Evaluation of a one-dimensional cloud model for yellow and green thunderstorms

Frank W. Gallagher III and William H. Beasley

Many observers have reported observations of green light emanating from severe thunderstorms in the midwestern United States. Spectral measurements have demonstrated that the dominant wavelength of the light is in the green portion of the visible spectrum and that this is not just a subjective impression. According to the theory proposed by Bohren and Fraser [Bull. Am. Meteorol. Soc. 74, 2185 (1993)], two effects combine to produce green light from thunderstorms. First, incident solar radiation is reddened by selective scattering by air molecules and particles in the atmosphere before it enters the cloud. Second, the radiation that passes through an optically thick cloud is attenuated in the longer wavelengths because of selective absorption by liquid water. Model calculations indicate that realizable combinations of mean drop diameters, mean liquid-water contents, and cloud thicknesses can satisfy the conditions required for shifting the dominant wavelength of the incident solar radiation to green. © 2003 Optical Society of America

OCIS codes: 010.0010, 010.1290, 010.1320, 010.3920.

1. Introduction

Much folklore has developed as a result of an apparent association between severe weather, such as hail and tornadoes, and the green light that is occasionally observed in conjunction with that type of severe weather. Some scientists1–4 have proposed explanations for the occurrence of the green light occasionally associated with thunderstorms, but until recently there have been no quantitative observations of the spectrum of light from thunderstorms. During the spring and summer of 1995 and 1996 we traveled from Colorado to Florida in an effort to observe light from thunderstorms under a variety of meteorological conditions. To do this we used a hand-held spectrophotometer,5 with which we obtained spectra of light emanating from green and nongreen thunderstorms. The explanation for green light from thunderstorms provided by Bohren and Fraser4 invokes sunlight, depleted in shorter wavelengths by atmospheric scattering before it enters the cloud, in combination with the filtering effect of water, which reduces the radiance of light with longer wavelengths, to yield green light. Our observations and calculations presented here show that the explanations of Bohren and Fraser4 can account for green light from storm clouds that have appropriate bulk microphysical properties. That, in turn, suggests that it might be feasible, at least under some well-defined circumstances, to use spectral observations to make quantitative estimates of the bulk microphysical properties of storms.

2. Green Light from Thunderstorms: The Theory of Bohren and Fraser

One of the principal differences between the findings by Bohren and Fraser4 and the suggestions of Fraser1 is as follows: Bohren and Fraser4 suggest that the green light we see from severe thunderstorms actually comes from the bottom of the thunderstorm cloud. Fraser, however, proposed that the thunderstorm is a black background only and that the light we see really comes from scattering by the atmosphere along the line of sight from the observer to the thunderstorm cloud. Because absorption of visible light by water in either a solid or liquid state is at a minimum in the wavelengths of light that correspond to blue and at a maximum in the wavelengths that are typically associated with red,6,7 any light that passes through an appreciable mass of cloud hydrometeors (all water and ice particles that make up the cloud and precipitation) will be depleted of red light. Late in the day, sunlight that is incident upon a cloud is depleted in the shorter wavelengths because a
large portion of the light at shorter wavelengths is scattered out of the path between the Sun and the observer by molecules and by small particles in the atmosphere. When this reddened light passes through a cloud of water droplets, the resulting transmitted light can have a dominant wavelength in the green spectral band if the path through the water is long enough to permit sufficient absorption of the light of longer wavelengths. In other words, the color of light transmitted by or emanating from a thunderstorm depends on the optical depth of the cloud, the wavelength dependence of the absorption and scattering of light by the hydrometeors in the cloud, and the spectrum of the incident light. Bohren and Fraser found that the effects of drop size, liquid-water content, and cloud thickness can be combined in a term that represents the bulk optical depth \( \tau \) of a cloud:

\[
\tau = \frac{3h}{d\rho_w},
\]

