineichen (1997) model is not as accurate as the corresponding agreement seen for the Heliosat Version 2n model.

Heliosat derives surface global irradiance from actual satellite counts along with corresponding cloud-free, respectively overcast, reference counts. The success of Heliosat critically depends on an adequate predetermination of these cloud-free/overcast reference counts. Our data demonstrate that a variable snow-cover strongly hampers an adequate predetermination of cloud-free reference counts, particularly in rural areas.

5. REFERENCES

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Table 1 Geographical coordinates and elevation above sea level for 9 northern stations, along with average clear sky indices observed at surface and derived from Meteosat by Heliosat Version 2n for the snow-free period and the period possibly affected by snow.
(MBD = Heliosat Version 2n - Observed).

<u>Station</u>	Lat., long., elev. (°N °E m asl.)			No snow			"Snow"		
				<u>Obs.</u>	<u>V2n</u>	<u>MBD</u>	<u>Obs.</u>	<u>V2n</u>	<u>MBD</u>
Kvithamar	63°27'	10°57'	30	0.568	0.584	0.016	0.597	0.561	-0.036
Furuneset	61°22'	5°35'	10	0.608	0.613	0.005			
Løken	61°08'	9°08'	525	0.622	0.644	0.022	0.703	0.669	-0.034
Apelsvoll	60°43'	10°51'	250	0.612	0.646	0.034	0.707	0.648	-0.059
Gävle	60°40'	17°10'	16	0.683	0.682	-0.001			
Bergen	60°24'	5°19'	45	0.589	0.603	0.014			
Ås	59°40'	10°51'	90	0.636	0.669	0.033	0.736	0.700	-0.036
Særheim	58°48'	5°08'	85	0.653	0.668	0.015			
Landvik	58°19'	8°30'	6	0.713	0.733	0.020			
<u>Overall</u>				<u>0.632</u>	<u>0.649</u>	<u>0.017</u>	<u>0.686</u>	<u>0.645</u>	<u>-0.041</u>

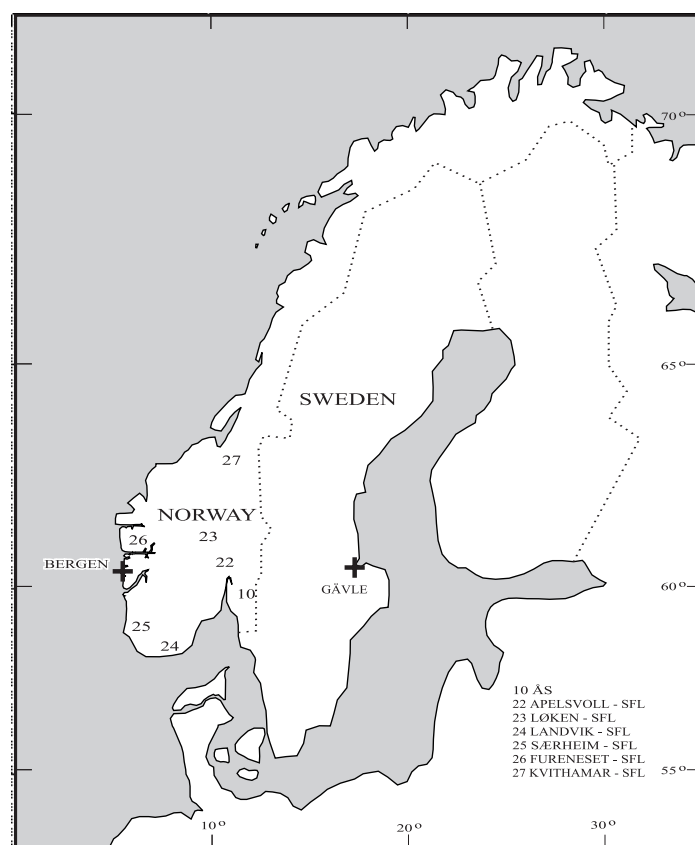


Fig. 1 Map with 9 ground stations plotted: Bergen (University of Bergen), Gävle (Royal Institute of Technology), Ås (Norwegian Agricultural University), and 6 stations run by the Norwegian Crop Research Institute (SFL).

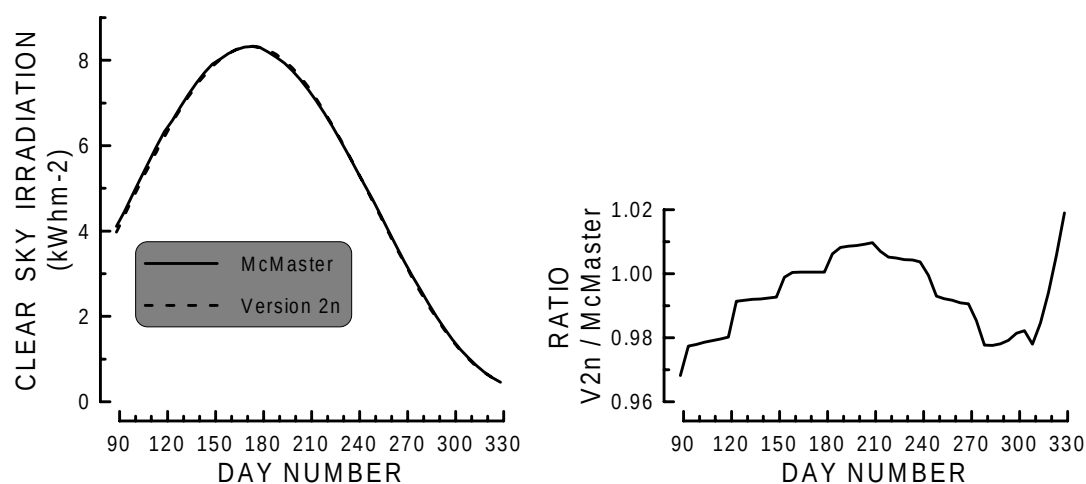


Fig. 2 Left: Daily average clear sky irradiation modelled by the McMaster model and by Heliosat Version 2n [average over 5 days, 9 stations (Table 1), and hours with solar elevation above 10°]. Right: Ratios between the daily averages at the left.

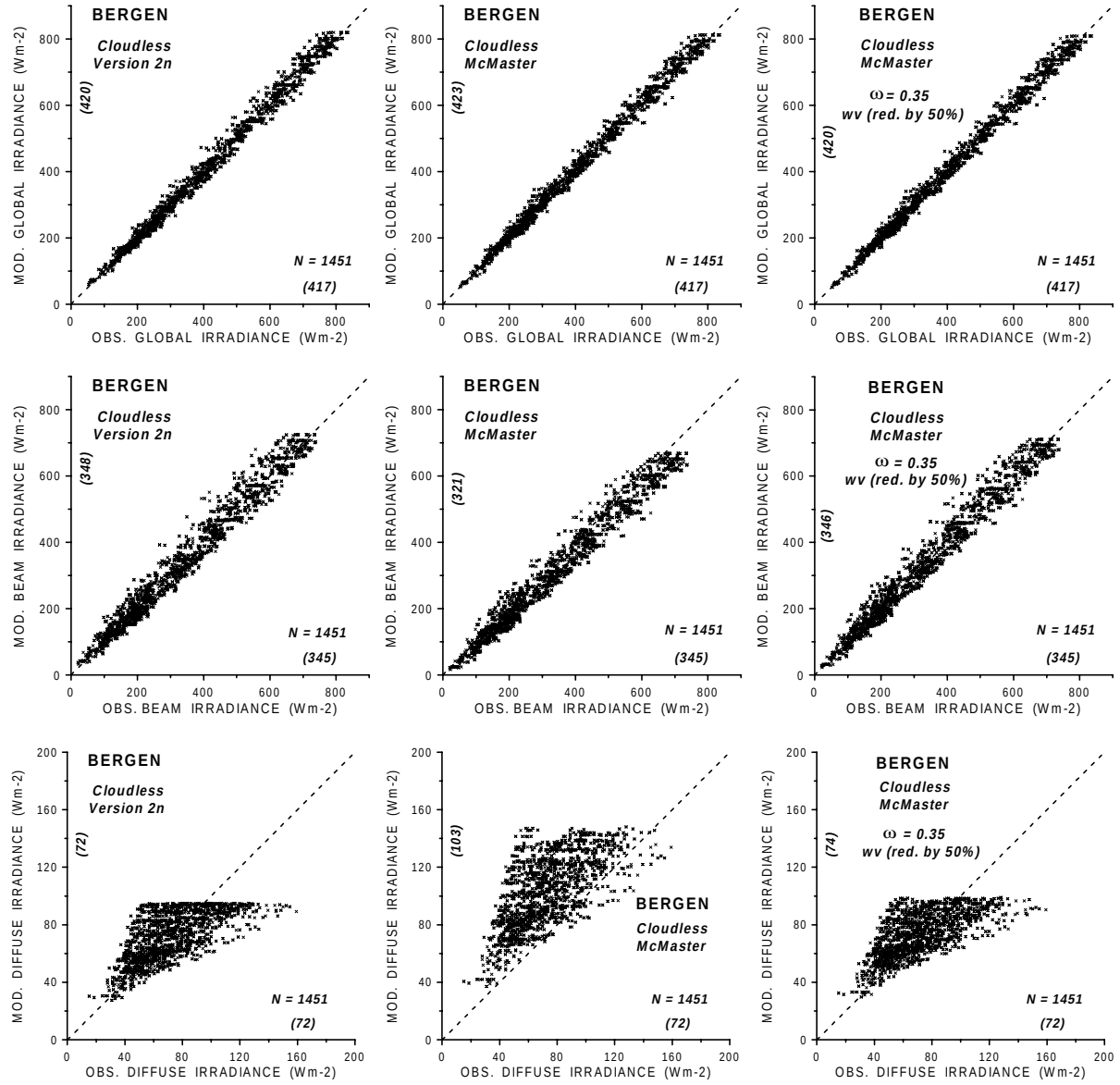


Fig. 3 Observed vs modelled hourly global (upper row), horizontal beam (middle row), and horizontal diffuse (lower row) irradiance for cloudless days in Bergen (1965-1996). The models used are Heliosat Version 2n (with Linke turbidity=3; left column), McMaster (with monthly averages of water vapor and turbidity as input; middle column), and McMaster (with modified input [see text]; right column). Number of hours (N) are given together with observed and modelled averages (given as Wm⁻² in parentheses along the axes).

