1. Introduction

For students of atmospheric radiative transfer, tropospheric haze has long been a source of highly valuable, if often difficult, lessons on spectral scattering and extinction [1–5]. Yet on the subject of clear-sky colors, haze may at first seem to have little to teach us. After all, does not scattering by haze droplets merely (1) reduce distant objects’ luminance contrast and (2) desaturate sky blueness? Although the answer to both questions is a qualified “yes” [6,7], this answer’s details have been explored only occasionally [8–13]. Many such studies of haze’s effects on skylight spectra and colors are often restricted to near-horizon paths (i.e., to directions with view-elevation angle \( h \sim 0^\circ \)) [8,11,14–16]. Furthermore, some authors are interested in object colors seen over long optical pathlengths, rather than skylight colors per se [13,17]. This limits the lessons on haze colors that can be drawn from such studies.

To define this color palette more fully, both a spectroradiometer [18] and a hyperspectral imaging system [19] were used to measure narrow field-of-view (FOV) skylight along sky meridians (i.e., at constant azimuth relative to the sun \( \phi_{rel} \)) in 20 clear daytime skies from 2010 to 2013. Although unrefracted sun elevations \( h_0 \) ranged from 3° to 45° for these meridional scans, most were made when \( h_0 \sim 30° \) so that at shared azimuths of \( \phi_{rel} = 90°, 180°, \) and 270° their single-scattering angles \( \Psi \) are comparable. The resulting skylight spectra and chromaticities come from both coastal and inland sites, and they consistently show visible spectral shifts associated with changes in aerosol normal optical depth \( \tau_{aer} \). Although the chromaticity patterns are similar to those obtained from colorimetrically calibrated digital photographs [10,20], such three-channel techniques have metameric uncertainties that are avoided by calculating chromaticities from detailed spectra.

An important caveat applies to the spectral and colorimetric results presented here. As both Henry et al. [11] and Lynch and Mazuk [13] note, even spectrally calculated chromaticities may not predict color appearance realistically. Thus an outdoor observer’s visual perception of skylight is only indirectly related to absolute chromaticity. Among other factors, viewing duration and observer FOV, luminance level, and simultaneous color contrast can all affect a person’s direct visual experience of skylight.
However, persistent chromaticity trends that occur over wide FOVs are more likely to correspond to perceptible skylight features. One common example is the decrease in sky blueness near the horizon, a trend that is both measurable and readily seen. So the emphasis here is on skylight color and spectral trends, rather than on absolute chromaticities.

2. Measured Chromaticities of Clear and Hazy Skies at USNA

Most of the clear-sky spectra in this paper were measured at the United States Naval Academy (USNA) in Annapolis, Maryland, which is located on the Chesapeake Bay's western shore at 38.983° N, 76.484° W. Additional measurements were made at a rural inland site near Marion Center, Pennsylvania at 40.810° N, 79.080° W (elevation above mean sea level = 451 m) and at the summit of Cadillac Mountain, Maine at 44.353° N, 68.224° W (elevation = 470 m) near the Atlantic Ocean.

Figure 1 plots the spectral aerosol extinction $\tau_{aer,\lambda}$ measured near USNA in several clear and hazy skies as a function of wavelength $\lambda$ [21]. Although optical depth data is not available for the other two sites, Table 1 lists their meteorological ranges $V$ as well as USNA's 380-nm $\tau_{aer,\lambda}$. For all sites, the visual criterion for the presence of tropospheric haze (as opposed to stratospheric haze) is that the contrast of distant objects near the horizon must be perceptibly less than under the least turbid conditions.

