Comparison of Different Glare Indices through Metrics for Long Term and Zonal Visual Comfort Assessment

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Abstract

Nowadays different indices are used for the assessment of the visual discomfort related to glare, such as Daylight Glare Index, Daylight Glare Probability, and Vertical Eye illuminance. Regardless of their effectiveness in detecting glare perception, all these indices are intended to be local and instantaneous, not summarizing the long term glare perception through the space (Carlucci et al. 2015). In this work, a set of metrics able to express both the time constancy, i.e. availability, and the spatial uniformity, i.e. usability, has been used for detecting discrepancies and inconsistencies between the glare indices when dealing with time and space distribution. Results confirm that different glare indices can lead to different conclusions not only when considering point and instantaneous values but also when analysing availability and usability. Moreover, the availability and usability representations, indirectly confirm themselves effective in providing a global assessment of the confined space analysed, even when visual comfort is concerned.

Introduction

In the past, the visual discomfort related to glare has been described focusing on the contrast ratio between the background average luminance and the glare source luminance, generally an artificial light, without considering the global brightness of the scene (Carlucci et al. 2015). This limitation becomes a problem when it is necessary to consider the solar radiation contribution to visual comfort conditions. In order to overcome this lack a new glare index, the Daylight Glare Probability (DGP) (Wienold & Christoffersen 2006) has been proposed, which is able to better correlate the user's response to glare perception caused by natural light. Nevertheless, due to its high computational cost, this index is not so commonly used. For this reason different authors tried to simplify the DGP formulation, as in the case of simplified Daylight Glare Probability, DGP_s (Wienold, 2007) and enhanced simplified Daylight Glare Probability, $eDGP_s$ (Wienold, 2009), focusing their attention in particular on the vertical eye illuminance (E_v) contribution, while some others still prefer using other indices, as the Daylight Glare Index (DGI) (Hopkinson 1972; Chauvel et al. 1982). Moreover, as specified in Wienold (2009), in order to evaluate the effectiveness of a façade configuration, the analysis cannot focus only on a specific moment. The overall assessment of the glare occurrence in a representative period, which could be a year, a season or a month, is necessary.

Furthermore, regardless of their effectiveness in detecting glare perception, as underlined in Carlucci et al. (2015), all these indices are related to a precise position, so they are unable to summarize the glare conditions throughout the space.

As underlined by the same authors, metrics able to provide a long term or a zonal evaluation of the whole environment through a single value would be crucial, as they could be used to easily communicate with non specialists or to be passed to other analysis techinques. Additionally, they could facilitate the comparison between different design solutions and optimize the overall performance in multi-objective analysis. In the recent literature, Jakubiec & Reinhart (2015) introduced an empiric equation able to predict long term visual discomfort due to glare, direct sunlight and low monitor contrast. However, as specified by the authors, the equation represents the result of specific and not general conditions.

In this work, the long term and zonal visual performance have been investigated by means of the availability and usability metrics proposed by Atzeri et al. (2016). Four different glare indices, namely DGI, $eDGP_s$, DGP_s and E_v, have been calculated, and represented through the above-mentioned metrics, to highlight further discrepancies and inconsistencies between them when dealing with time and space distribution. Since the primary aim of this research was evaluating if glare index calculated by common simulation tools can lead to misleading results in visual comfort assessment, DGI has been calculated through EnergyPlus, while $eDGP_s$, DGP_s and E_v by means of a RADIANCE/DAYSIM based lighting simulation software.

Simulation Method

As previously stated, EnergyPlus can only provide DGI profiles, according to the equation reported in the Engineering Reference document (US DOE 2016):

$$DGI = 10log_{10} \sum_{i=1}^{n} \frac{L_{s,i}(i_s)^{1.6}\Omega^{0.8}}{B(i_s)+0.07\omega^{0.5}L_{s,i}(i_s)} \quad (1)$$

To calculate $eDGP_s$, E_v and $E_{v,beam}$ annual profiles, a RADIANCE/DAYSIM based lighting simulation software is necessary. eDGPs, according to Wienold (2009), is defined as:

$$eDGP_s = c_1 \cdot E_v + c_2 \cdot log_{10}\left[1 + \sum_{i=1}^{n}\left(\frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_v^{1.87} \cdot P_i^2}\right)\right] + c_3 \quad (2)$$

DGP_s values have been obtained starting from the above E_v profiles, according to the equation proposed in Wienold (2007):

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$$DGP_s = 6.22 \cdot 10^{-5} \cdot E_v + 0.184 \quad (3)$$

For all the RADIANCE based simulations, the ambient bounce (-ab) parameter has been set to 5, but for the $E_{v,beam}$ calculation has been set equal to 0, due to the necessity of considering only the vertical eye illuminance related to the direct component of the solar radiation. Then, all the annual profiles have been processed through a MATLAB code to obtain availability and usability values, according to Atzeri et al. (2016).

Regardless of the specific procedure, all the indices have been calculated on a grid of points over the room, 1.2 m above the floor (Figure 1) as suggested by Wienold & Christoffersen (2006), along the year considering a hourly time-step.

