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Use of the Deciview Haze Index as an Indicator for Regional Haze

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ABSTRACT

The U.S. Environmental Protection Agency (EPA) Notice of Proposed Rulemaking (NPR) for regional haze uses the deciview haze index (dv) as the indicator for visibility impairment and proposes a change of 1 dv as "a small but noticeable change in haziness under most circumstances." All previous visibility rules have specified human perception as the indicator for visibility impairment. This article examines the technical basis cited in the NPR for this new indicator for visibility impairment and for the perception threshold of approximately 1 dv. Derivations based on the assumptions and approximations cited in the NPR show that the deciview haze index does not have the correct functional form to relate changes in haze within federal Class I areas to the visual perception of those changes. The just-noticeable change in light extinction is, in most cases, inversely proportional to the sight path length instead of proportional to the light-extinction coefficient. These derivations also indicate that a 1-dv change in haziness is typically too small to be perceived in most Class I areas.

INTRODUCTION

The deciview haze index (dv) was introduced by Pitchford and Malm[1] for use in presenting data for the light-extinction coefficient (b_{ext}) of ambient air. (Technical terms are defined in a glossary at the end of this article.) For example, their paper contains a map of the United States with isopleths indicating the average visibility conditions. Pitchford and Malm[1] indicated that the deciview haze index is the preferred metric for such presentations because it is more linearly related to the human perception of regional haze than other metrics that have commonly been used, such as the visual range (VR) or b_{ext}. The deciview haze index has been widely accepted, with the result that the majority of publications on the relation between air quality and visibility use the deciview haze index to present light-extinction data.

> **IMPLICATIONS**
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> EPA has proposed a regional haze rule that uses a new indicator for visibility impairment. The technical basis for this new indicator was developed for faint scenic elements that are almost obscured by haze, and this technical basis can be used to show that the indicator does not have the correct functional form to relate changes in haze within federal Class I areas to the visual perception of those changes.

The importance of the deciview haze index as an indicator for visibility impairment was increased by the regional haze regulations published in a Notice of Proposed Rulemaking (NPR) by the U.S. Environmental Protection Agency (EPA) on July 31, 1997.[2] If this rule were to be promulgated as proposed, it would be the first rule to specify an indicator different from human perception for determining the existence of visibility impairment. The NPR proposes using the deciview haze index as a metric for determining reasonable progress toward the national goal in Section 169(a) of the Clean Air Act, which calls for "the prevention of any future, and the remedying of any existing, impairment of visibility in mandatory Class I Federal areas, which impairment results from manmade air pollution."

The proposed rule would require that haze in Class I areas be monitored, that the average haze level during the 20% of the days that have the highest $PM_{2.5}$ concentrations decrease by 1 dv every 10 or 15 years, and that the average haze level during the 20% of the days that have the lowest $PM_{2.5}$ concentrations not increase by more than 0.1 dv. Three-year running averages would be used to determine compliance. It is proposed that once the visibility conditions are within 1.0 dv of natural conditions, the visibility State Implementation Plan would be considered a type of maintenance plan. The NPR states, "The EPA proposes a one-deciview increment above natural conditions to be perceived as sufficiently near to natural conditions for those sensitive scenes that are thought to exist in all mandatory Class I federal areas."

The use of the deciview haze index in the NPR is compatible with the EPA Office of Air Quality Planning and Standards (OAQPS) Staff Paper on the National Ambient Air Quality Standards for Particulate Matter,[3] which states, "Under many circumstances, a change of one deciview represents a change perceptible to the average person."

One effect of the NPR is to propose giving the deciview haze index regulatory status as an indicator for visibility impairment. Another effect is to propose establishing a perception threshold with the statement, "A one deciview change in haziness is a small but noticeable change in haziness under most circumstances when viewing scenes in mandatory Class I Federal areas."