Haze aerosols at coastal sites such as USNA and Cadillac Mountain typically are solution droplets that form by deliquescence and have modal diameters of ~0.1 μm [22,23], and both locations' aerosol species tend to be dominated by dissolved sulfates [24]. A further distinction is sometimes made between dry haze and damp haze, with the latter being caused by scatterers of diameter >0.1 μm [25]. If the slant-path aerosol optical thickness $\tau_{slant}$ through a haze layer is relatively small (say, $\tau_{slant} < 0.3$), then spectrally selective scattering by the smaller particles of dry haze will make it appear bluish when seen against a dark background. Conversely, spectrally neutral scattering by the larger particles in damp haze can be expected to make it appear white or grayish for any $\tau_{slant}$ [26,27].

Some of these haze properties are evident in Fig. 2, which pairs a clear, haze-free sky in Fig. 2(a) with a visually hazy one in Fig. 2(b). Because of their similar $h_0$ and scattering symmetry about the clear-sky principal plane (i.e., $\phi_{rel} = 90°$ and $270°$ produce identical single-scattering results), these visible-wavelength color images span the same range of single-scattering $\Psi$. Both images are calculated from meridional hyperspectral scans made with the Resonon Pika II imaging spectrometer [19]. Each scan required ~16 sec to complete, and each has angular dimensions of ~45° by 36°. Because trees at the bottom of Fig. 2(b) are only ~1 km away, their contrast against the horizon sky is reduced only slightly compared with trees seen through Fig. 2(a)’s less turbid atmosphere [28]. However, some more obvious visual signs of the much larger $\tau_{aer,\lambda}$ in Fig. 2(b) are its: (1) broader local maximum in sky luminance $L_\psi$ near the horizon, (2) more desaturated sky colors there,

<table>
<thead>
<tr>
<th>Figure(s)</th>
<th>Date (month-day-year)</th>
<th>site name</th>
<th>$h$-interval</th>
<th>$\phi_{rel}$ (°)</th>
<th>mean $\omega'$</th>
<th>mean $\nu'$</th>
<th>$\hat{g}$</th>
<th>$h_0$ (°)</th>
<th>$\tau_{aer,\lambda}$ at 380 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 4</td>
<td>9-1-2010</td>
<td>USNA</td>
<td>1.5–46</td>
<td>270</td>
<td>0.18621</td>
<td>0.45248</td>
<td>0.039692</td>
<td>30.2</td>
<td>0.4752</td>
</tr>
<tr>
<td>1, 2(b), 3, 5, 11(a), 12</td>
<td>9-13-2011</td>
<td>USNA</td>
<td>1.5–46</td>
<td>270</td>
<td>0.18586</td>
<td>0.44222</td>
<td>0.041353</td>
<td>33.4</td>
<td>0.3568</td>
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<tr>
<td>1, 5</td>
<td>8-27-2010</td>
<td>USNA</td>
<td>2.4–47</td>
<td>180</td>
<td>0.17882</td>
<td>0.43333</td>
<td>0.046378</td>
<td>42.9</td>
<td>0.3257</td>
</tr>
<tr>
<td>1, 9, 10</td>
<td>8-31-2012</td>
<td>USNA</td>
<td>n/a</td>
<td>90, 180</td>
<td>n/a</td>
<td>n/a</td>
<td>30</td>
<td>0.2799</td>
<td>0.08727</td>
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<tr>
<td>1, 4</td>
<td>11-8-2011</td>
<td>USNA</td>
<td>0.7–45</td>
<td>270</td>
<td>0.17883</td>
<td>0.4217</td>
<td>0.048756</td>
<td>32.6</td>
<td>0.07341</td>
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<td>1, 2(a), 3, 7</td>
<td>9-20-2011</td>
<td>USNA</td>
<td>1.1–46</td>
<td>90</td>
<td>0.17632</td>
<td>0.43031</td>
<td>0.051016</td>
<td>30.4</td>
<td>0.05346</td>
</tr>
<tr>
<td>8</td>
<td>8-1-2013</td>
<td>Cadillac</td>
<td>1.2–90</td>
<td>93</td>
<td>0.17741</td>
<td>0.41509</td>
<td>0.033822</td>
<td>39.2</td>
<td>(V ~ 15 km)</td>
</tr>
<tr>
<td>8</td>
<td>8-1-2013</td>
<td>Cadillac</td>
<td>0.6–90</td>
<td>180</td>
<td>0.17622</td>
<td>0.40925</td>
<td>0.044723</td>
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<td>6(a), 7</td>
<td>10-9-2011</td>
<td>Marion Center</td>
<td>2.0–46</td>
<td>90</td>
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<td>0.43066</td>
<td>0.048275</td>
<td>30.6</td>
<td>(V &gt; 30 km)</td>
</tr>
</tbody>
</table>

