Effective Visualization of Radar Data for Users Impacted by Color Vision Deficiency

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ABSTRACT

Color Vision Deficiency (CVD) is a decreased ability to discern between particular colors. Eight percent of genetic males and half a percent of genetic females have some form of CVD, with many in the radar community falling into this group. When presenting data on a two-dimensional plane, it is common to use colors to represent values via a colormap. Colormap choice in the radar community is influenced by the ability to highlight scientifically interesting features in data, institutional choices, and domain dominance of legacy colormaps. The problem with these current colormaps is that many do not project well for those with CVD (i.e., green next to red). In working with the CVD community to address this problem, multiple colormaps for moments such as equivalent reflectivity factor and Doppler velocity were created for users with forms of CVD such as deuteranomaly, protanomaly, protanopia, and deuteranopia using Python tools such as colorspacious and viscm. We show how these colormaps can improve interpretability for four cases: a mesoscale convective system, a pyrocumulonimbus storm, a wintertime mid-latitude cyclone, and widespread storms with a large bird migration. These new radar equivalent reflectivity factor, Doppler velocity, and polarization colormaps are designed to highlight rain, frozen precipitation, non-meteorological targets, velocity-based items, be perceptually uniform, and visually friendly for those with CVD.

1. Introduction

Color Vision Deficiency (CVD) is a decreased ability to discern between particular colors. An estimate of eight percent of genetic males and half a percent of genetic females have some form of CVD (Sharp et al. 1999; Neitz et al. 2011), with many in the science community falling into this group. When presenting data on a two-dimensional plane, it is common to use colors to represent values via a colormap. Individuals that have CVD can have issues with reading this data depending on the colormap that is used. This is especially true in the weather radar community. Colormap choice in the radar community is influenced by the ability to highlight scientifically interesting data, institutional choices, and dominance of legacy colormaps in the radar community. This becomes problematic as many colormaps in the radar community that are typically used do not highlight features of interest well for those with CVD. Crameri et al. (2020) states that scientific results should be accessible to all, therefore CVD-friendliness should be considered for researchers and publishers. CVD-friendly colormaps should also be accessible for weather radar imagery, in order to allow for readability of radar data for those with CVD while still being able to highlight scientifically interesting data such as regions of heavy rain, snow, hail, as well as velocity-based features such as couplets and inbound and outbound scatterers.

To understand why common colormaps in the weather radar community are problematic, we first need to understand the different types of CVD. The most common form of CVD is difficulty discerning between red and green. The four types of red-green CVD are deuteranomaly which makes green look more red, protanomaly which makes red look more green and less bright, and protanopia and deuteranopia which make green and red indistinguishable (Sharp et al. 1999; Neitz et al. 2011). There are also two types of blue-yellow CVD. Tritanomaly makes it difficult to distinguish between blue and green as well as between yellow and red. Tritanopia makes the individual less able to distinguish between blue and green, purple and red, as well as yellow and pink (Sharp et al. 1999; Neitz et al. 2011). Complete color blindness is also possible, but quite rare. The colormaps used in the radar community, such as the National Weather Service (NWS) equivalent reflectivity factor (i.e., Ze) colormap, use uneven gradients and include green and red colors with similar lightness, which are not distinguishable for the majority of those with CVD.

Another problem with the current colormaps is that they are not perceptually uniform. Perceptual uniformity is when changes in color (lightness or color) and data values are

weighted equally and thus do not create artificial structure. This is why rainbow or jet colormaps, such as the NWS Ze colormap, are problematic, as small data variations can be interpreted as more important than others due to the corresponding color changes not being perceptually uniform (Crameri et al. 2020; Stauffer et al. 2015). Stated differently, the data should describe the color breaks, not the colormap. Crameri et al. (2020) and Stauffer et al. (2015) note that colormaps should also have perceptual order or lightness that increases linearly to avoid perception of artificial gradients and to ease comparison of significant values. Data visualization with colomaps that lack perceptual order can complicate discerning between convection and non-convection for those with CVD. As an example of perceptual uniformity, Fig. 1 shows three Ze colormaps. The NWS Ze colormap has the most discontinuities followed by the ChaseSpectral and then HomeyerRainbow. Fewer discontinuities in the lightness derivative reduces the possibility of artificial structure or visual error (Crameri et al. 2020), such as clutter in a radar image having a similar lightness value and having similarities visually to snow. Having similar brightness values or breaks with reds and greens can also visually appear identical to an individual with protanopia or deuteranopia.