Because proposals in the NPR would give regulatory status to the deciview haze index as an indicator for regional haze, it is appropriate at this time to review its derivation and examine some of its properties. The purpose of this review is to increase the understanding of atmospheric optics and visual perception thresholds related to regional haze. The NPR cites only Pitchford and Malm[1] as the technical basis for using the deciview haze index as an indicator for visibility impairment, and for using a 1-dv change in haziness as the level corresponding to a significant change in the indicator. The citations considered in this article are restricted to those cited by the NPR or by Pitchford and Malm.[1] Mathematical derivations appear in the appendix, while the approach used in these derivations and the resulting conclusions are presented in the following text.

DERIVATION OF THE DECIVIEW HAZE INDEX

Pitchford and Malm[1] based the derivation of the deciview haze index on the three assumptions described below. This review accepts these assumptions without modification and does not attempt to examine results that could be obtained from other assumptions or to evaluate the relative merits of these assumptions compared to other assumptions that could be made. Thus, the scope of this article is narrowly directed toward examining the technical basis presented in the NPR.

The assumptions used by Pitchford and Malm[1] are:

(1) Contrast is a good indicator of visibility. The apparent contrast of an element of a scene can be used to estimate whether the element can be perceived and, when it can be perceived, the apparent contrast can also be used to evaluate the visual quality of its appearance.

(2) The magnitude of the change in apparent contrast of a distant terrain feature against the horizon sky required for a change to be just noticeable is proportional to the apparent contrast of the terrain feature.

(3) The apparent contrast of a distant terrain feature against the horizon sky is given by eq 6 in the appendix.

The first and third assumptions are widely used and accepted. The third assumption is valid if the horizon sky radiance has the same value at each end of the sight path. It could be regarded as a restriction; that is, that the derivation of the deciview haze index applies only to the apparent contrast of terrain features viewed against the horizon sky. The second assumption is the one most easily questioned, as indicated in the appendix.

The initial steps of the derivation of Pitchford and Malm[1] are presented in Section A.1 of the appendix and are accepted without modification. They derive an equation for Δb_{extJNC}, which is the change in the light-extinction coefficient corresponding to a just-noticeable change (JNC) in the contrast of an element in a scene. Since Pitchford and Malm[1] state that their paper develops the theory previously presented by Pitchford et al.,[4] Section A.2 presents additional equations from this prior work. Section A.3 presents a simple extension of the equations of Pitchford and Malm. An equation derived by Pitchford and Malm can be rearranged to obtain

$$\Delta b_{extJNC} = (1/r)\ \ln(1\text{-}L) \qquad (1)$$

where r is the length of the sight path and L is a constant whose value depends on the spatial frequency of elements in a scene but does not depend on the values of b_{ext} or r. Pitchford and Malm[1] state that this equation "indicates that the change in extinction coefficient corresponding to a JNC in a scenic element is inversely proportional to the distance to the element. The most sensitive scenic element is the one at the greatest distance that is still visible at the lower extinction coefficient value, but just disappears at the higher extinction coefficient. In other words, the most sensitive distance for a scenic element is near the visual range."

FUNCTIONAL FORM

The 1/r functional form in eq 1 is not new. This relation and the curves in Figure 1 were derived by Pitchford et al.[4] as described in Section A.2 of the appendix. The percent changes in b_{ext} shown in this figure can be approximately converted into changes in the deciview haze index by dividing the percent changes by a factor of 10. The curve for L = 0.24 gives a threshold change of approximately 1 dv for sight paths with a length equal to the visual range (VR), so this curve gives the best correspondence with the assumptions used in the NPR. The curves in Figure 1 show that when the length of the sight path is a small fraction of the visual range, b_{ext} must change by several tens of percent (several deciview units) for the change to be perceptible. For example, more than a 40% change (more than a 4-dv change) in regional haze is required for the change to be perceptible in sight paths shorter than 20% of the visual range.