Note: Rows are sorted in order of decreasing normal optical depth $\tau_{aer,\lambda}$ at 380 nm.
Fig. 2. Visible-wavelength images calculated from hyperspectral scans made along fixed sky meridians for view-elevations \( h \sim 0°-46° \) at USNA on the (a) haze-free day of 20 September 2010 at unrefracted sun elevation \( h_0 = 30.4° \) and relative azimuth \( \phi_{\text{rel}} \sim 90° \), and (b) hazy day of 13 September 2011 at \( h_0 = 33.4° \) and \( \phi_{\text{rel}} \sim 270° \) at image center. For display purposes, the latter scan is flipped horizontally so that the sun is to the left of both images.

and (3) greater dynamic range in \( L_u \) along almucantars (note especially the stronger brightening near Fig. 2(b)'s left or sunward edge).

Figure 3 plots the distinct colorimetric differences between Figs. 2(a) and 2(b) in a section of the CIE 1976 uniform-chromaticity-scale (UCS) diagram. Colorimetric landmarks in Fig. 3 include part of the Planckian or blackbody locus and its corresponding color-temperature limits, with bluer (i.e., higher color temperature) colors to the lower left and redder colors (i.e., lower color temperatures) to the upper right. To provide a perceptual scale here and in subsequent UCS diagrams, the major semiaxis of a local MacAdam just-noticeable difference (JND) is drawn near Fig. 3's left ordinate [29]. Separate meridional chromaticity curves of \( u', v'(h) \) are drawn in Fig. 3 for Fig. 2's clear and hazy skies.

In Fig. 3 and other UCS diagrams, \( u', v' \) chromaticity coordinates are averaged at constant \( h \) across an interval \( \Delta \phi_{\text{rel}} = 4° \) wide (sample size \( N = 88 \) hyperspectral pixels per \( u', v' \) pair). The lowest \( h \) of each scan was measured with a calibrated digital inclinometer (repeatability of \( \pm 0.1° \)), and higher \( h \) were calculated as the cumulative angular width of subsequent scan lines. \( \phi_{\text{rel}} \) was set with a combination of (1) a sunlit gnomon aligned with the spectrometer’s optical axis and (2) the true compass azimuths of surface features visible along the horizon of a scan.

Both of Fig. 3's chromaticity curves have features that correspond to our \textit{in situ} perception of sky color. First, each of its \( u', v'(h) \) curves has redder colors at lower \( h \). In purely visual terms, this describes the everyday experience that sky colors look less blue closer to the horizon. Second, the shape of each curve is roughly that of the nearby Planckian locus. In hindsight, this near-congruence is unsurprising because clear-sky colors derive from scattered sunlight. Thus, at a given time and place, meridional trends in atmospheric spectral extinction usually differ only by degree (i.e., \( r_{\text{slant}} \) changes continuously in \( h \)) rather than in kind (i.e., normal \( r_{\text{aer}} \) spectra change very little in \( h \)). As a result, a particular daytime clear sky’s meridional pattern of chromaticities tends to follow a path along the Planckian locus rather than toward or away from it.