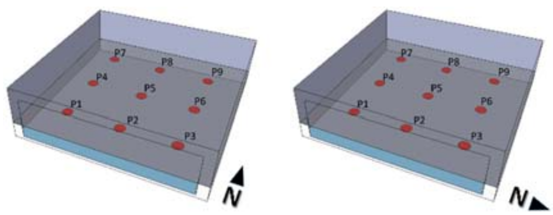

Figure 1: analysis grid with southward (left) and eastward (right) windows

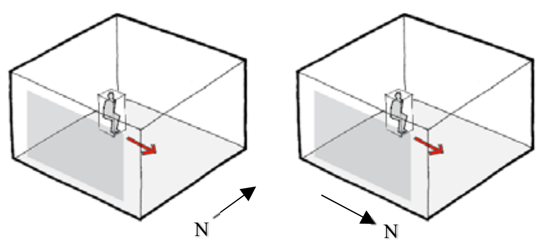

Figure 2: observers' view sight with southward (left) and eastward (right) windows

Nine different points of view, uniformly distributed in the room, have been considered, assuming that the observer's view is always directed parallel to the windows, the main glare source (Figure 2). The view direction will be eastward for South or South/North oriented windows and northward for East or East/West oriented windows. In this way, it has been possible to overcome the ineherent limitation which characterizes DGP_s, i.e. the inability to represent effectively the glare perception when the observer looks directly at the glare sources (Carlucci et al. 2015). The number of grid's points have been defined according to the maximum number of occupants in an office suggested by the Italian Standard UNI 10339:1995 (UNI 1995) and excluding from the usable surface a peripheral band 0.5 m deep beside the walls.

Model setup

The four glare indices have been calculated considering, as test environment, an open space office located in Rome, Italy. Hourly weather data for one year have been used as climatic inputs (US DOE 2009). The simulation runs for the entire year with a time step of 5 minutes in order to ensure numerical stability.

The workspace has a 100 m^2 floor area and a 3 m interior height. Different design configurations have been analyzed, combining different values for the windows dimension, position and orientation and the glazing type.

Since the aim of this work is the evaluation of the metrics' effectiveness (i.e. VCU, VCA, sVCA, tVCU) in providing not only a global assessment of the confined space, but also in the estimation of specific indices (i.e. DGI, DGPs and eDGPs) performance, only bare windows have been considered. Actually, with roller shades, these differences may not be as easy to be detected as in the cases used. Table 1 shows the configuration parameters used for this study, together with the labelling key to represent the different cases in the following.

Table 1: Configuration Parameters

Configuration Parameters	**Values**	**Labels** (to be used in the code key WP_WWR_GS)
Location: Rome	Lat. N 41° 53' 30'' Lon. E 12° 30' 30'' HDD_{18}: 1420 K d - CDD_{18}: 827 K d	
Windows' Position (WP)	South - South/North East - East/West	S – SN E – EW
Window Wall Ratio (WWR)	45%	S1
	75%	S2
Glazing Systems (GS)	High τ_{vis} 0.81	DH
	Low τ_{vis} 0.58	DL

To model the interaction between light and the room surfaces, different visible light reflectance values have been assigned to indoor walls, ceiling, floor and to outdoor ground. In particular to both walls and ceiling, 70% reflectance has been assigned, while 30% and 20% have been used for floor and external ground respectively.

Metrics thresholds definition

Availability and usability metrics are calculated for each position and each timestep respectively, considering the four glare indices above described. As specified in A. M. Atzeri et al. (2016), the Visual Comfort Availability (VCA) expresses the local availability of a sufficient visual comfort in the considered period, while the Visual Comfort Usability (VCU) indicates the instant usability, in terms of the fraction of space with an adequate visual comfort in a given moment. Each metric can be calculated for different glare indices, considering for each a specific threshold up to which the comfort condition is achieved.

DGP_s and $eDGP_s$ suitable values are lower than 0.35 (Wienold & Christoffersen 2006), while for the DGI the limit value is 22 (CEN 2007). As suggested in Chan et al. (2015), for the E_v two criteria have been used, which assess as visually uncomfortable an environment in which the $E_{v,beam}$ and the $E_{v,total}$ are, simoultaneously or singularly, higher than 1000 and 2670 lux respectively.

Two synthetic long term and zonal metrics can be derived from the Visual Comfort Availability (VCA) and Visual Comfort Usability (VCU). The first one is the spatial

VCA (sVCA), i.e. the fraction of space in the room with visual comfort for at least 90% of a period of one year (A. M. Atzeri et al. 2016). In this study the office has been considered occupied from 8:00 am to 6:00 pm, Monday to Friday. The second synthetic metric is the time VCU (tVCU), i.e. the fraction of time in the period of one year with at least 90% of space simultaneously in visual comfort.