where \( h \) is the thickness of the cloud, \( l \) is the liquid-water content (LWC), \( d \) is the mean drop diameter, and \( \rho_w \) is the density of water. The light emitted from the bottom of a simplified thunderstorm cloud can be represented by the following analytic model:

\[
F^i(\tau) = F^i(0) \frac{4K\exp(-K\tau)}{3(1-g)(1-\exp(-2K\tau))},
\]

\[
K = \left[(1-g)(d\alpha f(n))^2\right]^{1/2},
\]

where \( F^i(\tau) \) represents the downwelling diffuse flux at a level \( \tau \) in the atmosphere, \( F^i(0) \) is the flux of radiation at the top of the atmosphere, \( \tau \) is the optical depth, \( g \) is the asymmetry parameter, and \( K \) is a parameter that includes the effects of absorption; \( f(n) \) is defined by

\[
f(n) = \frac{n^3 - (n^2 - 1)^{3/2}}{n},
\]

and \( n \) is the real part of the index of refraction. In other words, Eq. (2) represents the downwelling diffuse irradiance emitted at the bottom of a simulated thunderstorm cloud. The downwelling irradiance at the top of the atmosphere is modified by the scattering and absorption of light by the molecules in the atmosphere and by hydrometeors in the cloud. If we assume the special condition that the irradiance is uniform, we can compute radiance values and measured radiance values. The wavelength dependence of the computed radiance is complicated and arises from the absorption coefficient \( \alpha \) in the \( K \) term [Eq. (3)].

Our attempt here is not to re-create an observed spectrum but rather to verify that colors observed by humans and instruments can be described by the theory of Bohren and Fraser and to investigate whether variations of the bulk microphysical properties of thunderstorm clouds can change the color of the light emitted from the bottom of a thunderstorm. Because of this approach, we have restricted ourselves to looking at single parameters that represent the entire cloud. For example, our formulation allows for only a single mean drop diameter, a single cloud height, and a single LWC for any given simulation. We independently vary these parameters to investigate the full span of possible parameter values. Given these independent parameters, we are able to simulate the perceived color observed under some thunderstorms.

3. Application of the Bohren–Fraser Theory

Calculations with Eqs. (2) and (3) illustrate the results of Bohren and Fraser. As an extension of their calculations that is suitable for comparison with observations, we include a more realistic illumination source and a greater range of solar zenith angles, mean drop diameters, and LWCs. The transmitted light is computed according to the Eddington radiative transfer approximation, assuming a cloud of uniform optical properties and infinite horizontal extent. Use of the Eddington approximation accounts for multiple scattering of the radiation inside the cloud. The solar zenith angle and the cloud properties (e.g., effective drop radius and cloud LWC) are varied to permit their effects on the transmitted light to be determined.

Incident solar radiation is represented in the calculations by a realistic solar spectrum in the wavelength band 380–780 nm by use of the standard top-of-the-atmosphere irradiance data given by Neckel and Labs. The effect of the setting Sun (variation in the cloud-free atmospheric optical thickness) is accomplished through the variation of the optical path for sunlight through the atmosphere, accounting for a spherical Earth and for ozone absorption. Skylight was incorporated into the incident radiance by use of the measurement of north-looking blue sky radiance.

A. Model Parameters

To determine the amount of liquid water, and thus the amount of absorption, to use in the model calculation we need to choose representative values for the optical thickness of the cloud. Equation (3) shows that we need to consider various combinations of cloud thickness, LWC, and mean drop diameter. Although they are interrelated, in the model we can vary them independently to learn whether particular values of any of them, alone or in certain combinations, will yield an optical depth that will affect the color of the emitted light at the base of the cloud. For example, if we keep the height of the cloud and the mean drop diameter fixed, we can vary the LWC (meaning that we have more drops) and compute the radiance of the transmitted light.