Yet Fig. 3's chromaticity curves are dissimilar in important ways. First, its \( u', v'(h) \) curve for 13 September 2011 is much closer to the Planckian locus, meaning that chromaticities for Fig. 2(b)'s hazy sky are less chromatic than those for Fig. 2(a)'s haze-free sky. However, this simple measure of clear-sky color's desaturation by haze is not infallible (see Section 3). Second, Fig. 3's shorter \( u', v'(h) \) curve for 13 September 2011 shows the reduced gamut of blues in Fig. 2(b)'s hazy sky. In colorimetric terms, this particular hazy sky has a normalized colorimetric gamut \( g \sim 19\% \) smaller than that measured on 20 September 2010. (Ref. [10] defines \( g \).) Although this haze-induced gamut reduction is not negligible, it differs greatly from the colorimetric uniformity of fog. Table 1 lists Fig. 3's values for \( g \) and their corresponding mean \( u' \) and \( v' \) as well as the geometrical parameters of \( h_0, \phi_{\text{rel}} \), and \( h \). Finally, Fig. 3 includes what seems at first glance to be only a minor colorimetric curiosity: a small hook in the 13 September 2011 \( u', v'(h) \) curve at \( h = 39° \). Yet as shown below, this seemingly small detail offers an unexpected insight into how aerosols alter clear-sky scattering. Romero et al. produced similar chromaticity hooks (although with opposite curvature) in their airlight simulations as horizontal distances increased between targets and observers [17].

Figure 4 shows a common variation on Fig. 3's clear-versus-hazy sky meridional chromaticity.
were produced by a single interval, perceptible green-purple shifts occur in colors, even if your 3 shifts in the two figures val-
and colorimetric calculations.) Even though those with smaller slightly more vivid than those 2 and 5 distance from the Planckian locus, although are calculated using exactly the same spectral shows some of this 6 chromaticities to red-green-blue (RGB) pixel trip-
aagain listing the corresponding (min).

3. Measured Chromaticities of Clear and Hazy Skies at Other Sites

Some subtle differences are visible between the hyperspectral scans in Figs. 2 and 6, with the latter coming from the rural Marion Center site on 9 October 2011. All of the color maps in Figs. 2 and 6 are calculated using exactly the same spectral integration and coordinate transform that map from the absolute spectral radiances $L_\lambda$ of the Planck II to $u'$, $v'$ chromaticities to red-green-blue (RGB) pixel triplets. (See Ref. [29], pp. 156–159 for details of similar CIE 1931 $x$, $y$ colorimetric calculations.) Even though your display device likely differs from mine in its chromaticity and luminance gamut, the pixel RGB values in Figs. 2 and 6 were produced by a single mapping algorithm. As a result, we can compare relative shifts in the two figures’ colors, even if your color shifts differ visibly from mine.

With this important caveat in mind, note that Fig. 6(a)’s blues look slightly more vivid than those
in Fig. 2(a), even though both scans were made using nearly identical $h_0$, $\phi_{\text{rel}}$, and $h$ intervals (see Table 1). Note too that the meridional range of $L_\omega$ is visibly larger in Fig. 6(a), which is consistent with its having slightly purer blues [10]. Although no $\tau_{\text{aer}}$ measurements are available to supplement Fig. 6’s estimated 30-km meteorological range, we can compare surface relative humidities at the two sites. Each suggests a low-turbidity troposphere: 25% on 20 September 2010 at USNA and 37% on 9 October 2011 at Marion Center.

What then might explain the two figures’ visible color differences? Two possible aerosol explanations are differences in the sites’ (1) elevations (20 m versus 451 m) and (2) inventory of aerosol species. However, the greatest puzzle posed by Figs. 2(a) and 6(a) is visual rather than micrometeorological. Figure 7 plots $\phi', \psi(h)$ curves for these two figures, whose colors would differ visibly if we could compare them in situ as well as photographically. Despite the fact that blues look purer throughout Fig. 6(a), Fig. 7 shows that its $h = 2^\circ$–46° chromaticity curve is much closer to the Planckian locus, and thus the colors of Fig. 6(a) should appear closer to neutral (i.e., less chromatic) than those in Fig. 2(a). Yet the opposite is true. This visual fact is all the more puzzling considering that Fig. 2(a)’s sky looks more vivid than its Fig. 2(b) counterpart, and Fig. 3 shows that Fig. 2(a)’s more vivid blues produce, as expected, a $\phi', \psi(h)$ curve that is further from the Planckian locus. Thus Fig. 6 is one case where color appearance seems at odds with colorimetry, a possibility raised in Section 1.