Results and discussion

In this work VCA, VCU, sVCA and tVCU, calculated for the different glare indices, are represented for the diverse building configurations in order to compare their relative performance. VCA, sVCA and tVCU have been represented by means of colour gradient scales using two approaches. In Tables 2 and 4 and in the upper part of Tables 6 to 9 the colour from dark red to dark green express the transition from a state of low comfort to a total comfort condition in absolute terms. In Tables 3, 5, and in the bottom part of Tables 6 to 9 the color scale indicate the relative performance with respect to the design configuration with smaller windows and higher τ_{vis} (from white to red for worse, and from white to green for improved performance. Moreover, Tables 2 to 5 represent simplified plans of the office layout subdivided into 9 coloured cells which reproduce the area associated to each grid's point. Borders missing represent the windows' position. For the VCU a carpet plot representation has been used (Fig. 2-5), expressing the fraction of space that at a given moment is simultaneously in comfort condition and providing consequently a zonal assessment of the configuration analysed. As expected, due to the threshold value chosen for the $E_{v,total}$ and the definition of DGP_s, the results obtained using DGP_s and E_v as glare base quantities are identicals. For this reason the results related to these two glare base quantities have been presented together.

All the three indices, DGI, $eDGP_s$ and DGP_s, give similar results in the reference case, i.e. for east orientation and small window size with DH glazings. Considering Table 2, VCA is almost 100 % in the points further from the window, and reduces moving towards the window. However, DGI foresees higher comfort than the other indices, while DGPs gives the worse. The three other building configurations with smaller windows, seem to perform better close to the eastern window with DL glazing, and worse close to the West façade when windows are added and with DH glazing also towards the East (Table 3). DGI seems less sensitive to changes in the positions closer to the North side, and more when considering the positions close to the South. The opposite holds for the DGPs. When larger windows are considered, patterns are similar to the corresponding small windows case. However, this time eDGPs and DGPs predict always larger discomfort conditions, while DGI larger comfort than in the reference case.

Very similar considerations holds for southward or south/northward windows (Table 4): this time, DGI foresees comfort similar to the other metrics in the reference building.

Table 2: VCA with eastward and east/westward windows

	E_S1_DH	E_S1_DL	EW_S1_DH	EW_S1_DL	E_S2_DH	E_S2_DL	EW_S2_DH	EW_S2_DL
DGI	100 100 100	100 100 100	100 100 100	100 100 100	100 100 100	100 100 100	100 100 100	100 100 100
	100 100 92	100 100 100	96 100 99	100 100 100	100 100 99	100 100 100	100 100 100	100 100 100
	100 96 54	100 100 80	79 83 80	94 97 97	100 100 70	100 100 86	94 97 94	100 100 100
$eDGP_s$	100 99 87	100 100 96	83 98 86	93 100 95	100 98 80	100 100 88	71 98 80	85 99 87
	100 100 88	100 100 97	82 99 83	93 100 96	100 99 74	100 100 87	61 99 74	83 100 84
	100 100 90	100 100 98	81 98 85	93 100 96	100 99 74	100 100 88	55 99 74	83 100 86
DGP_s/E_v	99 96 70	100 100 80	53 80 57	100 96 100	99 90 55	100 99 71	27 45 32	62 91 64
	100 99 73	100 100 83	64 94 69	75 97 76	100 96 60	100 100 76	36 76 43	66 98 71
	100 100 90	100 100 97	86 100 90	81 99 81	100 100 83	100 100 91	73 100 78	87 100 90

Table 3: Differential VCA with eastward and east/westward windows (E_S1_DH base case)

	E_S1_DH	E_S1_DL	EW_S1_DH	EW_S1_DL	E_S2_DH	E_S2_DL	EW_S2_DH	EW_S2_DL
DGI	100 100 100	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0
	100 100 92	0 0 8	-4 0 7	0 0 8	0 0 7	0 0 8	0 0 8	0 0 8
	100 96 54	0 4 26	-21 -13 26	-6 1 43	0 4 16	0 4 32	-6 1 40	0 4 46
$eDGP_s$	100 99 87	0 1 9	-17 -1 -1	-7 1 8	0 -1 -7	0 1 1	-29 -1 -7	-15 0 0
	100 100 88	0 0 9	-18 -1 -5	-7 0 8	0 -1 -14	0 0 -1	-39 -1 -14	-17 0 -4
	100 100 90	0 0 8	-19 -2 -5	-7 0 6	0 -1 -16	0 0 -2	-45 -1 -16	-17 0 -4
DGP_s/E_v	99 96 70	1 4 10	-46 -16 -13	1 0 30	0 -6 -15	1 3 1	-72 -51 -38	-37 -5 -6
	100 99 73	0 1 10	-36 -5 -4	-25 -2 3	0 -3 -13	0 1 3	-64 -23 -30	-34 -1 -2
	100 100 90	0 0 7	-14 0 0	-19 -1 -9	0 0 -7	0 0 1	-27 0 -12	-13 0 0

Table 4: VCA with southward and south/northward windows.