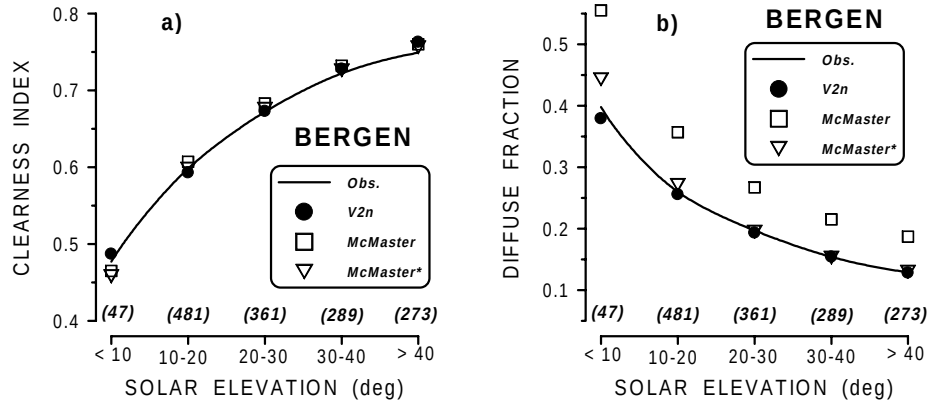


Fig. 4 a) Observed clearness index and b) diffuse fraction plotted vs. solar elevation for cloudless days at Bergen (1965-96), along with values modelled by the clear sky models Heliosat V2n (Linke turbidity=3) and McMaster (with montly averages of water vapor and turbidity as input, and with modified input (* see Fig. 3 and text). Note that the "observed" curves are cubic splines through observed group mean values within solar elevation intervals, with number of hours per group given in parenthesis along the abscissa.

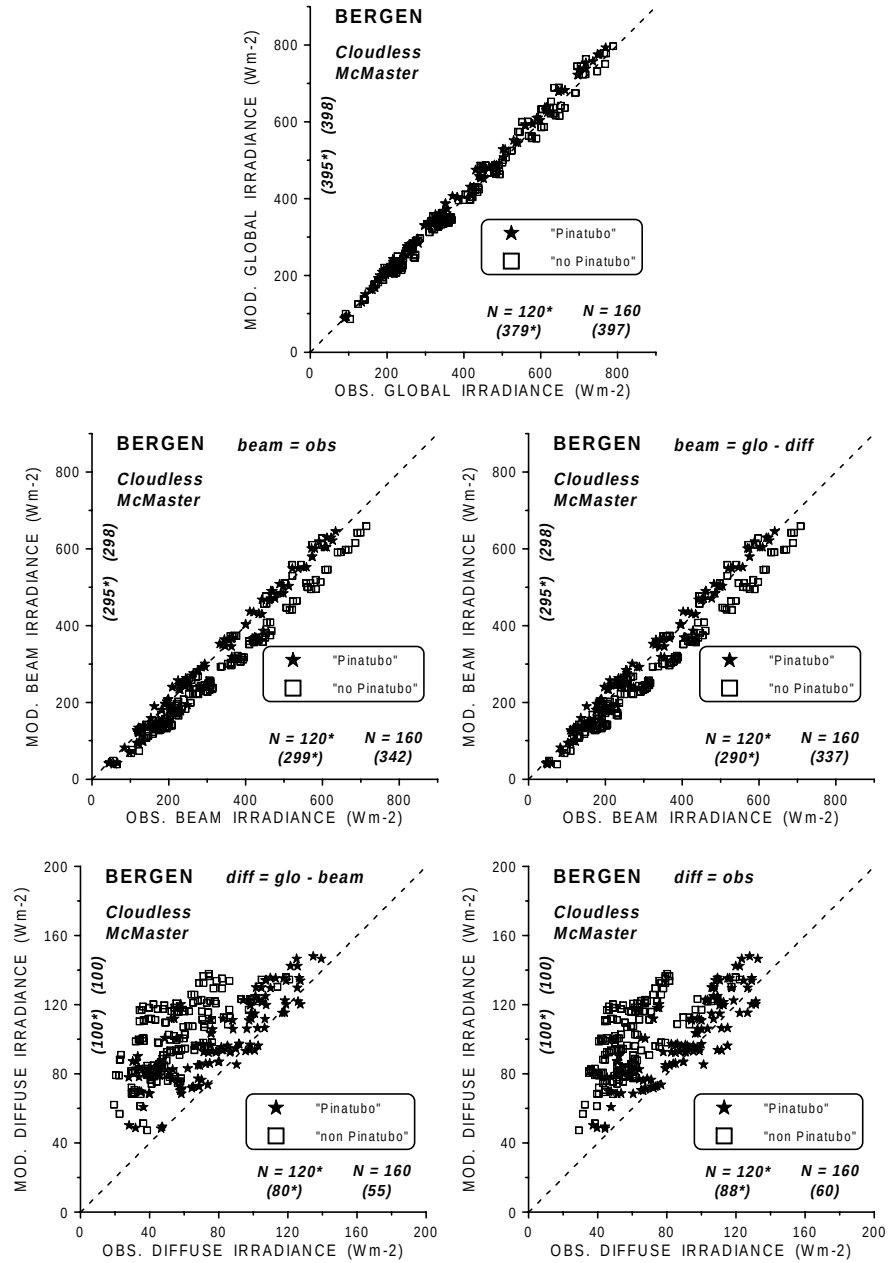


Fig. 5 Observed vs modelled (McMaster with monthly averages of water vapor and turbidity as input) hourly global (upper row), horizontal beam (middle row), and horizontal diffuse (lower row) irradiance for cloudless days in Bergen (1991-1996). The data are divided into two periods (the period affected by Pinatubo [autumn 1991 - end of 1993], and the period not affected). For beam and diffuse irradiance the results are shown for beam irradiance observed by Eppley NIP (beam = obs. and diffuse = global - beam; left) and diffuse irradiance observed with shading disk (beam = global - diffuse and diffuse = obs.; right). The number of hours (N) and the observed and modelled averages (in parentheses) for the two periods are also given.