The full derivation of the deciview haze index by Pitchford and Malm is not reproduced in the appendix. Their first step beyond the equations presented in the

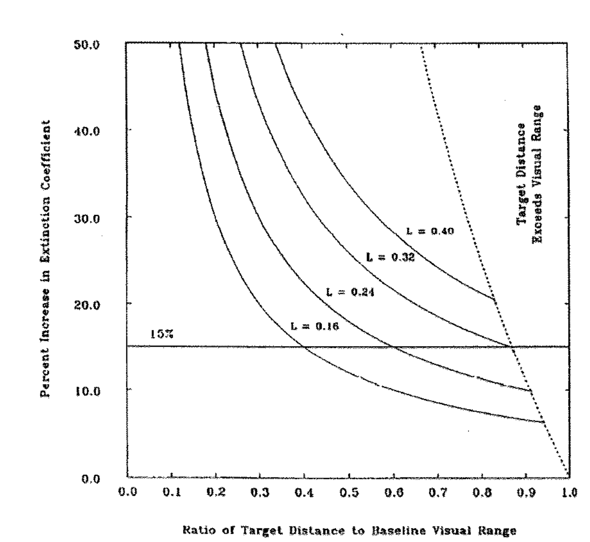

Figure 1. Figure 1 from Pitchford et al.[4] The curves were calculated from eq 12 using a liminal contrast of 5% ($-\ln\varepsilon = 3.0$). The line labeled L = 0.24 best corresponds with the analyses in the NPR. This line indicates that a 10% increase in b_{ext} (i.e., a 1-dv change) corresponds to a JNC in haze when the length of the sight path is equal to the VR. For points below and to the left of this line, the change in b_{ext} "is too small for a noticeable visibility change to occur." Points to the right of the dotted line are beyond the VR. Points above the L = 0.24 line and to the left of the dotted line correspond to noticeable changes in visibility. The horizontal line at a 15% increase was proposed by Pitchford et al.[4] as the basis for a regulatory strategy.

appendix is to restrict the derivation to the special case in which the sight path length *r* is equal to the visual range *VR*. Pitchford and Malm[1] state that their derivation applies to a scenic element at the most sensitive distance, that is, an element "at the greatest distance that is still visible at the lower extinction coefficient value, but just disappears at the higher extinction coefficient." This restriction in the derivation of the deciview haze index was ignored by EPA in the OAQPS Staff Paper[3] and the NPR.

PERCEPTION THRESHOLD

Pitchford and Malm[1] do not endorse a specific change in dv to be used as a visual perception threshold. They do conclude a discussion by saying, "It seems reasonable to presume that a fractional change in extinction coefficient between about 5 and 20% would produce a JNC in a scene." These percentage changes in light extinction correspond to changes of 0.5 and 2.0 dv, respectively. Malm and the authors of the NPR are vigorous in saying that a 1-dv change is not a perception threshold. However, the quotations from the NPR cited above and the above statement by Pitchford and Malm would make it difficult in any future regulatory process to use a threshold for the perception of changes in regional haze outside the range of a 0.5 to 2-dv change.

Because of the NPR's endorsement of a 1-dv change as a noticeable change under most circumstances, a derivation is presented in Section A.3 of the value of the constant *L* in eq 1 that causes both eq 1 and a 1-dv change in haze to give the same value for Δb_{extJNC} when *r* is equal to *VR*. This value of *L* causes eq 1 to give results in agreement with those calculated from a 1-dv change under conditions where the derivation of the deciview haze index is applicable. The value of *L* depends on the liminal (threshold) contrast assumed in the calculation of VR. Conservative analyses sometimes assume that a terrain feature must have a contrast of 5% against the horizon sky to be perceptible, but it is more commonly assumed that features with a 2% contrast can be perceived. These two assumptions lead to different values of VR, hence different values of *r* at which the two calculation methods should give the same value for Δb_{extJNC}. The derivation in Section A.3 shows that if a liminal contrast of 2% is used, eq 1 becomes

$$\Delta b_{extJNC} = 0.41/r \tag{2}$$

and if a liminal contrast of 5% is used, eq 1 becomes

$$\Delta b_{extJNC} = 0.32/r \tag{3}$$

Eqs 2 and 3 apply to sight paths of any length less than or equal to the visual range, and give the values for Δb_{extJNC} equal to those calculated from a 1-dv change when the length of the sight path is equal to the visual range. Thus, a Δb_{extJNC} calculated from these equations is more generally applicable than the value recommended in the NPR, and it equals the NPR value in the special case where the NPR value is applicable. Because of their general applicability, it is recommended that EPA give consideration to using either eqs 2 or 3 in the regional haze regulations for Class I areas instead of the deciview haze index.