As shown in Eq. (1), the optical thickness that determines effects on light transmitted through a cloud is directly proportional to the thickness \( h \) of the cloud. For this study we used a path length that was representative of the distance from the base to the top of a visible cloud. Note that slantwise paths could...
be longer or shorter for a given incident geometry. Typical path lengths through the thickness of a cloud can range from 1.5 km for cumulus clouds to more than 15 km for cumulonimbus clouds. Most observed green thunderstorms appear to be of the supercell type; therefore a thickness of 15 km, representing deep convection, is used here except as noted.

Measurements of cloud microphysical parameters by cloud-penetrating aircraft show that cloud drop size diameters can range from less than 15 to larger than 45 µm with concentrations of 100–1500 cm$^{-3}$, whereas raindrops as large as 5 mm have been observed in concentrations of 7.5 $\times$ 10$^{-5}$ cm$^{-3}$ (75 m$^{-3}$). Because we are interested in determining whether the simple model can approximate the observed color rather than in calculating a precise spectrum, we shall use the mass-averaged equivalent drop size and concentration measurements: 17 µm at a concentration of 1500 cm$^{-3}$ and 5 mm at a concentration of 7.5 $\times$ 10$^{-5}$ cm$^{-3}$ (75 m$^{-3}$). We assume that the homogeneous cloud is entirely filled with such droplets without regard to measurements of cloud heights, LWCs, or the presence or absence of precipitation.

As we are also concerned with the LWC of the storm as a parameter in our optical depth calculation [Eq. (1)], we need to know the bounds on observed LWCs. Aircraft studies indicate that the LWC in deep convection can vary from as little as 3 g m$^{-3}$ to as much as 14 g m$^{-3}$. In our calculations the LWC was varied in 0.1-g m$^{-3}$ increments, from 0.5 to 15 g m$^{-3}$, to account for a wide range of average and extreme cloud LWCs.

B. Model Calculations

1. Small Drops

We performed the first calculation, not shown in the figures, to investigate how the chromaticity of simulated spectra varies with changes in LWC for a fixed cloud thickness, a fixed mean drop diameter, and a fixed solar zenith angle and to show that clouds that consist of small drops and have high LWC appear to be of the typical blue-gray color normally associated with cumulonimbus clouds. The assumption was made that the simulated storm would be a mature cumulonimbus of 15-km height but would consist of only small cloud drops; all the hydrometeors (liquid or ice spheres) had the same diameter, 5 µm. The solar zenith angle was fixed at 70° to simulate an afternoon Sun. We found that, as the LWC was varied, starting with small values of LWC, the cloud with a small LWC (0.2 g m$^{-3}$) had a dominant wavelength of 577 nm, a wavelength that is normally associated with yellow. The dominant wavelength decreases with increasing LWC. For a LWC of 1.7 g m$^{-3}$ the dominant wavelength is 498 nm, a wavelength normally associated with a blue-green color. Further increases in LWC result in a storm that appears more blue. At a LWC of 5 g m$^{-3}$ the dominant wavelength is 491 nm, a wavelength that is normally associated with the color greenish-blue. The computed dominant wavelength matches well typical observations of gray clouds that have dominant wavelengths near 485 nm. On the basis of this result, one would expect a thick cumulonimbus cloud consisting of small drops and high LWC to appear bluish-gray in color, and this is the color typically seen when one is observing a severe thunderstorm. A green color (dominant wavelengths of 500–510 nm) is a possible result for very tall clouds with very small drops with LWCs of 1.0–1.6 g m$^{-3}$. However, for mature thunderstorms the mean droplet size is much larger than the 5 µm used in this calculation. A larger drop size would be more representative of the LWC measured in precipitating cumulonimbus clouds.