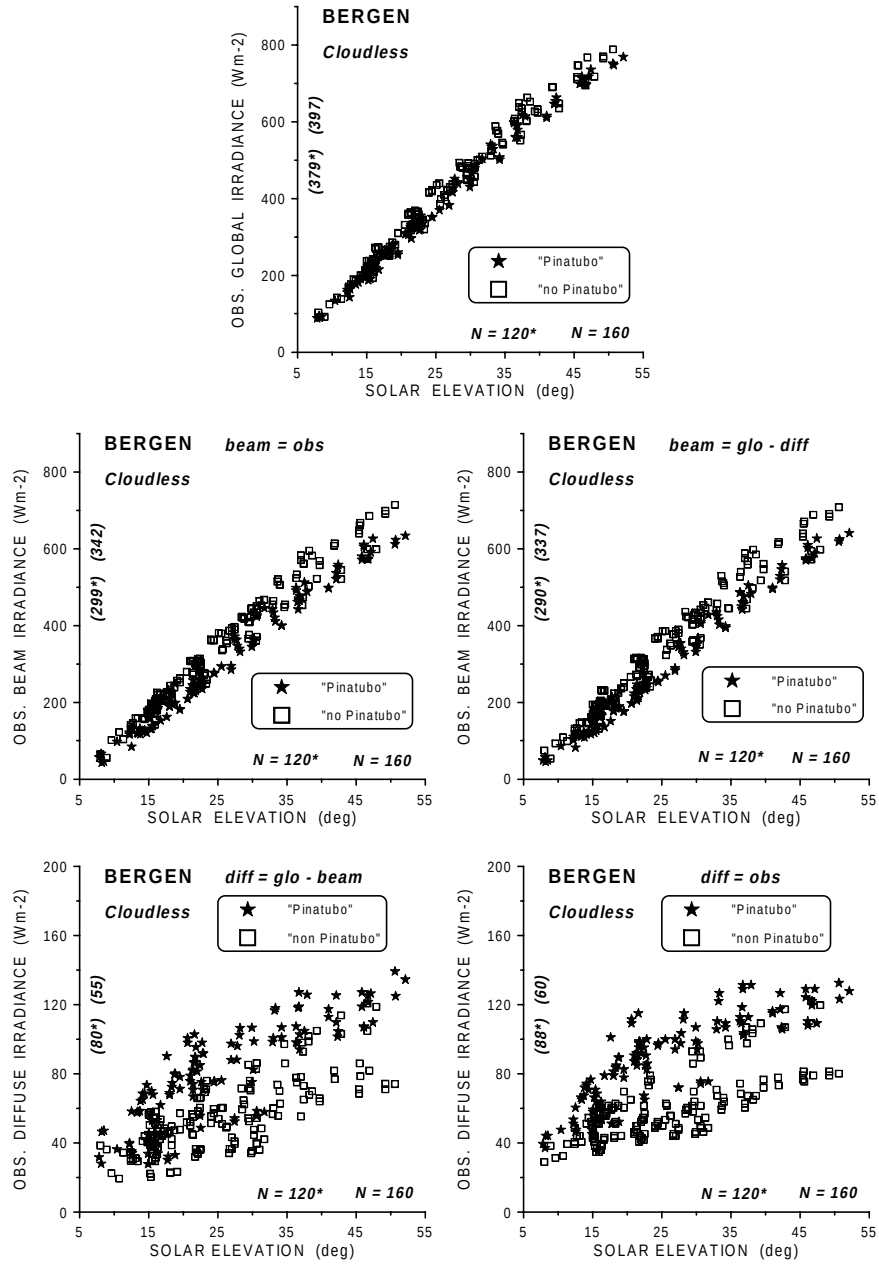


Fig. 6 The observed hourly global (upper row), horizontal beam (middle row), and horizontal diffuse (lower row) irradiances in Fig. 5 plotted vs solar elevation. The number of hours (N) and the modelled averages (in parentheses) for the two periods are also given.

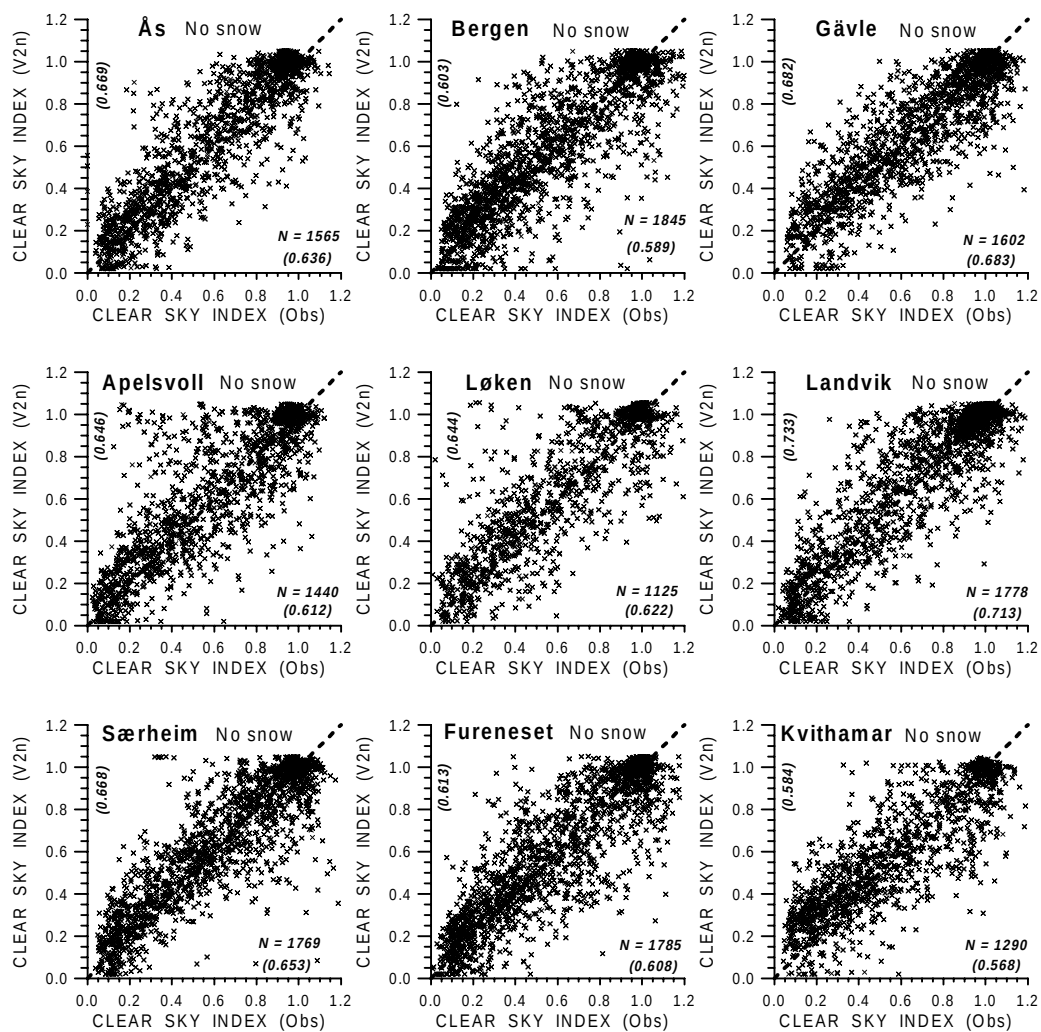


Fig. 7 Observed vs modelled (Heliosat Version 2n) hourly global clear sky index for the snow free periods at 9 northern stations. The number of hours (N) together with observed and modelled averages (in parentheses along the axes) are also given.

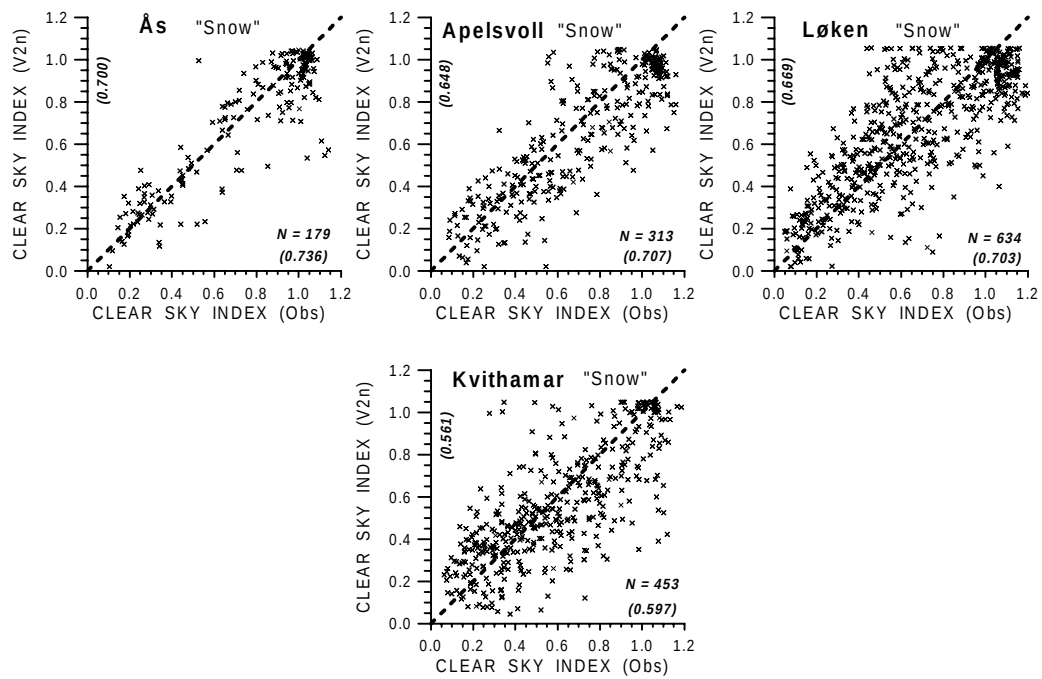


Fig. 8 Observed vs modelled (Heliosat Version 2n) hourly clearness index for the possibly snow-affected periods at 4 northern stations. The number of hours (N) together with observed and modelled averages (in parentheses along the axes) are also given.