PROTECTION OF VIEWS OUTSIDE CLASS I AREAS

The deciview haze index was designed to apply to the most sensitive sight paths, that is, sight paths to the farthest features that are perceptible. The use of the deciview haze index as the indicator for regional haze in the NPR instead of eqs 2 or 3 has the effect of protecting integral vistas, which are views that extend beyond the boundaries of Class I areas. Current visibility impairment regulations apply to sight paths within Class I areas, so use of the deciview haze index in the NPR increases the scope of visibility regulations.

If the indicator for regional haze had the functional form of eqs 2 or 3, the protections of the regional haze rules would apply to sight paths within each Class I area. The application of these equations requires determining the longest sight path in each Class I area. In some areas, the longest sight paths are at high elevations, where the air is typically clearer than at lower elevations. In a Class I area where long sight paths are available only at high elevations, it would be appropriate to use data for haze at those elevations in visibility analyses.

Work is now in progress to estimate the length of the longest sight path available in each Class I area, and to compare these lengths with the VR calculated from the average light-extinction coefficient on the 20% of days that are most impaired and the 20% of days that are least impaired each year. Figure 2 shows preliminary results for 35 Class I areas that are national parks. The length of the longest line that could be drawn within each park and the length of the longest sight path were estimated from the maps in National Park Service brochures. The VR data were calculated by Sisler from IMPROVE monitoring data.[5] The dotted lines in Figure 2 compare the lengths of the longest lines in the parks with VR, and the solid lines compare the estimated lengths of the longest sight paths within the parks with VR.

These data show that for average conditions during the 20% of the days that are least impaired, the longest sight paths within all 35 parks were shorter than the VR, and in many cases, the longest sight paths were substantially shorter than the VR. For average conditions during the 20% of days that were most impaired, the longest lines that could be drawn in the Class I areas were shorter than the VR in more than half the parks. It was also estimated for the hazy conditions that the longest sight path was shorter than the VR in more than 80% of the parks, and the longest sight path was less than half the VR in about half of the parks. These data show it is the exception, rather than the rule, for a sight path with a length equal to the VR to be available anywhere within a national park.

APPLICATION TO A WESTERN CLASS I AREA

A 1-yr intensive visibility study was recently completed for the Mt. Zirkel Wilderness Area (MZWA) in north-central Colorado.[6] The purpose of the Mt. Zirkel Visibility Study (MZVS) was to determine the effects of local and regional sources on visibility impairment in the MZWA. The database from this study is complete enough to support an analysis of the issues raised in this article, and results for a wavelength of 550 nm are presented in Table 1. The longest sight path length within the MZWA is 35 km (22 mi), and it is assumed that the monitoring data from a site at the southern boundary of the MZWA are applicable to this sight path.

Eq 2 was derived during the MZVS (see Appendix B.6 and Section 6.8.3 in reference 6) and gives a value of 11.7 Mm^{-1} for the Δb_{extJNC} for the longest sight path within the MZWA. The Δb_{extJNC} from eq 2 is nearly 10 times larger than the change in b_{ext} corresponding to a 1-dv change in haze on the 20% of the days that were least impaired and about 4.5 times larger on the 20% of the days that were most impaired. As stated above, this calculation is based on the assumptions used by Pitchford and Malm,[1] including the assumption that the JNC in contrast corresponds to the contrast change resulting from a 1-dv change in

Table 1. Data for the longest sight path in the MZWA.