2. Larger Drop Sizes

Because real thunderstorms have many drops that are larger than small cloud drops, we increased the mean drop size in the model calculations. Figure 1 shows the variation in chromaticity with changes in LWC for a cloud thickness of 15 km, a mean drop diameter of 22 µm, and a solar zenith angle of 70°. The dominant wavelength, for a LWC of 0.5 g m$^{-3}$, is 576.5 nm, a wavelength that is not too different from that of the incident solar radiation. As the LWC is increased, the selective absorption increases and the dominant wavelength progressively decreases. At LWC values of 2.2–3.2 g m$^{-3}$ the dominant wavelength is in the band associated with greenish colors, with yellow-green for the low-LWC end and blue-green at the high end. The model calculations suggest that there are two ranges of LWC values, with all other cloud parameters remaining unchanged.

![Fig. 1. CIE 1976 UCS chromaticity diagram showing the variation in chromaticity of a simulated cumulonimbus cloud with changes in cloud LWC. The LWC (g m$^{-3}$) is shown next to the chromaticity points (in increments of 1 g m$^{-3}$). The cloud thickness is 15 km, the mean drop diameter is 22 µm, and the solar zenith angle is 70°. D$_{65}$ is the CIE 6500-K achromatic reference.](image-url)
which, in the model, produce light that would be associated with green thunderstorms. Musil and Smith\(^\text{16}\) showed that on several flights by the T-28 (a research aircraft), values of LWC were found close to 0.6 \(\text{g m}^{-3}\), with the measured LWC never exceeding a value of 3 \(\text{g m}^{-3}\). This result suggests that the larger drops are partially responsible for producing the yellowish-green type of green thunderstorm but are not needed for the blue-green type, a result that is consistent with subjective impressions that severe storms sometimes have a yellow-green color. In other words, for a given LWC, clouds that contain larger drops transmit light of longer wavelengths than light emitted by a cloud of smaller drops. Figure 1 also shows that, for a 22-\(\mu\text{m}\) mean drop size, the LWC values \(< 6 \text{ g m}^{-3}\) measured by Musil and Smith\(^\text{16}\) produce the yellow-green type of green thunderstorm. Higher LWCs, which are associated with the updraft or core regions of the storm, can produce the blue-gray color that is seen in most thunderstorms. The higher-LWC clouds will increase the optical thickness such that more absorption of the longer-wavelength light can occur, resulting in a blue-green color rather than a yellow-green color. The larger the mean drop size for a given LWC, the lower the optical depth and the less the amount of absorption of the longer wavelengths of light by the cloud water. So larger mean drop sizes will result in a yellow-green color rather than in a blue-green color.

C. Comparisons with Measurements for Two Computed Cloud Thicknesses

The optical model used in this study is neither intended nor expected to duplicate the spectrum of light from a thunderstorm in exact detail. Our objective is to obtain a satisfactory colorimetric representation of the light that is being observed, given realistic assumptions about the cloud hydrometeors. To accomplish this, we consider two different storm thicknesses. We chose a thickness of 15 km to represent the situation for sunlight that is incident on the top part of a thunderstorm. We chose a thickness of 5 km to represent a situation in which sunlight is incident upon the side of the thunderstorm. Solar radiation passes through more of the atmosphere to reach the cloud at the 5-km level than at the 15-km level. The radiation that is incident upon the lower part of the cloud is therefore relatively greater toward the red end of the spectrum than the radiation incident upon the top of the 15-km cloud. The solar zenith angle of the incident radiation in the model was fixed at 55°, the mean solar zenith angle between a yellow-green observation (57°) recorded on 7 May 1995, and a blue-green observation (53°) recorded on 31 May 1995.\(^5,20\)

1. 15-km Thickness

Figure 2 shows a CIE 1976 UCS (uniform chromaticity scale) diagram of the variation in chromaticity with LWC for a 15-km-thick cloud with a mean drop diameter of 5 \(\mu\text{m}\). Absorption of light by cloud water changes the dominant wavelength of the transmitted light to a blue color even with low LWC. Increasing the LWC causes the transmitted light to become bluer. Thus blue-green light can result from a LWC as little as 1.5 \(\text{g m}^{-3}\). The calculated spectrum, for a LWC of 2.7 \(\text{g m}^{-3}\), is compared in Fig. 3 with a recorded spectrum of a blue-green thunderstorm observed on 31 May 1995 near Sweetwater, Texas. Although the curves appear to be somewhat different in
shape, the dominant wavelength is identical for the two spectra.