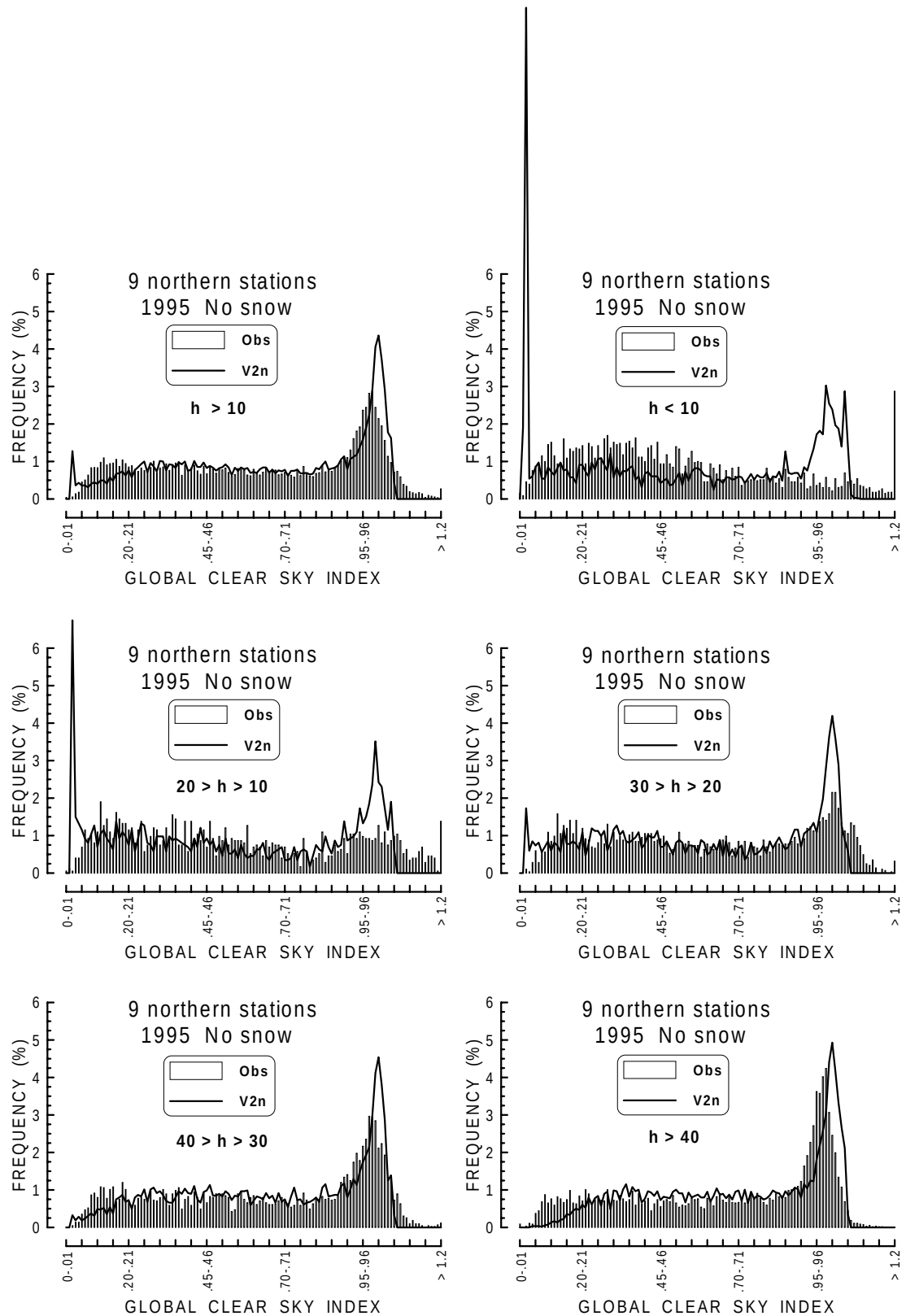


Fig. 9 Observed (histograms) and modelled (Heliosat Version 2n) frequency distributions of hourly clear sky indices for snow-free period at the 9 northern stations in Fig. 7 for different solar elevation (h) intervals.

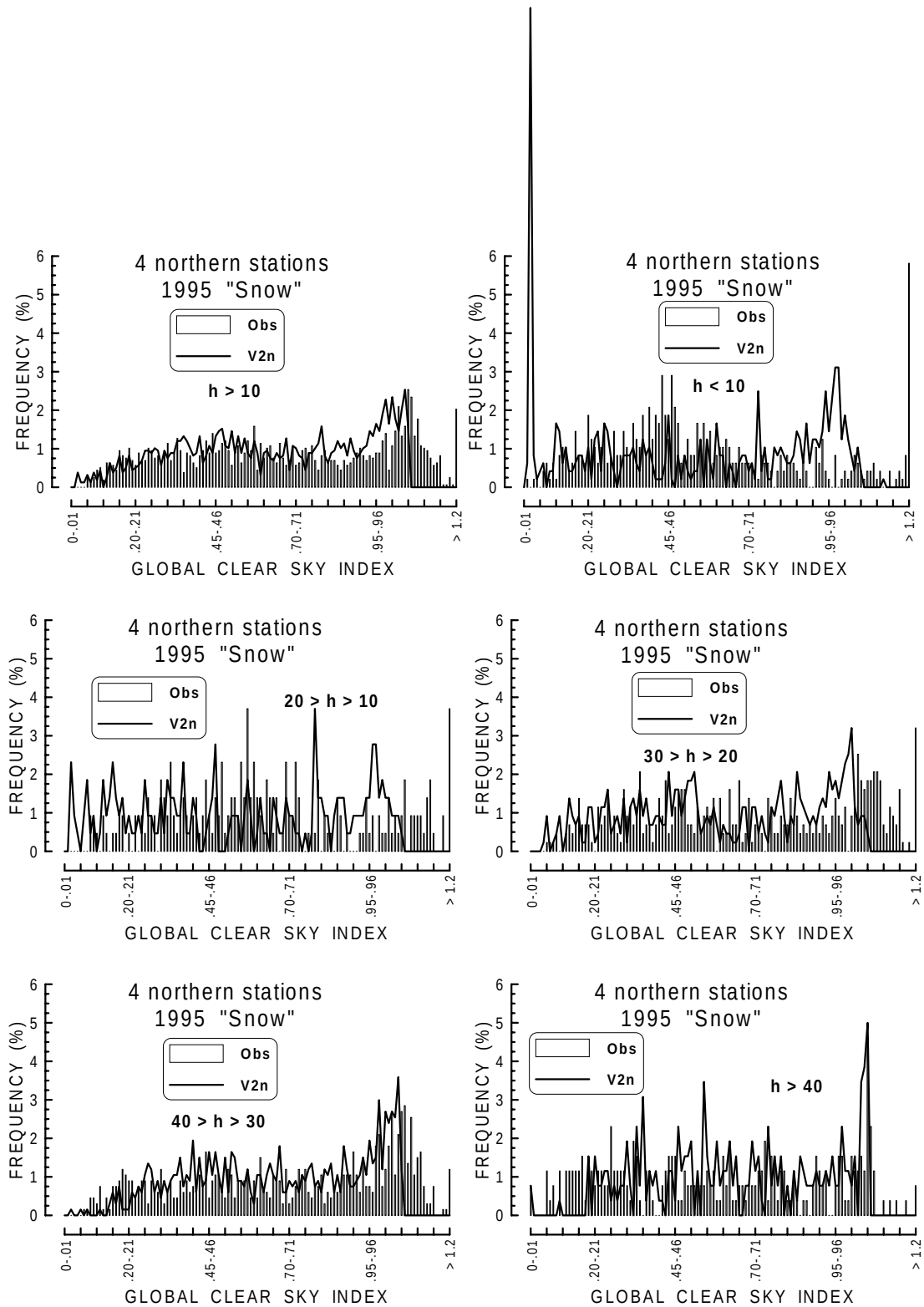


Fig. 10 Observed (histograms) and modelled (Heliosat Version 2n) frequency distributions of hourly clear sky indices for the possibly snow affected period at the 4 northern stations in Fig. 8 for different solar elevation (h) intervals.