Parameter	20% Least Impaired Days	20% Most Impaired Days
b_{sp} (Light scattering by particles)	2.5 Mm^{-1}	14 Mm^{-1}
b_{ap} (Light absorption by particles)[a]	0.6 Mm^{-1}	2.6 Mm^{-1}
b_{sg} (Rayleigh scattering)	8.4 Mm^{-1}	8.4 Mm^{-1}
b_{ext}	11.5 Mm^{-1}	25 Mm^{-1}
VR (from eq 11)	340 km^{-1}	156 km^{-1}
r/VR	0.10	0.22
Δb_{extJNC} (from eq 2)	11.7 Mm^{-1}	11.7 Mm^{-1}
Δb_{ext} for a 1-dv change	1.2 Mm^{-1}	2.6 Mm^{-1}
Increase in non-Rayleigh light extinction required for a change in b_{ext} to be perceptible in the MZWA	380%	71%
Decrease in non-Rayleigh light extinction for 1-dv change		16%
Δb_{ext} for a 0.1-dv change	0.12 Mm^{-1}	

[a]Approximate upper limit.

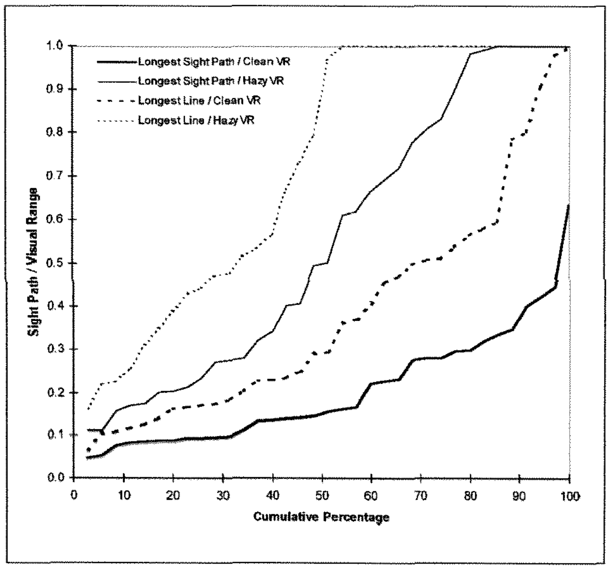

Figure 2. Comparison of the lengths of the longest lines that can be drawn within 35 national parks and the estimated lengths of the longest sight paths within these parks with the VR. The VRs were calculated from the average light-extinction coefficient for both the 20% of days that are the least impaired (clean) and the 20% of days that are the most impaired (hazy). A point on a line indicates the percentage of the parks that have a ratio equal to or smaller than the value at that point. Most ratios are less than 1.0, so sight paths are typically shorter than the VR, and some are much shorter than the VR.

regional haze in a sight path with a length equal to VR. With one exception, these assumptions are completely consistent with the assumptions used as the technical basis for the NPR. The single exception is that the calculations in Table 1 do not assume that sight paths equal in length to the VR were available within the MZWA.

One requirement proposed in the NPR is that the average deciview haze index not increase by more than 0.1 dv on the 20% of days that are least impaired. Such a requirement could be used to deny a permit (or require compensating emissions reductions before granting a permit) for a proposed project that is estimated to increase haze on the 20% least impaired days in the MZWA by an amount approximately 100 times smaller than the amount that would, according to the analyses of Pitchford et al.,[4] cause a perceptible change in haze. This requirement would also trigger the need for emissions reductions in the event that either natural variability in haze or regional growth caused a 0.1-dv increase in haze to be measured on the 20% least impaired days. The NPR does not provide the technical basis for limiting changes in haze to a value 100 times smaller than a visually perceptible change.

As a side issue, the VR of 340 km in Table 1 is unearthly. This value was calculated from the standard equation (eq 11 in the appendix). However, for the very clean conditions in the MZWA, the assumption that the atmosphere is uniform over a sight path of this length is incorrect.[7] An initially horizontal sight path of this length would end at an elevation of 9.1 km (29,700 ft) above the observer's elevation, which is well above the altitudes typically affected by regional haze. There are no peaks on Earth with an elevation that great, so the assumption of the presence of a dark terrain feature at the visual range cannot be satisfied.