Calculations that include a drop size of 22 μm with a 55° solar zenith angle produce yellow-green light from a cloud with a LWC of 0.8 g m⁻³. More absorption occurs with increasing amounts of liquid water in the cloud for the same mean drop diameter. Calculations show that a blue-green dominant wavelength, similar to the one measured on 31 May 1995, results when a LWC of 2.7 g m⁻³ is used. Although the model uses a single drop size and a single LWC to represent the entire cloud, the simulations produce dominant wavelengths that represent the colors of green thunderstorms observed with a model cloud thickness of 15 km with simulated sunlight incident only upon the top of the cloud.

2. 5-km Thickness

A better representation of a storm would allow for sunlight to be incident upon the sides of the cloud rather than just the top. To approximate this condition we reduced the height of the model cloud to 5 km, one third of the height of the 15-km cloud described above. We also adjusted the spectrum of the incident light to account for the longer path length through the atmosphere.

The additional scattering of light incident upon a cloud over a longer simulated path shifts the dominant wavelength toward the red, such that green color is produced with a smaller cloud LWC. Furthermore, the calculated spectrum is more realistic in that there is more transmitted radiance in the longer-wavelength portion of the spectrum. Figure 4 shows a CIE 1976 UCS diagram of the variation in chromaticity with changes in LWC for a cloud that consists of 5- and 22-μm drops. At a low LWC the dominant wavelengths for both drop sizes are near that of the incident radiation. As the LWC increases, absorption increases and the dominant wavelengths shift toward the short-wavelength portion of the spectrum. With a LWC of 15 g m⁻³, only the smaller drop sizes result in dominant wavelengths near 490 nm. Figure 5 shows a plot of a spectrum simulated with a mean drop diameter of 22 μm and a LWC of 4.1 g m⁻³ compared with an observed yellow-green spectrum. In this example, the computed spectrum matches the observation very well in the 380–650-nm band, essentially the entire range of primary human vision.

4. Discussion and Conclusions

We have shown that it is possible, under the appropriate conditions, that the dominant wavelength of sunlight can be shifted toward the blue end of the spectrum, sometimes resulting in dominant wavelengths that represent green light. These results show that Bohren’s transmission model simulates the observed colorimetric properties of green thunderstorms reasonably well, considering the simple model approximations. We have shown that green light can be produced in clouds that are as thick as 15 km with sunlight incident only on the top of the storm. A blue-green colored storm is predicted for small drop sizes, and a yellow-green storm is predicted for larger drop sizes. Both types can be produced with intermediate-sized drops. To simulate better the effects of sunlight incident upon the sides of the clouds, we reduced the cloud thickness to 5 km. Then both shades of green could be produced with small drop sizes, no green light could be produced with large drops (or hail), and only the yellow-green...
type could be produced with intermediate drop sizes. The green light produced by yellow-green storms comes from a cloud of much lower optical thickness. This effect can occur, and has been observed, in the green light from storms that have significant precipitation or from near the rear flank downdraft of severe thunderstorms.

This research was supported by National Science Foundation (NSF) grant ATM-9400208, Physical Meteorology Program. C. Bohren’s optical model was used substantially in this study. The authors thank Erik Rasmussen and Jerry Straka for their cooperation that allowed us to pursue this research in conjunction with project Vortex (Verification of the Origins of Rotation in Tornadoes Experiment). Much of the vehicle support for Vortex was provided by the Center for Analysis and Prediction of Storms and guidance were provided by the National Hail Research Experiment. Additional vehicle support for Vortex was provided by the National Severe Storms Laboratory in Norman, Okla. We also appreciate the very helpful comments of the reviewers.

References