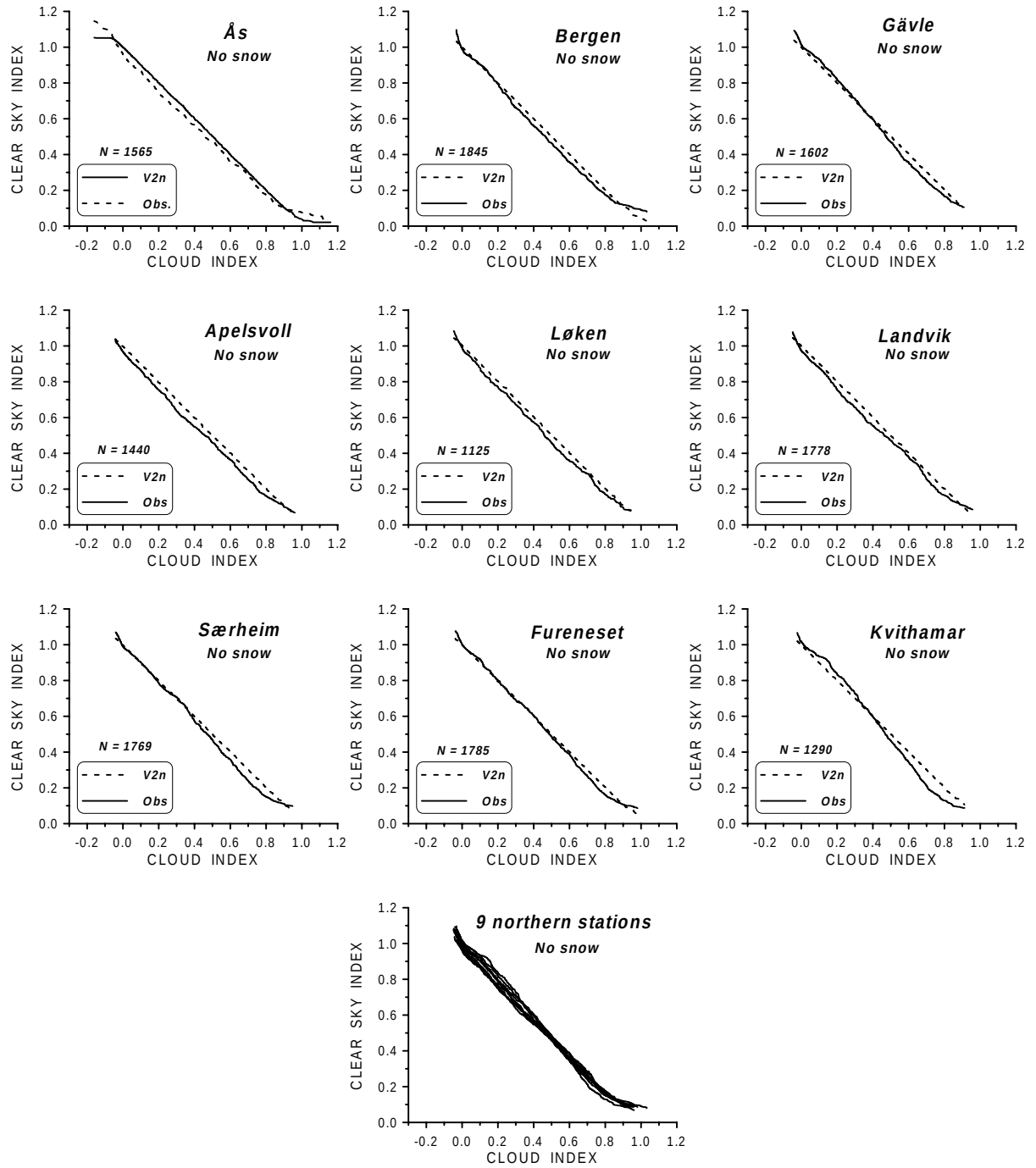


Fig. 11 "Percentile match curves" of hourly clear sky index (observed and modelled from Heliosat Version 2n) and cloud index (modelled from Heliosat Version 2n) [see text] for hours with solar elevation above 10° for the snow-free period at each of the 9 northern stations in Fig. 7. Curves are drawn for the central 95% of the distributions. The number of hours (N) are also given. At the bottom the above observed curves are drawn for all the 9 stations.

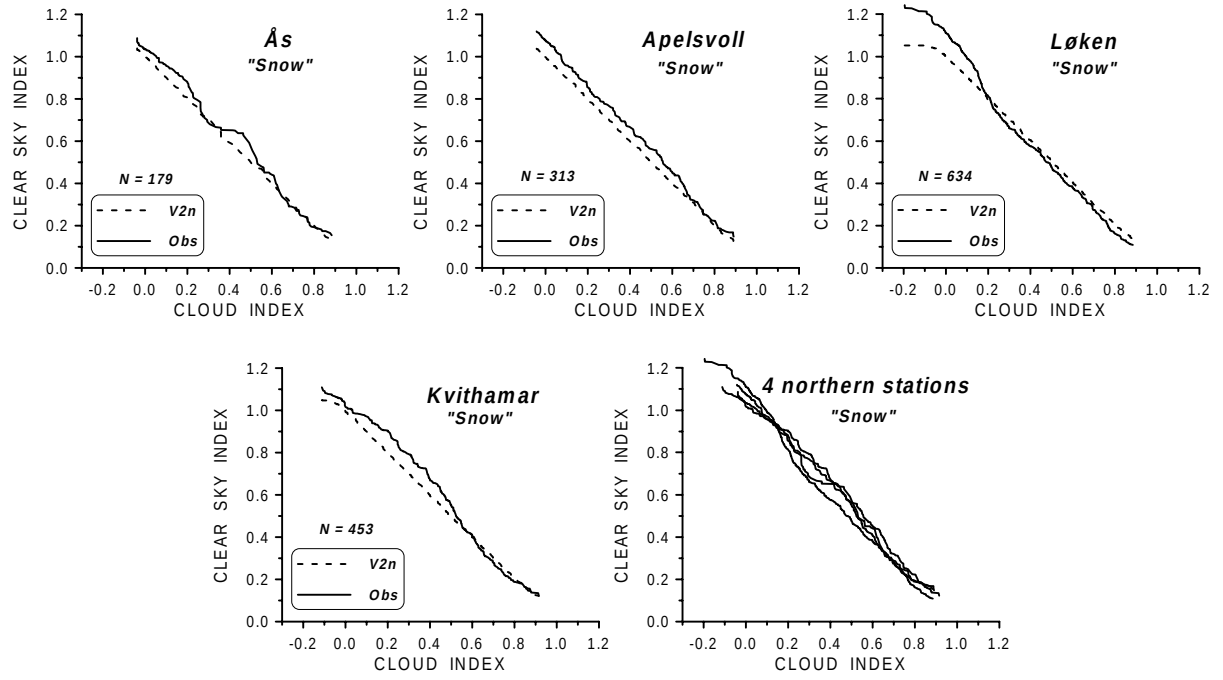


Fig. 12 "Percentile match curves" of hourly clear sky index (observed and modelled from Heliosat Version 2n) and cloud index (modelled from Heliosat Version 2n) [see text] for hours with solar elevation above 10° for the possibly snow-affected periods at each of the 4 northern stations in Fig. 8. Curves are drawn for the central 95% of the distributions. The number of hours (N) are also given. At the bottom right observed curves are drawn for all the 4 stations.

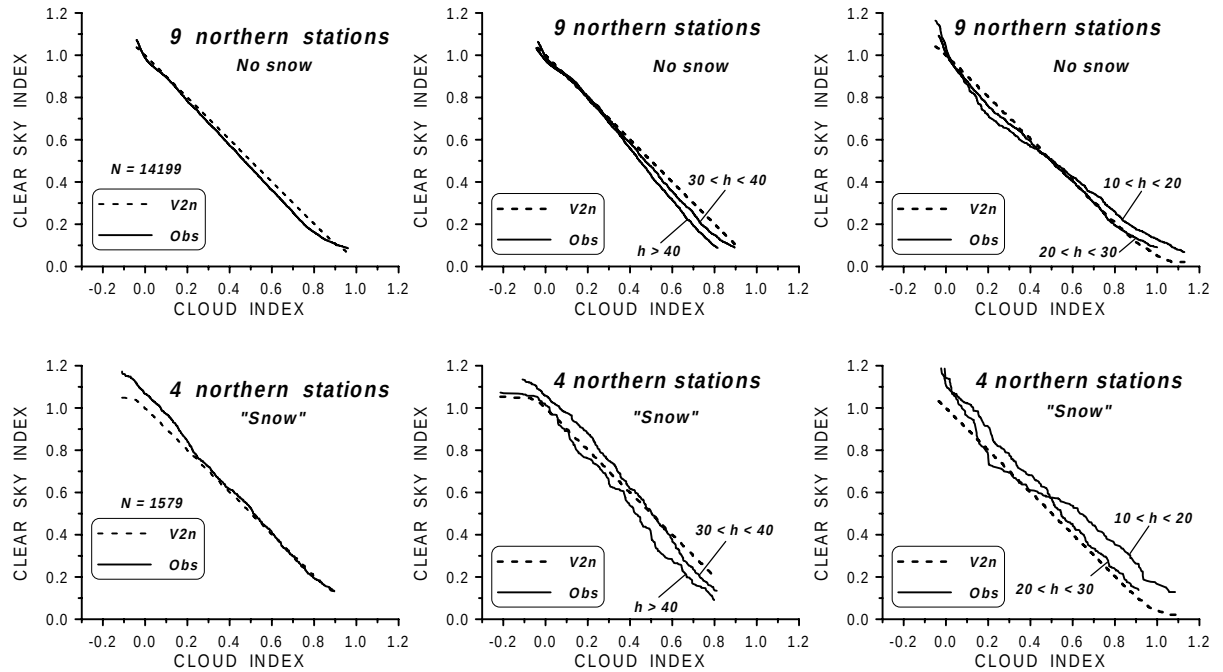


Fig. 13 "Percentile correspondence curves" of hourly clear sky index (observed and modelled from Heliosat Version 2n) and cloud index (modelled from Heliosat Version 2n) [see text] for all hours with solar elevation above 10° (left) and for different solar elevation (h) intervals (middle and right) collectively for the snow-free period at the 9 stations in Fig. 11 (upper row) and for the possibly snow affected periods at the 4 stations in Fig. 12 (bottom row). Curves are drawn for the central 95% of the distributions.

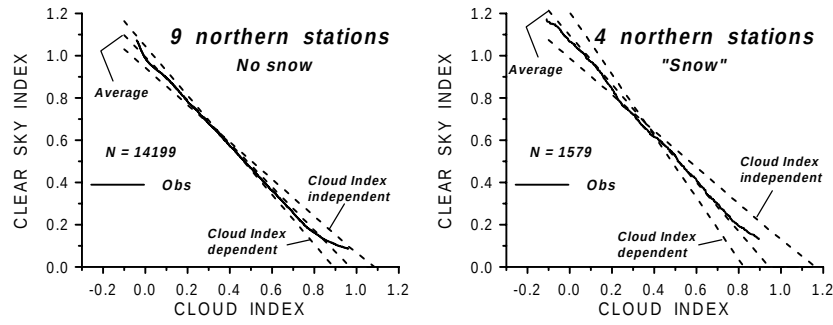


Fig. 14 The "percentile correspondence curves" of observed hourly clear sky index vs modelled cloud index (from Fig. 12, left part) for the snow-free period (left) and for the possibly snow affected periods (right), together with regression lines (with cloud index as independent, respectively dependent variable, and as an average between these two).