	S_S1_DH	S_S1_DL	SN_S1_DH	SN_S1_DL	S_S2_DH	S_S2_DL	SN_S2_DH	SN_S2_DL
DGI	98 100 100	99 100 100	61 92 100	76 96 100	100 100 100	100 100 100	83 97 100	91 99 100
	67 99 100	75 100 100	55 99 100	68 100 100	80 100 100	87 100 100	70 100 100	81 100 100
	41 58 94	55 66 94	45 62 94	57 69 94	56 69 94	67 76 94	59 72 94	69 79 94
$eDGP_s$	100 100 100	100 100 100	100 100 100	100 100 100	100 100 100	100 100 100	65 86 100	100 100 100
	95 98 98	99 100 100	92 96 98	99 100 100	91 94 97	98 100 99	76 91 96	96 99 99
	61 62 81	81 82 91	51 56 77	78 80 90	38 38 62	62 65 83	33 34 55	54 58 81
DGP_s/E_v	100 100 100	100 100 100	89 99 100	100 100 100	100 100 100	100 100 100	42 51 100	99 100 100
	94 96 97	100 100 99	88 93 96	98 99 99	87 92 95	96 98 98	55 77 93	93 95 97
	51 52 73	74 74 87	44 43 69	68 70 75	34 34 50	50 51 75	29 31 45	44 45 71

Table 5: Differential VCA with southward and south/northward windows (S_S1_DH base case)

	S_S1_DH	S_S1_DL	SN_S1_DH	SN_S1_DL	S_S2_DH	S_S2_DL	SN_S2_DH	SN_S2_DL
DGI	98 100 100	1 0 0	-37 -8 0	-22 -4 0	2 0 0	2 0 0	-15 -3 0	-7 -1 0
	67 99 100	8 1 0	-12 -1 0	1 1 0	13 1 0	19 1 0	3 1 0	14 1 0
	41 58 94	14 8 0	4 4 0	16 11 0	15 11 0	26 18 0	18 14 0	28 21 0
$eDGP_s$	100 100 100	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	-35 -14 0	0 0 0
	95 98 98	4 2 2	-3 -2 0	4 2 2	-4 -4 -1	3 2 1	-19 -7 -2	1 1 1
	61 62 81	20 20 10	-10 -6 -4	17 18 9	-23 -24 -19	1 3 2	-28 -28 -26	-7 -4 0
DGP_s/E_v	100 100 100	0 0 0	-11 -1 0	0 0 0	0 0 0	0 0 0	-58 -49 0	-1 0 0
	94 96 97	6 4 2	-6 -3 -1	4 3 2	-7 -4 -2	2 2 1	-39 -19 -4	-1 -1 0
	51 52 73	23 22 14	-7 -9 -4	17 18 2	-17 -18 -23	-1 -1 2	-22 -21 -28	-7 -7 -2

In order to explain the above behaviour and the differences between the indices, it is worth considering that DGI (equation 1) expresses the glare sensation as a function of: (i) the average luminance of the window as seen from the reference point; and (ii) the luminance of the background area surrounding the window, so it is a function only of the contrast.

Moreover, DGI considers all the light sources as a single uniform one. For these reasons, DGI does not predict glare when the background luminance equals the average source luminance, as it can happens considering a space wellilluminated with only natural light in presence of large windows. This aspect seems easily recognizable considering the VCA distributions over the space. This appears more important when eastward or westward windows orientation are considered, probably because of an underestimation of the direct solar view. When southern windows are considered, even if the differences between DGI, eDGPs and DGPs are still present, they are less consistent, probably due to the lower weight of the direct component. In this respect, the VCA metric built using $eDGP_s$ or DGP_s/E_v probably allow a more realistic identification of the more problematic positions. As regards the comparison between eDGPs and DGPs, regardless of the specific orientation considered, the glare metrics built using DGP_s highlight more critical conditions compared to $eDGP_s$. This can be explained considering that DGP_s (equation 3), when the contrast is null, assumes a value higher than eDGPs for the same E_v.

Tables 6 and 7 show, for all the building's configurations analysed, the results related to the sVCA, which confirms what has been previously underlined for the VCA values.

In this study a grid of only 9 nodes has been used for determining the glare perception distribution, leading to a sVCA variation of large steps of around 11 %.

Sometimes his kind of grid is not enough detailed for all possible purposes. A larger number of points or the evaluation of each position could be preferable when computationally sustainable.

The VCU carpet plots (Figures 2 to 5), show more clearly the described DGI limitations. Moreover, with this representation, it is also possible to understand how the DGI is not particularly affected by the sun directly framed by the windows. In particular:

- DGI discomfort occurs in moment of the day and of the year that are different from those detected through $eDGP_s$ and DGP_s (i.e. in the central part of the occupation period for East and not in the morning when the contrast may be lower, or mainly during summer for all the orientations)
- Considering double sided windows, DGI discomfort reduces with East and West or increases just in the morning for North and South windows, while for $eDGP_s$ and DGP_s it always increases.
- According to all the metrics, comfort is improved by using DL glazings, because of their positive effects on both the contrast and the vertical eye illuminance.

Finally, DPG_s based VCU emphasizes the discomfort with respect to the $eDGP_s$, because of the absence of the contrast term to balance the vertical eye illuminance effect and the luminance background.