COMMENTS

As mentioned above, this review was narrowly restricted to analyses based on the same assumptions as used by Pitchford and Malm.[1] Those assumptions were not amplified or modified, nor were they compared with other possible assumptions. The most significant findings of this review are:

(1) The derivation of the deciview haze index was based on a special case that is not typically encountered by visitors in federal Class I areas. Typical scenes within Class I areas do not include scenic elements "at the greatest distance that is still visible at the lower extinction coefficient value, but just disappears at the higher extinction coefficient."

(2) The deciview haze index does not have the correct functional form to serve as an indicator for visibility impairment within federal Class I areas for cases typically encountered by visitors.

(3) In most circumstances in Class I areas, a 1-dv change in regional haze on the 20% least impaired days is smaller than a perceptible change. This article presents an example in which a 1-dv change is nearly 10 times smaller than the perceptible change (derived from the assumptions in the NPR).

(4) The requirement that the average value of the deciview haze index increase by no more than 0.1 dv on the 20% least impaired days sets a standard that can be 100 times smaller than a perceptible change in regional haze.

The difference between these findings and the information in the NPR occurs primarily because the derivation of the deciview haze index is based on a special case—a sight path length equal to the VR—while the general case of sight paths of any length is addressed in this review.

RECOMMENDATIONS

It is recommended that the technical basis for the NPR be extended and broadened so that it is more robust. It would be desirable for the additional analyses to consider more than the contrast of faint ridges against the horizon sky. Most visitors to Class I areas are also interested in the clarity of views of features on cliffs, mountainsides, and views in valleys. Simple calculation methods exist for relating the clarity of such views to light extinction,[8] and they have the potential to provide a sound technical basis for rule-making.

The recommended approach for additional analyses resembles the approach used when setting air quality standards to protect human health. Neither visibility nor human health are closely linked to air quality. It is not possible to predict the health of an individual or the visual quality of a scene from air quality information alone. In both cases, a wide range of effects can be observed at a given level of air quality. However, relationships can be established and used as the technical basis for the level of the indicator selected for the standards. For visibility impairment, these relationships can be established experimentally or by calculations. The State of Colorado used an experimental determination of the level of a visibility indicator. Photographs showing various levels of haze were judged by panels to be acceptable or not acceptable, and the standard was set at a level of light extinction that corresponded to the change in the consensus.[9] The IMPROVE Monitoring Program has a large library of photographs and air quality data that could be used in this manner.

A theoretical relationship between the appearance of elements in a scene and light extinction can be constructed by (1) selecting views in Class I areas that are representative of sensitive views; (2) determining the properties of elements in the view that affect the appearance of these elements, such as their orientation and reflectance; and (3) calculating apparent contrasts and contrast transmittances for these scenic elements for a range of sun angles, different cloud covers, different ratios of scattering to absorption, and so forth. Scatter plots and other statistical relations between the calculated apparent contrasts or contrast transmittance and the light-extinction coefficient can be used, in comparison with best estimates of perception thresholds, to set standards. Calculations similar to those recommended here have recently been performed for the MZVS[6] and for the Dallas-Fort Worth Winter Haze Project.[10]

Because of the limitations of the assumptions cited in the NPR and used in this article, the derivations herein do not provide an indication of whether more complete and appropriate technical analyses would support more or less stringent regional haze regulations than those in the NPR.

APPENDIX

This appendix presents the mathematical derivations that underlie the discussions in the body of the paper. The derivations in Section A.1 are taken from Pitchford and Malm,[1] those in Section A.2 are taken from the earlier paper by Pitchford et al.,[4] and Section A.3 presents an extension of those derivations.

A.1. Derivation of Pitchford and Malm

The deciview haze index (dv) was introduced by Pitchford and Malm[1] and is defined by the relation

$$dv = 10 \ln_e(b_{ext}/10\ Mm^{-1}) \qquad (4)$$

The value of b_{ext} for green light and particle-free air at 1.8-km elevation is approximately 10 Mm^{-1}. Therefore, *dv* has a value of zero for particle-free air under these conditions and increases by approximately one unit for each 10% increase in b_{ext}.