Despite their differences, Figs. 3–5 and 7 all share one colorimetric feature. Each UCS diagram has at least one $\phi', \psi(h)$ curve with a small but distinct chromaticity hook near $h = 45^\circ$. The presence of this hook seems to be independent of both $\tau_{\text{aer}}$ and absolute chromaticity. Initially, such routine reversals in clear-sky $\phi', \psi(h)$ trends seem counterintuitive. Explaining the desaturation of skylight with decreasing $h$ is straightforward: $\tau_{\text{slant}}$ and thus multiple scattering increase with decreasing $h$, with the result that skylight is redder at lower $h$ (in the sense of being more spectrally uniform) [26,30]. But why might skylight redden slightly as $h$ increases and $\tau_{\text{slant}}$ decreases above $\sim 45^\circ$?

To answer this question, we start by noting the basic colorimetric features of Fig. 8 from Cadillac Mountain. First, Fig. 8’s high-$h$ chromaticity hooks are more pronounced because its meridional scans extend to the zenith, with each scan requiring $\sim 33$ sec to complete. Its two clear-sky $\phi', \psi(h)$ curves were measured within 10 min of each other in a clear sky that had some visible haze (horizontal $V' \sim 15$ km), a narrow band of thin cirrus near the horizon, and a few small cumulus far above it. Neither Fig. 8 scan includes these cumulus clouds, and the cirrus appear colorimetrically only as bending of the $\phi_{\text{rel}} = 180^\circ$ curve below $h \sim 4^\circ$. Second, the $\phi_{\text{rel}} = 93^\circ$ and $180^\circ$ curves would intersect at the single chromaticity of the zenith if these two scans were made simultaneously; their small difference in $h_0$ causes the curves not to intersect.

Third, to show more colorimetric detail, Fig. 8 has a smaller $\phi'$ scale than do Figs. 3–5 and 7, and this by itself slightly increases the chromaticity hooks’ apparent sizes. Nonetheless, including chromaticities from $h > 45^\circ$ does in fact increase their absolute colorimetric size. Fourth, skylight is visibly bluer from Cadillac Mountain’s summit at all $h$ because of the site’s slightly smaller normal $\tau_{\text{aer}}$ compared with that at sea level. Fifth, note that Fig. 8 illustrates another common property of clear skylight: compared with

![Fig. 7. Meridional $\phi', \psi(h)$ chromaticity curves of two clear skies measured at USNA (20 September 2010) and Marion Center, Pennsylvania (9 October 2011) at $\phi_{\text{rel}} = 90^\circ$, with each plotted $\phi', \psi$ averaged at constant $h$ across $\Delta \phi_{\text{rel}} = 4^\circ$.](image1)

![Fig. 8. Meridional $\phi', \psi(h)$ chromaticity curves of the same slightly hazy sky measured on 1 August 2013 from the summit of Cadillac Mountain, Maine at $\phi_{\text{rel}} = 93^\circ$ and $180^\circ$, with each plotted $\phi', \psi$ averaged at constant $h$ across $\Delta \phi_{\text{rel}} = 4^\circ$.](image2)
sky colors at right angles to the sun ($\phi_{\text{rel}} = 90^\circ$ or $270^\circ$), colors along the antisolar azimuth ($\phi_{\text{rel}} = 180^\circ$) of the same sky usually are bluer at corresponding $h$ values. Here “bluer” means that one skylight color has a higher correlated color temperature than another, not necessarily that its colorimetric purity is larger. This holds true even though the antisolar horizon has a higher-contrast band of increased $L_v$ near its horizon [e.g., compare Figs. 6(a) and 6(b)], and this is sometimes interpreted visually as a whiter antisolar sky.