Table 6: absolute sVCA - upper part - and differential - bottom part - (E_S1_DH base case) with eastward and east/westward windows

	E_S1		EW_S1		E_S2		EW_S2	
	DH	DL	DH	DL	DH	DL	DH	DL
DGI	89	89	67	100	89	89	100	100
$eDGP_s$	78	100	33	100	67	67	22	33
DGP_s/ E_v	78	78	22	44	67	78	11	44
	E_S1		EW_S1		E_S2		EW_S2	
	DH	DL	DH	DL	DH	DL	DH	DL
DGI	89	0	-22	11	0	0	11	11
$eDGP_s$	78	22	-45	22	-11	-11	-56	-45
DGP_s/ E_v	78	0	-56	-34	-11	0	-67	-34

Table 7: absolute sVCA - upper part - and differential - bottom part - (S_S1_DH base case) with southward and south/northward windows

	S_S1		SN_S1		S_S2		SN_S2	
	DH	DL	DH	DL	DH	DL	DH	DL
DGI	67	67	56	56	67	67	56	67
$eDGP_s$	67	78	67	67	67	67	33	67
DGP_s/ E_v	67	67	44	67	56	67	22	67
	S_S1		SN_S1		S_S2		SN_S2	
	DH	DL	DH	DL	DH	DL	DH	DL
DGI	67	0	-11	-11	0	0	-11	0
$eDGP_s$	67	11	0	0	0	0	-34	0
DGP_s/E_v	67	0	-23	0	-11	0	-45	0

Finally, DPG_s based VCU emphasizes the discomfort with respect to the $eDGP_s$, because of the absence of the contrast term to balance the vertical eye illuminance effect and the luminance background.

Tables 8 and 9, reporting the tVCU results, underline trends similar to sVCA. The DGI appears to underevaluate the influence of the windows dimension, assessing as less comfortable the design configurations characterized by smaller transparent surfaces.

The same happens if the results related to double windowed facades are considered. Again, DGP_s based results point out more critical situations compared to $eDGP_s$.

Table 8: absolute tVCU - upper part - and differential - bottom part - (E_S1_DH base case) with eastward and east/westward windows

	E_S1		EW_S1		E_S2		EW_S2	
	DH	DL	DH	DL	DH	DL	DH	DL
DGI	54	80	69	91	70	86	91	100
$eDGP_s$	85	94	60	82	71	84	32	62
DGP_s/ E_v	70	80	28	50	55	71	21	32
	E_S1		EW_S1		E_S2		EW_S2	
	DH	DL	DH	DL	DH	DL	DH	DL
DGI	54	26	15	37	16	32	37	46
$eDGP_s$	85	9	-25	-3	-14	-1	-53	-23
DGP_s/Ev	70	10	-42	-20	-15	1	-49	-38

Table 9: absolute tVCU - upper part - and differential - bottom part - (S_S1_DH base case) with southward and south/northward windows

	S_S1		SN_S1		S_S2		SN_S2	
	DH	DL	DH	DL	DH	DL	DH	DL
DGI	46	70	40	64	32	47	27	41
$eDGP_s$	57	78	48	74	36	60	31	51
DGP_s/ E_v	44	67	39	63	32	46	26	40
	S_S1		SN_S1		S_S2		SN_S2	
	DH	DL	DH	DL	DH	DL	DH	DL
DGI	46	24	-6	18	-14	1	-19	-5
$eDGP_s$	57	21	-9	17	-21	3	-26	-6
DGP_s/E_v	44	23	-5	19	-12	2	-18	-4

Conclusion

Results have confirmed that the use of different glare indices, calculated with the most common approach, for visual comfort assessment of an indoor environment, can lead to different conclusions especially when analysing availability and usability. Both the figures and the tables underline a different behaviour of the glare indices used, with DGI underestimating the discomfort in terms of availability and missing to find the usability issues in a significant part of winter, due to its definition that includes only the luminance ratio between the source and the background. In contrast, DGP, regardless of the specific calculation formula, and the E_v allow detecting a lower space fraction that, on an annual basis, has an adequate percentage of time under comfort conditions, and a lower comfort uniformity all over the year.

Finally, the availability and usability representations adopted in this paper, indirectly confirm their effectiveness not only in providing a global assessment of the confined space analysed, even when visual comfort is concerned, but also in the relative assessment of specific indices performance.

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Nomenclature

B	background luminance	[cd m^{-2}]
E_v	vertical eye illuminance	[lx]
i	reference point index	
i_S	window shade index	
L_S	luminance of the source (window)	[cd m^{-2}]
P	position index	
Ω	modified solid angle	
ω	solid angle	
ω_s	solid angle of the source seen by an observer	