The second assumption listed in the body of the article is most easily questioned: for a change in contrast to be noticeable, the magnitude of the change is proportional to the apparent contrast (*C*).

$$\Delta C_{JNC} = L\ C \qquad (5)$$

where *L* is a constant that depends on the spatial frequency but not the contrast. Neither Pitchford et al.[4] nor Pitchford and Malm[1] explicitly say so, but it is believed this equation is intended to be applicable for either positive or negative values of ΔC_{JNC} for either positive or negative contrasts. Carlson and Cohen[11] have shown that eq 5 is not generally valid but that it may provide a reasonable approximation in viewing environments such as a view of a terrain feature against the horizon sky.

The third assumption is that the apparent contrast of a terrain feature at a distance *r* viewed against the sky is equal to

$$C = C_o \exp(-r\ b_{ext}) \qquad (6)$$

where C_o is the initial contrast of the terrain feature and b_{ext} is the average light-extinction coefficient for the sight path. This equation is valid for a terrain feature viewed against the horizon sky provided the sky radiance is the same at each end of the sight path. This third assumption could be regarded as a restriction; that is, the derivation of the deciview haze index applies only to terrain features viewed against the sky in the absence of variable clouds or other nonstandard conditions.

If b_{ext} is decreased to become $b_{ext} - \Delta b_{ext}$, the apparent contrast will become C - ΔC. If these values are substituted into eq 6 and then eq 6 as written above is subtracted, the result is

$$\Delta C = C_o \exp(-r\ b_{ext})\ [1 - \exp(r\ \Delta b_{ext})] = C\ [1 - \exp(r\ \Delta b_{ext})] \qquad (7)$$

The algebraic signs in this derivation have been selected to agree with Pitchford and Malm.[1] The conventions in eq 7 are that both Δb_{ext} and ΔC are positive numbers and C_o is negative. These choices of algebraic signs are appropriate for a decrease in b_{ext} in a view of a dark terrain feature against the sky. The change in Δb_{extJNC} that will make this contrast change equal to ΔC_{JNC} can be calculated by combining eqs 5 and 7

$$\Delta C_{JNC} = L\ C = C\ [1 - \exp(r\ \Delta b_{extJNC})] \qquad (8)$$

or

$$1 - L = \exp(r\ \Delta b_{extJNC}) \qquad (9)$$

Eq 9 is eq 4 in Pitchford and Malm[1] and, except for an arbitrary choice of algebraic signs, eq 7 is eq 4 in Pitchford et al.[4] Eq 1 in the text of this article is a rearrangement of eq 9.

The remainder of the derivation of the deciview haze index by Pitchford and Malm is not reproduced here. Their next step is to restrict the derivation to the special case in which the sight path length *r* is equal to the visual range *VR* when deriving their eq 6 from their eq 4. Pitchford and Malm[1] clearly state that their derivation applies to a scenic element at the most sensitive distance, that is, an element "at the greatest distance that is still visible at the lower extinction coefficient value, but just disappears at the higher extinction coefficient."

A.2. Interpretation by Pitchford et al.

The derivation of the deciview haze index by Pitchford and Malm[1] closely follows a derivation in an earlier article by Pitchford et al.[4] that foreshadows the general structure of the regional haze regulations in the NPR. In this earlier article, a percent change in b_{ext} was recommended as a metric for progress toward the national goal of no manmade visibility impairment. Pitchford et al.[4] take the derivation one step further by introducing the parameter X, which is the ratio of the sight path length r to the visual range VR

$$X = r/VR \tag{10}$$

and making use of the Koschmieder relation for the visual range

$$-\ln\varepsilon = VR\ b_{ext} \tag{11}$$

where ε is the liminal (threshold) contrast. For example, if the liminal contrast is 2%, $-ln\varepsilon$ is equal to 3.91. Pitchford et al.[4] obtain the relation