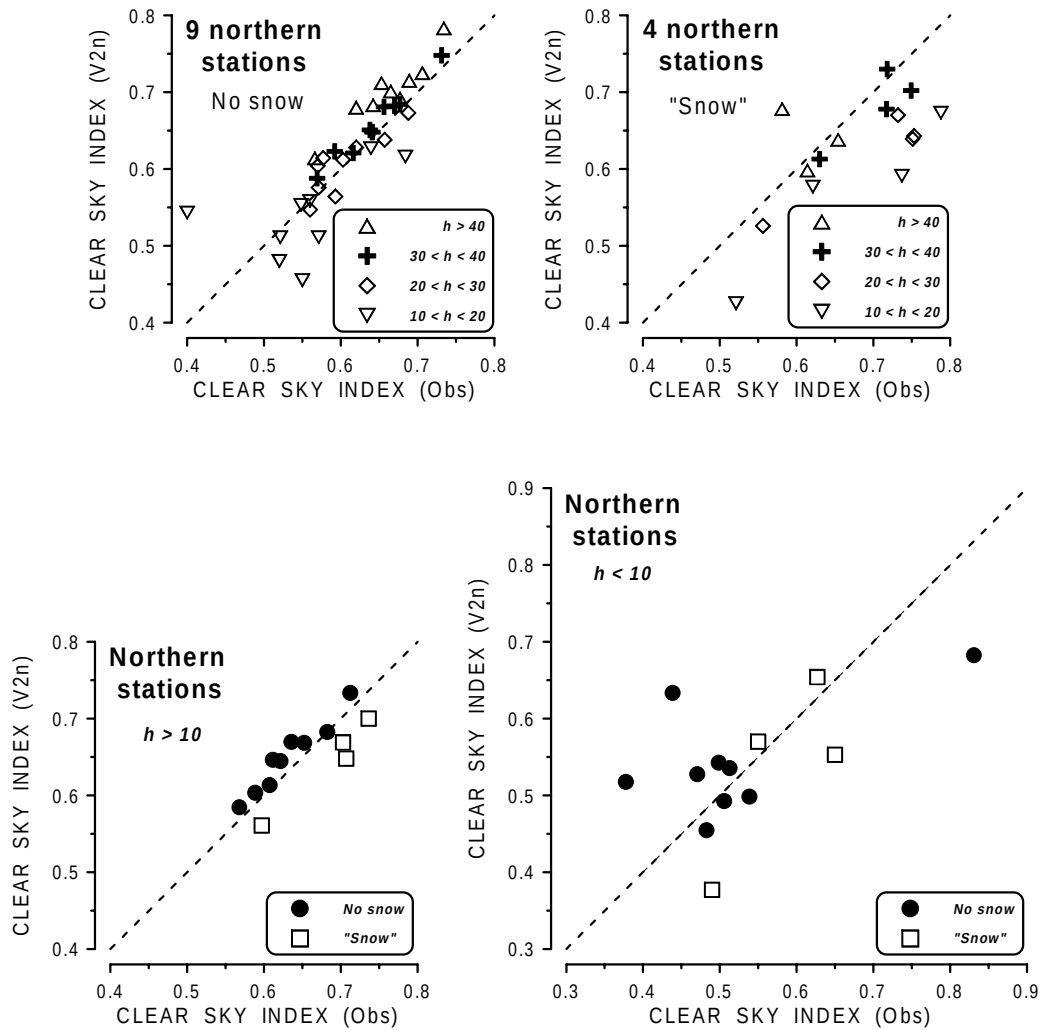


Fig. 15 Upper part: Group mean values of observed vs modelled (Heliosat Version 2n) hourly clearness index for different solar elevation intervals for the snow free periods at 9 northern stations (left) and for the possibly snow affected periods at 4 northern stations (right).

Lower part: Overall mean values for all hours with solar elevation above 10° (left) and below 10° (right) for each of the stations for the snow-free and the possibly snow affected periods.

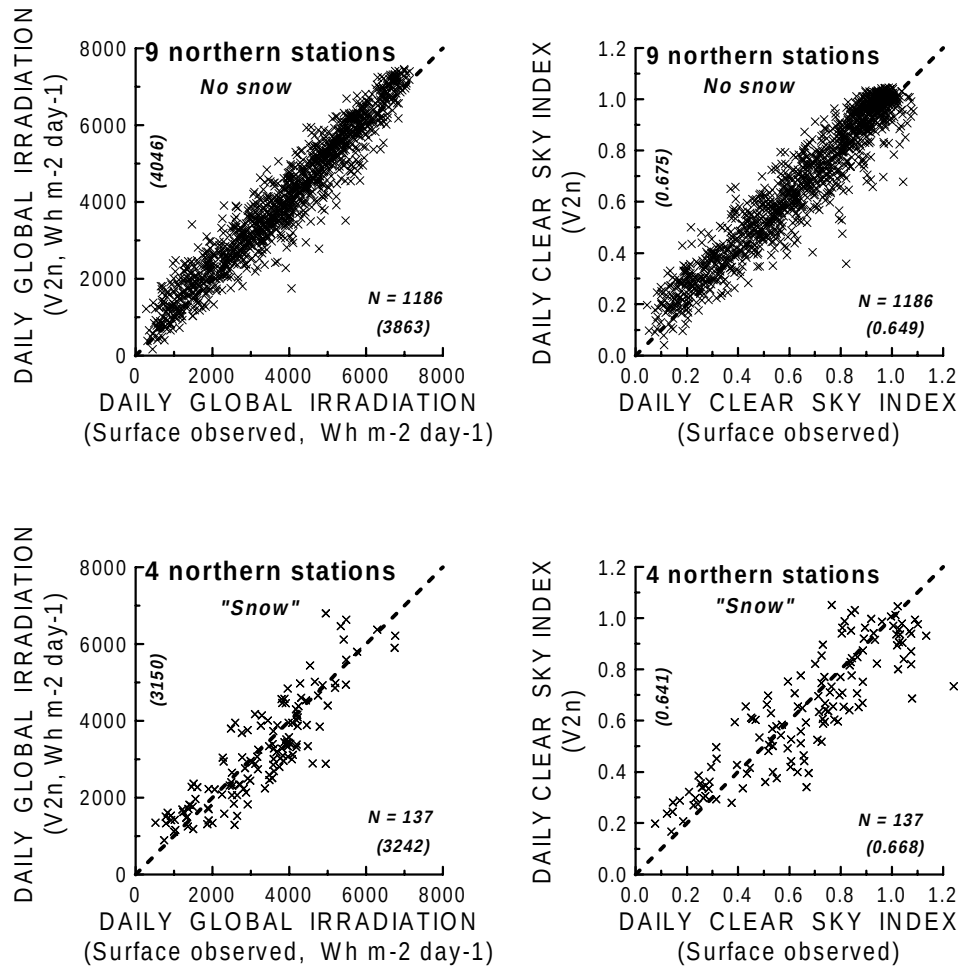


Fig. 16 Observed daily global irradiation (left) and clear sky index (right) plotted against modelled values (Heliosat Version 2n) at snow-free periods at 9 stations (upper) and at possibly snow affected periods at 4 stations (lower). The number of days (N) together with observed and modelled averages (in parentheses along the axes) are also given.