c_1	$5.87\ 10^{-5}$
c_2	$9.18\ 10^{-2}$
c_3	0.16

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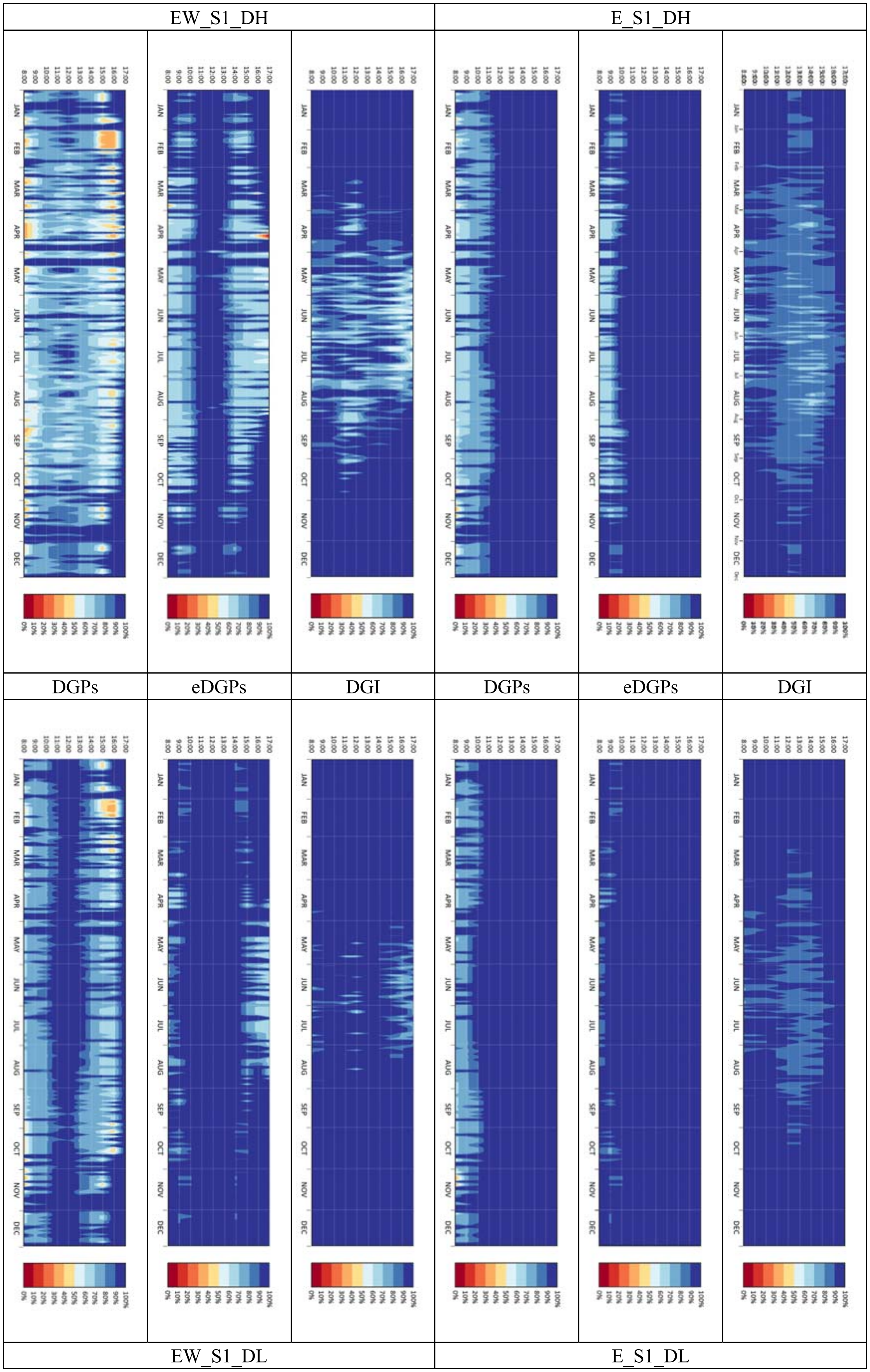

Figure 2: Visual Comfort Usability with eastward and east/westward windows with small windows