Finally, unlike my measurements made at sea level, Fig. 8’s bluest skylight (see $\phi_{\text{rel}} = 180^\circ$ curve at $h = 48.4^\circ$) has a correlated color temperature approaching $\infty K$, the theoretical limit for molecular single scattering $[10,26]$. Notice that the $h$ where skylight is bluest differs markedly for the two $\phi_{\text{rel}}$. This simple observation ultimately leads to an answer for the question posed above: blue skylight gets redder at high $h$ because scattering by aerosols redens slightly on our line of sight nears the sun.

Simulations with a 2nd-order scattering model developed for another paper in this issue $[31]$ show that the spectra of Mie aerosol phase functions for haze-L polydispersions $[22]$ produce net reddening by single scattering when $\Psi \sim 20^\circ$–135°. Haze-M polydispersions produce similar results in the 2nd-order model, as do MODTRAN4 colorimetric simulations of aerosols’ single-scattering effects on sky color. For $h_0 = 30^\circ$, this $\Psi$ interval corresponds to $h = 15^\circ$–90° at $\phi_{\text{rel}} = 180^\circ$ and all $h$ at $\phi_{\text{rel}} = 90^\circ$. For all $\phi_{\text{rel}} = 90^\circ$–180°, colorimetric analysis shows that the aerosol reddening is largest at the zenith and decreases toward the horizon, which is the trend measured in Fig. 8. If aerosols are removed from the 2nd-order model, then its high-$h$ chromaticity hooks disappear. Thus the size, shape, and position of these hooks depend on the combined effects of (1) aerosol absorption and single scattering and (2) multiple scattering by both molecules and aerosols.

As we look upward along a clear-sky meridian, these two processes’ relative weights change continuously. Desaturation from multiple scattering over large $r_{\text{slant}}$ predominates at low $h$, but this net reddening wanes (i.e., skylight becomes bluer) as $h$ increases and $\Psi$ decreases from $h \sim 35^\circ$–55°. Somewhere in this $h$ interval, reddening due to spectral scattering by aerosols begins to dominate. Because $r_{\text{slant}}$ decreases relatively little at higher $h$, the minor spectral effects of aerosol single scattering persist here, and skylight reddens slightly toward the zenith. Yet this subtle interplay of single and multiple scattering is often a visual disappointment, since clear skylight typically only looks bluer as we near the zenith.


Thus far, we have studied the effects of haze on clear-sky colors by juxtaposing separate chromaticity curves for clear and turbid tropospheres. Alternatively, we can examine haze extinction’s consequences directly by calculating an effective haze spectral transfer function $TF_h$, which I define as

$$TF_h = L_h(\text{hazy } \Psi)/L_h(\text{clear } \Psi).$$

or the ratio of spectral radiances in hazy and clear atmospheres at the same $\Psi$ and $h_0$. This is a phenomenological function rather than one that analyzes any intermediate radiative-transfer details. However, it is related to (and seems to be as useful as) my earlier definition of effective overcast transmissivity at the earth’s surface $[32]$. Thus Eq. (1) should be considered an illustrative tool rather than an analytical one, but when used with care it can provide some insights into the combined spectral and angular consequences of haze extinction.

Figure 9 shows the $TF_h$ at USNA for $\phi_{\text{rel}} = 90^\circ$ on the hazy day of 31 August 2012 [$r_{\text{aer}}(380 \text{ nm}) = 0.2799$] versus the clear day of 10 September 2012 [$r_{\text{aer}}(380 \text{ nm}) = 0.08727$; see Fig. 1]. In Figs. 9 and 10, all underlying $L_j$ were measured with the Photo Research PR-650 spectroradiometer and are averaged over its 1° FOV. In both figures, each $TF_h$ spectrum is calculated from Eq. (1) as the ratio of spectral radiances on the two days at corresponding $\Psi$, $h_0$, and $\lambda$. Although the $TF_h$ values plotted in Figs. 9 and 10 depend on the particular choice of clear and hazy skies, this choice is not crucial so long as it is representative of the observing site, which is the case here. Note that unlike direct-beam transmissivity, $TF_h > 1$ is entirely possible and simply means that the hazy sky is brighter than the clear sky at the given $\Psi$ and $\lambda$. 