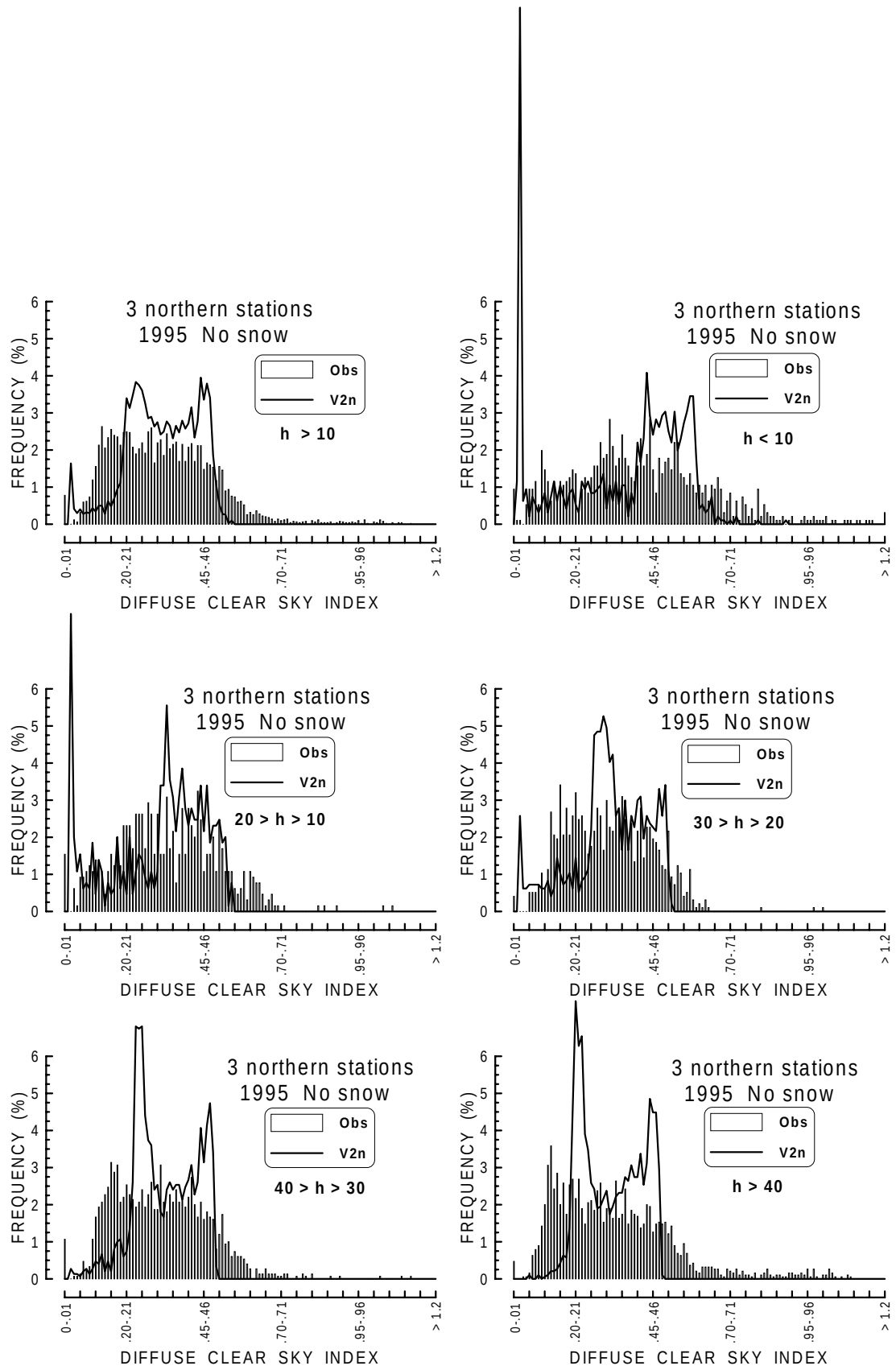


Fig. 17 Observed (histograms) and modelled (Heliosat Version 2n) frequency distributions of hourly diffuse clear sky indices for snow-free period at 3 northern stations (Bergen, Ås, Gävle) for different solar elevation (h) intervals.

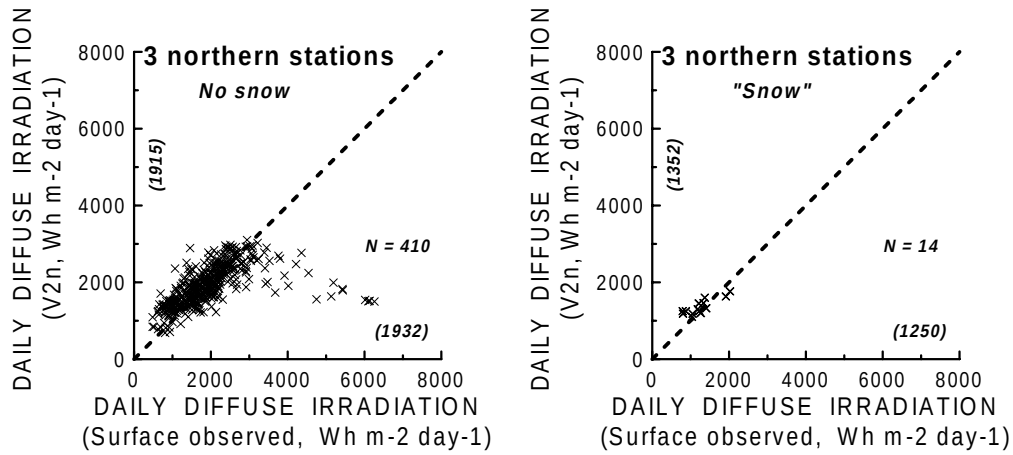


Fig. 18 Observed daily diffuse irradiation plotted against modelled values (Heliosat Version 2n) at snow-free periods at 9 stations (left) and at possibly snow affected periods at 4 stations (right). The number of days (N) together with observed and modelled averages (in parentheses along the axes) are also given.

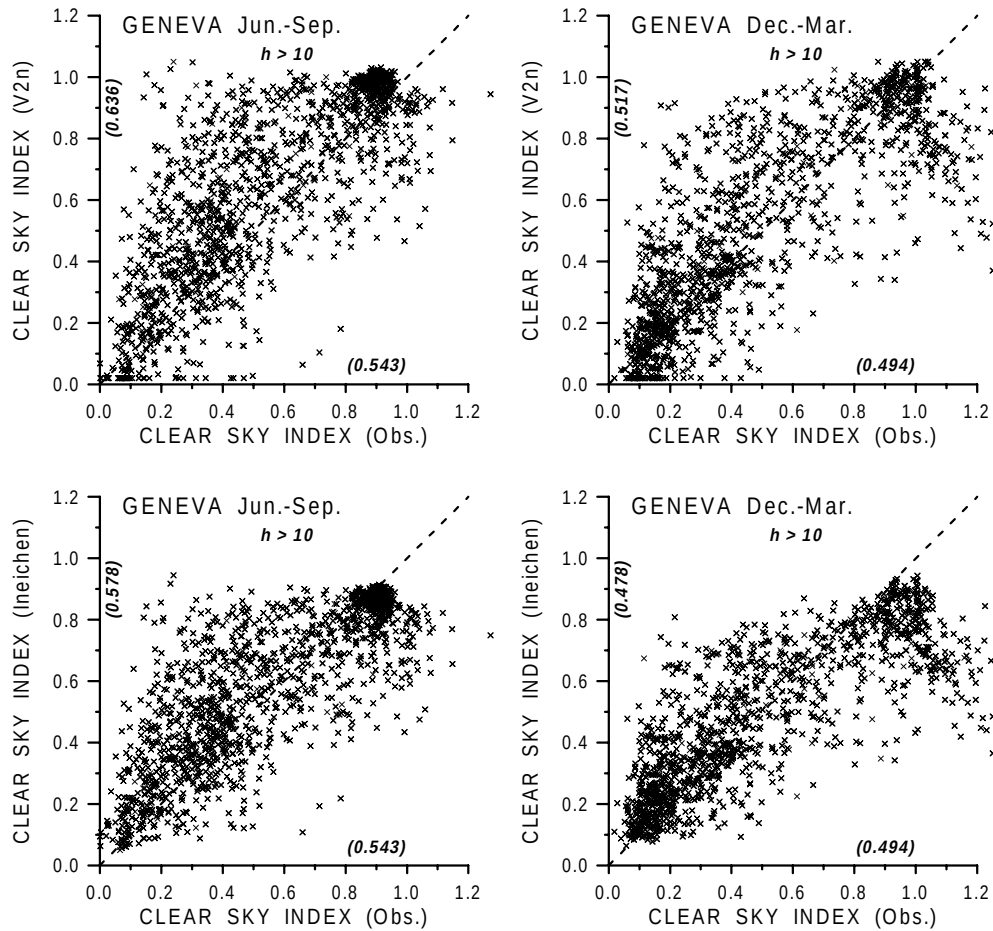


Fig. 19 Observed vs modelled (Heliosat Version 2n, upper and the Ineichen model, lower) half-hourly global clear sky index for the summer (Jun.-Sep., left) and the winter (Dec.-Mar., right) for all solar elevations above 10° at Geneva. Observed and modelled averages (in parentheses along the axes) are also given.

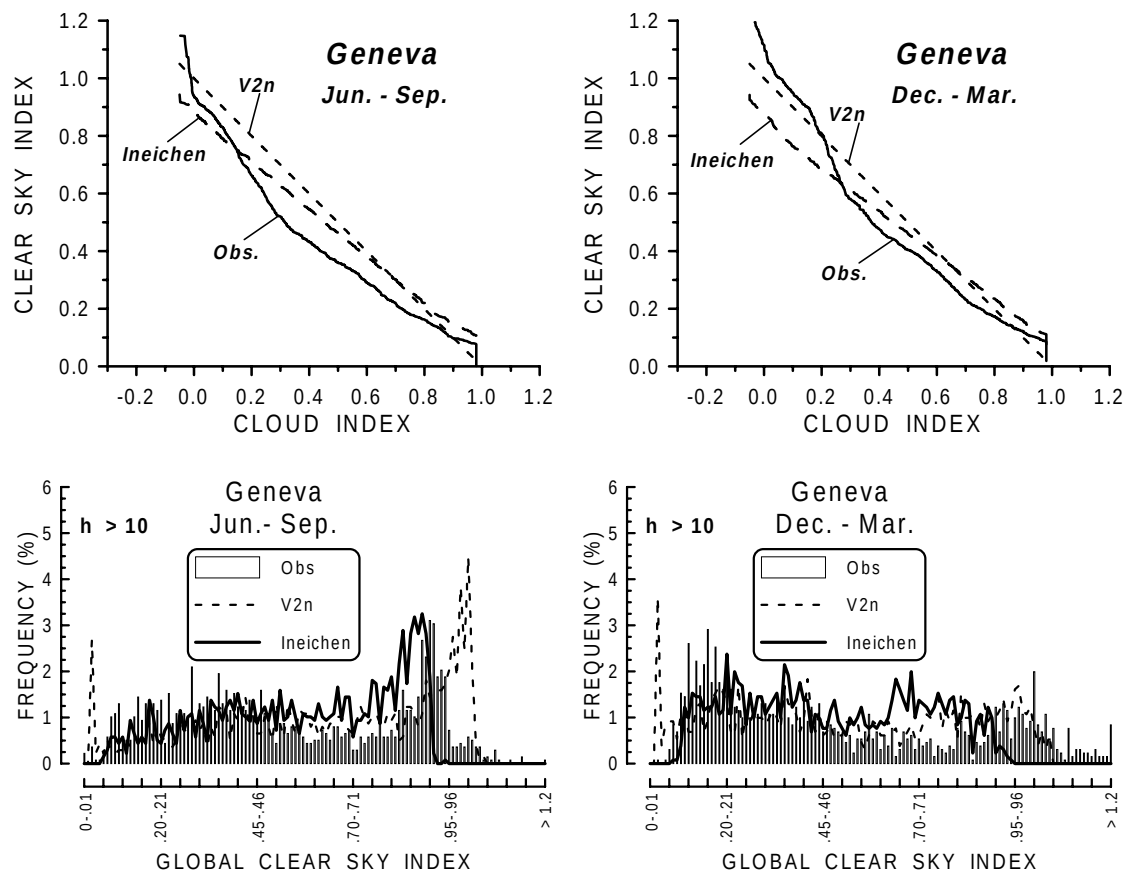


Fig. 20 Upper: "Percentile match curves" of half-hourly clear sky index (observed and modelled from Heliosat Version 2n and the Ineichen model) and cloud index (modelled from Heliosat Version 2n) [see text] for solar elevation above 10° for the summer (Jun.-Sep., left) and the winter (Dec.-Mar., right) at Geneva. Curves are drawn for the central 95% of the distributions.