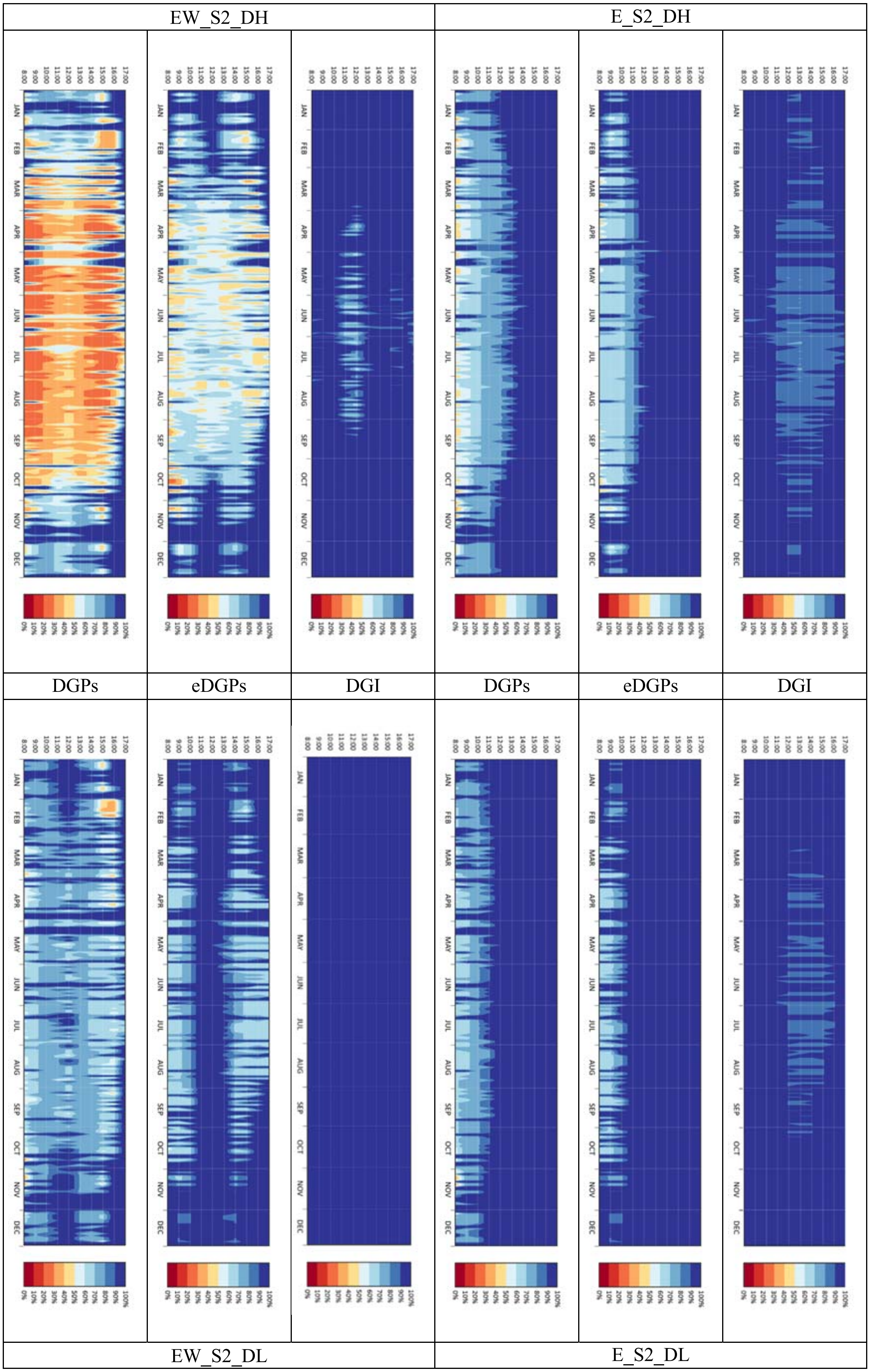

Figure 3: Visual Comfort Usability with eastward and east/westward windows with big windows