![Fig. 9. Haze spectral transfer functions $TF_h$ for $h = 5^\circ$, 10°, and 20° measured at USNA on 31 August 2012 and 10 September 2012 at $\phi_{\text{rel}} = 90^\circ$. Each spectrum is calculated from Eq. (1) as the ratio of spectral radiances on the two days at corresponding $\Psi$, $h_0$, and $\lambda$.](image-url)
At $\phi_{\text{rel}} = 90^\circ$ (or 270°), the following TF$_i$ trends are consistent in USNA clear skies: (1) a slight bluish bias at low $h$ disappears by $h \sim 10^\circ$, (2) with near-linear increases for $\lambda < 680$ nm at higher $h$, and (3) decreases for $\lambda > 680$ nm. The net result is that tropospheric haze often causes an orangish shift in clear-sky colors, except near the horizon where a purplish shift is more likely (see $h = 5^\circ$ spectra in Figs. 9 and 10). The most significant differences in Fig. 10’s antisolar sky are that Fig. 9’s TF$_i$ local minima and maxima have shifted to longer wavelengths (to $\lambda \sim 480$ nm and 750 nm, respectively). The net result is that haze-induced purplish and orangish color shifts tend to be more pronounced at $\phi_{\text{rel}} = 180^\circ$ than at 90°, although much of this larger shift stems from the haze-free antisolar sky’s more vivid blues. Strictly speaking, all such shifts also depend on $h_0$ and aerosol type, and they disappear (i.e., TF$_i \rightarrow 1$) as $\tau_{\text{aer}}$ decreases toward zero.

What might such haze-caused shifts in clear-sky colors actually look like? One answer appears in Fig. 11(a), a false-color map that plots Eq. (1)’s spectral pixel by pixel at equal $\Psi$ for the hazy sky of 13 September 2011 [Fig. 2(b)] versus the clear sky of 20 September 2010 [Fig. 2(a)]. Figure 11(a) maps TF$_i$ near $\phi_{\text{rel}} = 90^\circ$, while Fig. 11(b) does the same for TF$_i$ near $\phi_{\text{rel}} = 180^\circ$. At matching pixels in each hazy:clear image pair, the TF$_i$ spectrum is used to calculate a $u', v'$ chromaticity pair and a corresponding RGB ratio. Figure 11 plots these RGB triplets at maximum brightness, and so it only suggests each pixel’s spectral distribution of TF$_i$ rather than its magnitude. For easier visualization, the transform from $u', v'$ to RGB makes a completely uniform TF$_i$ spectrum equivalent to $R = G = B$ (i.e., the equal-energy spectrum is mapped into a white display color). Naturally, other false-color mappings are possible, but this one does address the question posed in Section 1: how to translate haze-induced shifts in clear-sky spectra directly into colors.

Figure 11’s color maps trade the fine spectral details of Figs. 9 and 10 for much greater spatial detail. Although Fig. 11 uses spectral data from a different instrument (the Pika II imaging spectrometer) and from different days than those in Figs. 9 and 10, it tells much the same story about the typical effects of haze on USNA clear-sky spectra. First, the skies in both Figs. 11(a) and 11(b) have a distinct orangish to pinkish cast that becomes stronger near the horizon. Second, the overall color shift is redder in the antisolar sky of Fig. 11(b), unlike the case in Fig. 10 [compare slopes of the TF$_i$($h = 20^\circ$) curves in Figs. 9 and 10]. Third, immediately above the horizon are purplish color shifts like those seen at $h = 5^\circ$ in Figs. 9 and 10, a shift that is stronger in Fig. 11(b)’s antisolar sky. These same angular trends appear in other USNA maps of TF$_i$, suggesting that Fig. 11’s haze color shifts are common here.