$$\Delta b_{extJNC}/b_{ext} = [\ln(1 - L)]/(X \ln\varepsilon) \tag{12}$$

In their derivation, the symbol K was used for $-ln\varepsilon$ and $-Y$ was used for $\Delta b_{extJNC}/b_{ext}$. All factors except X in the right-hand side of eq 12 are constants, so this equation shows in simple terms the dependence of Δb_{extJNC} on the ratio of the sight path length to the visual range. Eq 12 was used by Pitchford et al.[4] to calculate their Figure 1, which is reproduced as Figure 1 in this article.

A.3. Extension of the Derivation of Pitchford and Malm

Rearrangement of eq 9 gives

$$\Delta b_{extJNC} = (1/r)\ \ln(1 - L) \tag{13}$$

The following derivation determines the value of the constant, ln(1 - L) in eq 13, required for the value of Δb_{extJNC} calculated for the case of a sight path length equal to the VR to be the same as the Δb_{ext} that would cause a change of 1 dv. To change the deciview haze index by one unit, it is necessary to change b_{ext} by a factor of exp(0.1) = 1.10517. Thus, the value of Δb_{extJNC} that results in a 1-dv change is 0.10517 b_{ext}. When r is equal to VR, eq 13 becomes

$$\Delta b_{extJNC} = (1/VR)\ \ln(1 - L) = 0.10517\ b_{ext} \tag{14}$$

Use of eq 11 gives the result that

$$\ln(1 - L) = 0.10517\ (-\ln\varepsilon) \tag{15}$$

Eqs 13 and 15 are evaluated for liminal contrasts of 2% ($-\ln\varepsilon$ = 3.9) and 5% ($-\ln\varepsilon$ = 3.0) to obtain eqs 2 and 3, respectively.

GLOSSARY

Apparent: A modifier to indicate values measured at the location of the observer, that is, as the value appears to the observer.

b_{ext}: Symbol for the light-extinction coefficient.

Class I area: Certain large national parks and wilderness areas afforded visibility protection by the Clean Air Act.

Contrast: The difference between the radiance of an element of a scene and its viewing background divided by the radiance of the background. If a terrain feature viewed against the horizon sky has a contrast of −10%, the radiance of the terrain feature is 10% less than the radiance of the background sky.

Deciview haze index: A logarithmically scaled measure of the light-extinction coefficient similar to the decibel scale for sound (see eq 4 and the accompanying discussion).

dv: The abbreviation for the units of the deciview haze index.

Haze: A suspension in the atmosphere of minute particles that are not individually seen but nevertheless reduce visibility.

Indicator: An air quality parameter used as a surrogate for an effect of air quality. Air quality regulations specify upper limits and other constraints on the allowable levels of indicators.

Integral vista: A view outside the boundary of a Class I area that is important to the visual experience within the Class I area. Except for a few integral vistas designated by states, integral vistas are not protected by existing visibility regulations.

Light-extinction coefficient: The rate with respect to distance at which a collimated beam of light is attenuated by light scattering and light absorption. The value of the light-extinction coefficient for green light and particle-free air at 1.8-km elevation is approximately 1% per kilometer, which can be written as 0.01 km^{-1} or 10 Mm^{-1}.

Liminal: The threshold value for perception.

$PM_{2.5}$: Concentration of ambient particulate matter with an aerodynamic diameter less than 2.5 µm, referred to as fine particles.

Spatial frequency: A measure of the angles subtended by variations in contrast in a scene at the location of the observer. Spatial frequencies can be measured in cycles per degree.

Visual range (VR): In many applications, and in this article, the VR is defined by and calculated from eq 11 and is based on measurements of the light-extinction coefficient at the sampler inlet(s). If a case existed in which the atmosphere and its illumination were uniform over the VR and beyond and the atmospheric composition were the same as at the sampler inlet(s), the VR would be the greatest distance a dark target could be perceived against the horizon sky.

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