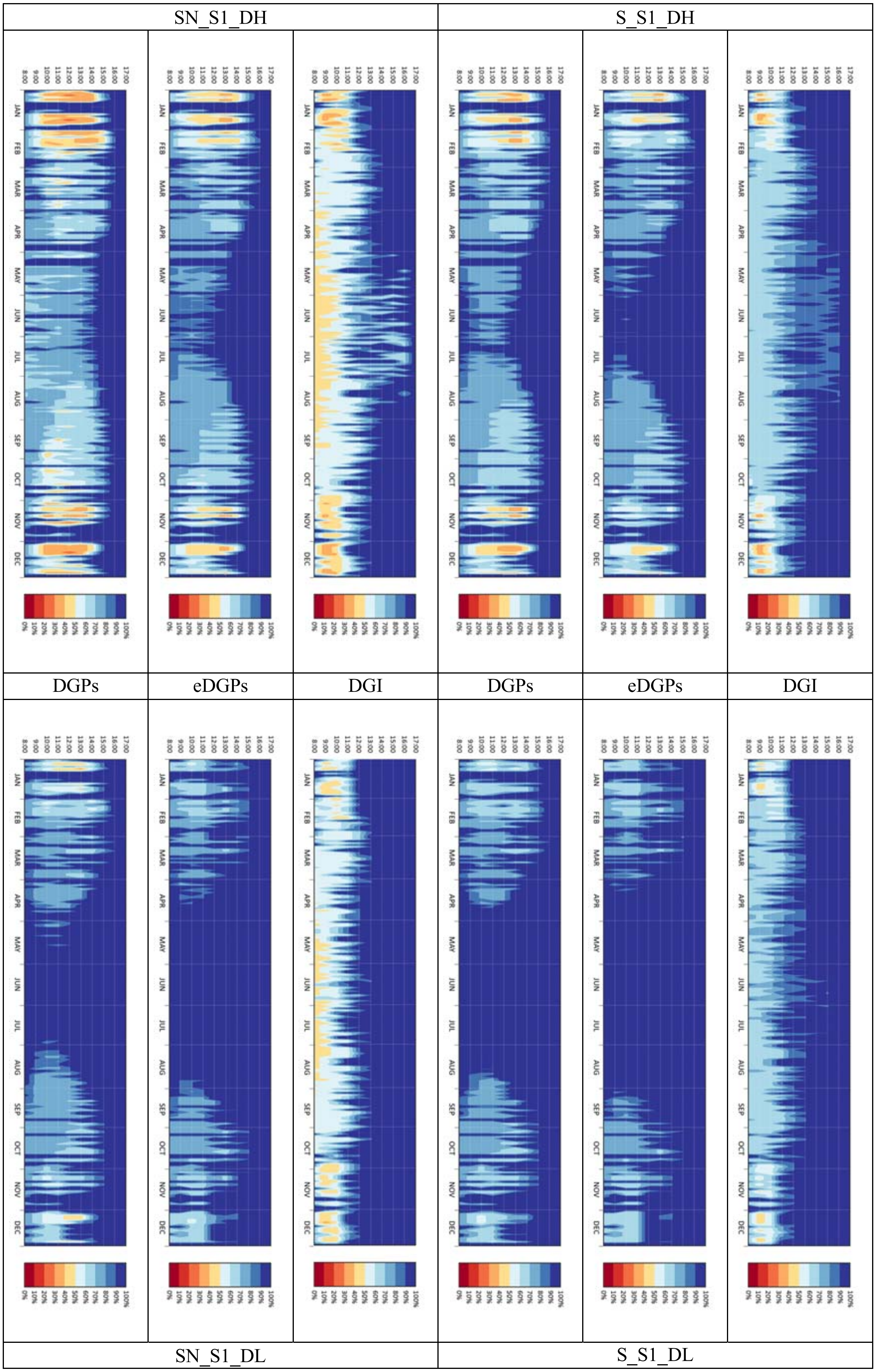

Figure 4: Visual Comfort Usability with southward and southnorthward windows with small windows

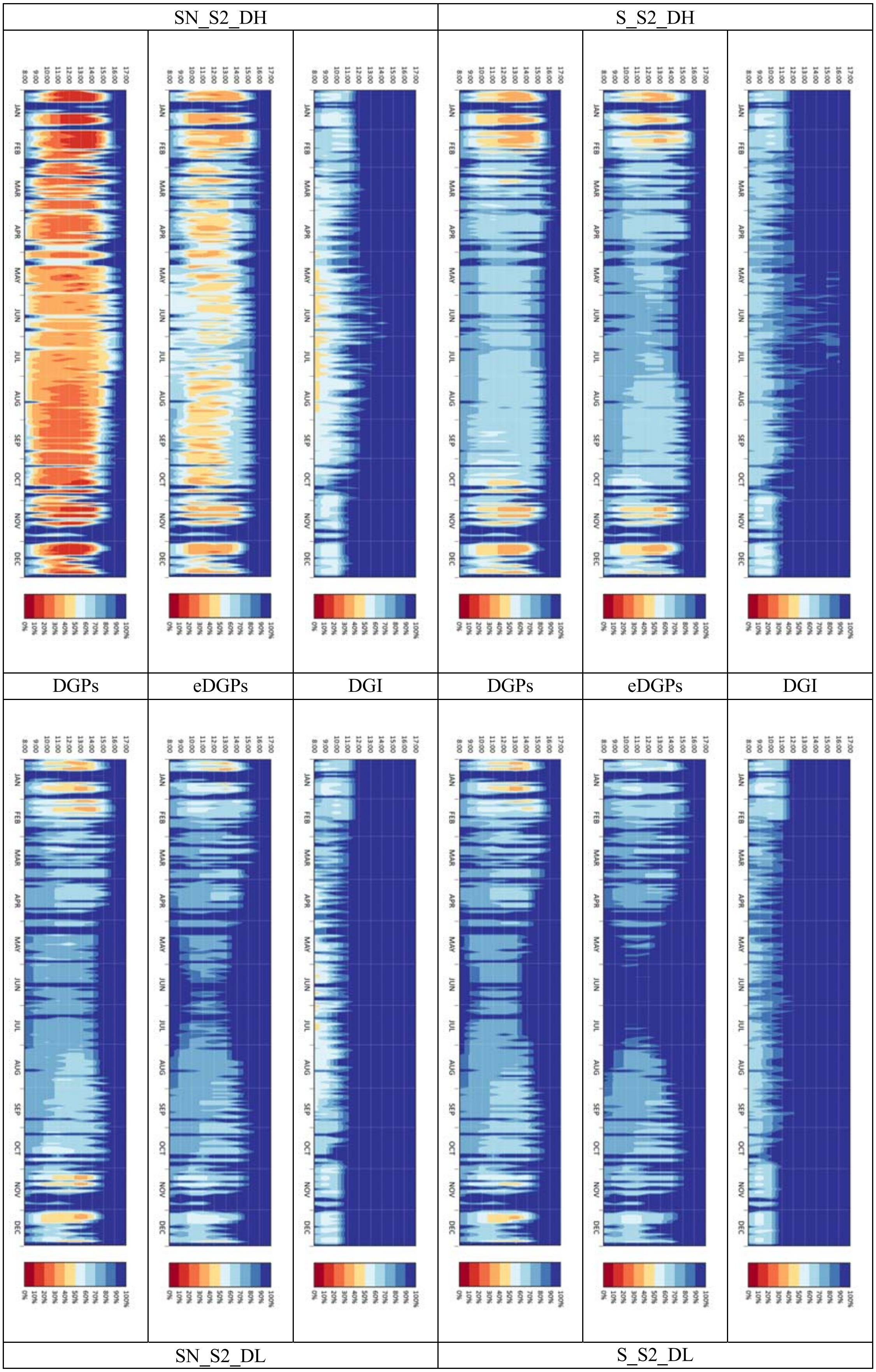

Figure 5: Visual Comfort Usability with southward and south/northward windows with big windows