Figure 12 is a colorimetric version of Fig. 11. In it, TF$_i$ spectra at each $h$ are averaged across a window 10° wide that is centered on $\phi_{\text{rel}} = 180^\circ$ or 270° [see Fig. 2(b) for a color image of the latter sky]. As in Fig. 11, a spectrally uniform TF$_i$ is mapped into the equal-energy spectrum whose chromaticity is marked in Fig. 12. Now Fig. 11’s TF$_i$ colors for the same hazy and clear skies (13 September 2011 and 20 September 2010, respectively), appear in Fig. 12 as chromaticity curves whose $u'$ values increase as $h$ increases near the horizon.

The gamut of these false colors is larger for TF($\phi_{\text{rel}} = 180^\circ$), as indicated by (1) its chromaticity curve’s larger span in Fig. 12 and (2) the more pronounced TF$_i$ colors in Fig. 11(b). Most of the change in Fig. 12’s two TF$_i$ curves occurs within 5° of the horizon, reflecting the same trends as in Fig. 11. One TF$_i$ feature that is not evident in Fig. 11 is Fig. 12’s pronounced pair of chromaticity hooks labeled “H” near $h = 40^\circ$. Presumably, these are
2. shift the loci of clear skylight chromaticities either parallel or perpendicular to the Planckian locus without much changing the original chromaticity curves’ shapes (Fig. 5),

3. produce the chromaticity hooks that often occur at high $h$ (see Figs. 3–5, 7, and 8),

4. redden skylight at all $h$ but do so more strongly near the horizon (Figs. 9–12), and

5. cause a slight purplish shift in skylight just above the horizon (Figs. 9–12).

Thus far from being a mere colorimetric contaminant, haze proves to have surprisingly profound and wide-ranging visible effects on clear-sky colors. The measured properties of haze presented here are in fact perceptible, and they offer valuable new criteria for assessing the performance of radiative transfer simulations at visible wavelengths.

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References and Notes


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18. PR-650 spectroradiometer from Photo Research, Inc., 9731 Topanga Canyon Place, Chatsworth, California 91311 (http://www.photoresearch.com). According to Photo Research, at specified radiance levels, a properly calibrated PR-650 measures luminance and radiance accurate to within ±4%, has a spectral accuracy of ±2 nm, and its CIE 1931 colorimetric errors are \( x < 0.001, y < 0.001 \) for a 2856 K black-body (CIE standard illuminant A).
19. Pika II hyperspectral imaging spectrometer from Resonon, Inc., 619 North Church Avenue, Bozeman, Montana 59715 (http://www.resonon.com). The system consists of a digital camera that has an internal diffraction grating and is coupled to a rotation stage controlled by a precision stepper motor and laptop computer. In this pushbroom system, the laptop acquires 640 different skylight spectra at each rotation stage position (i.e., for each line of the resulting hyperspectral data-cube). Each of the 640 pixels that make one scan line has its own spectral calibration, and the calibration procedure follows National Institute of Standards and Technology recommendations.
21. Sun photometer data and calculations of \( \tau_{\text{aer}} \) are acquired and archived by AERONET at http://aeronet.gsfc.nasa.gov. Fig. 1’s data comes from the Goddard Space Flight Center in Greenbelt, Maryland and the Smithsonian Environmental Research Center in Edgewater, Maryland.
28. For \( h < 15^\circ \), the near-infrared reflectance peak of trees and other vegetation along a given \( \phi_\text{col} \) is often seen in skylight spectra from \( \lambda \sim 700–900 \) nm. However, because surface reflections from 400 to 700 nm negligibly affect most clear skies for \( h > 0.5^\circ \), in this paper we can ignore surface reflectances along near-horizon paths and thus use relative (as opposed to absolute) azimuths.