Lower: Observed (histograms) and modelled (Heliosat Version 2n and the Ineichen model) frequency distributions of half-hourly clear sky indices for solar elevation above 10° for the summer (Jun.-Sep., left) and the winter (Dec.-Mar., right) at Geneva..

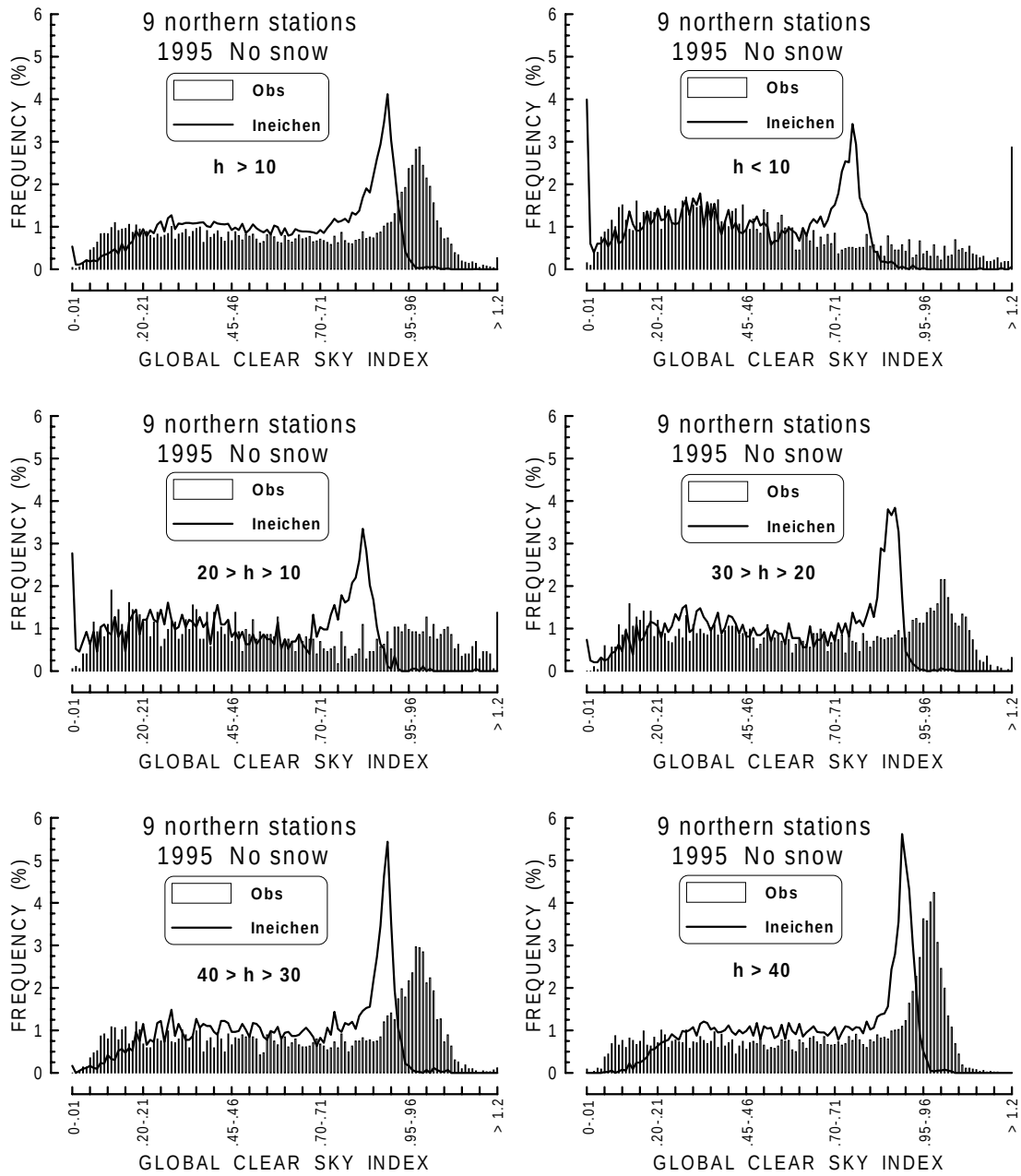


Fig. 21 Observed (histograms) and modelled (Ineichen model) frequency distributions of hourly clear sky indices for snow-free period at the 9 northern stations in Fig. 7 for different solar elevation (h) intervals.

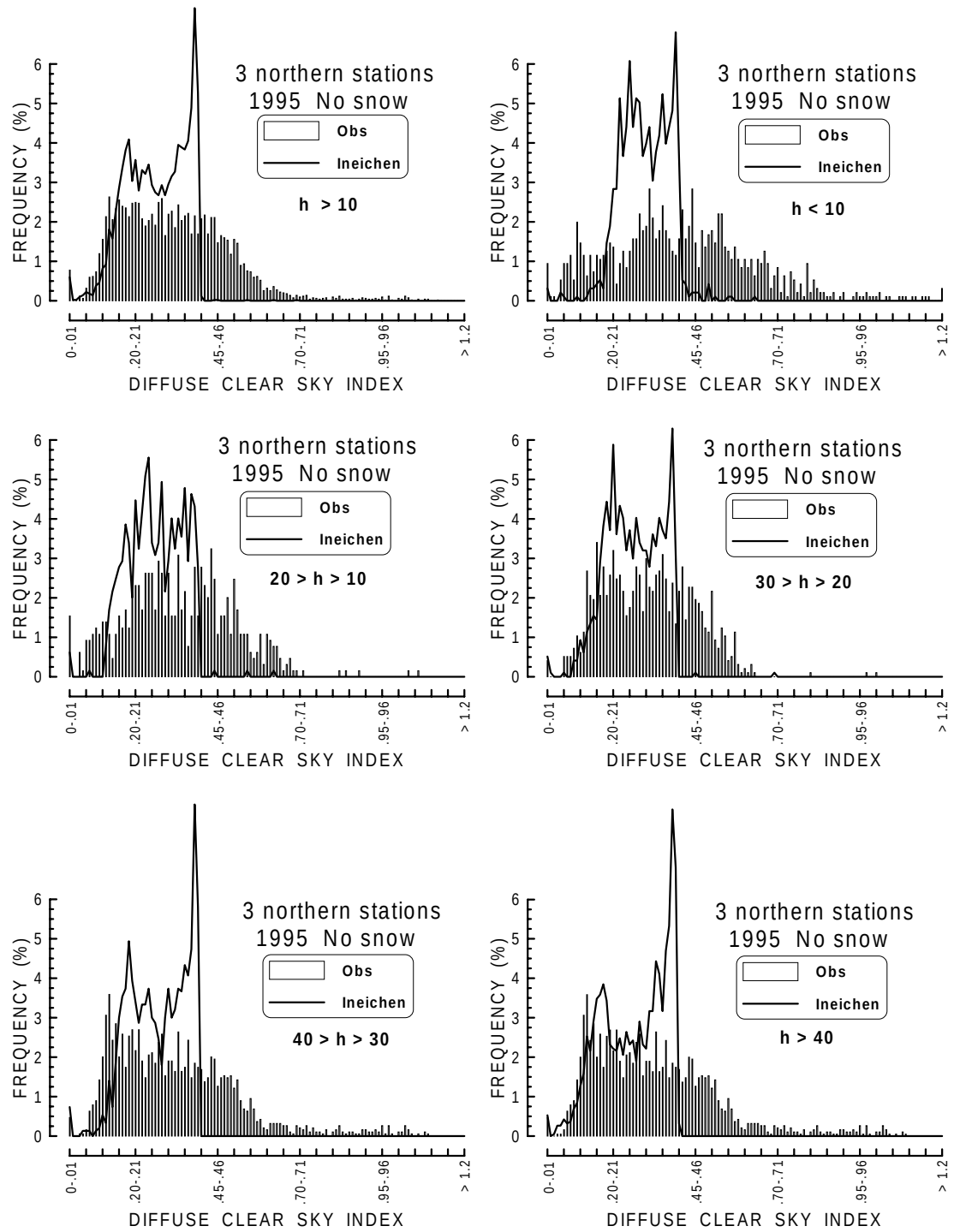


Fig. 22 Observed (histograms) and modelled (Ineichen model) frequency distributions of hourly diffuse clear sky indices for snow-free period at 3 northern stations (Bergen, Ås, Gävle) for different solar elevation (h) intervals.