In this article, we summarize how the discussion of radar colormaps and CVD began, discuss the methods of creating these new colormaps for radar imagery, and discuss lessons learned, future plans, as well as advocating the use of these colormaps. The goal of this paper is to answer, “Can CVD-friendly colormaps be created that highlight important characteristics of clouds and precipitation?”

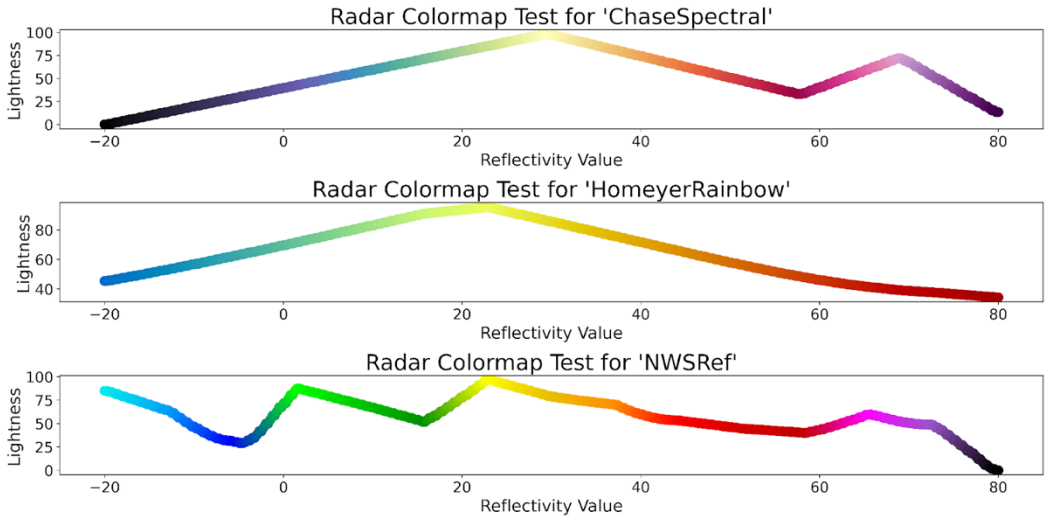

Fig. 1. Lightness comparison of typical Ze values using colorspacious showing the CVD friendly Chase spectral and Homeyer rainbow colormaps as well as the National Weather Service Ze colormap.

2. From Twitter to Python: Discussion of science communication and current colormaps

Scientists interact via a variety of social platforms, as it is another way to follow those of similar professions and backgrounds. This is how the discussion on CVD-friendly colormaps began for radar imagery. On Twitter, the original post stated the author's goal was to create a perceptually uniform colormap, while showing it through a CVD lens (Fig. S1). This then evolved into a larger discussion on GitHub, where individuals with CVD became involved. The discussion noted the overall lack of CVD-friendliness of current colormaps in the radar community. Colormaps such as the NWS and NCAR Ze are difficult for individuals with CVD to distinguish between varying types of precipitation and convection. With this in mind, the decision was made to work on a colormap with CVD-friendliness in mind while practicing good communication with colors (Crameri et al. 2020). That being said, determining quantitative values from a radar image is also important, and having no breaks in luminosity can be limiting. There also is a need for thresholds to identify convective features and hail. For the moments in radar data that we were developing these colormaps for, we needed to set clear expectations on how data can be visualized accurately, while still being inclusive towards the rest of the community.

3. Setting criteria and determining radar moment expectations

To create these colormaps, a set of criteria were created for the development of these colormaps. One criterion is that the colormaps should attempt to be perceptually uniform unless there is a very specific reason to create a break or discontinuity (e.g., identifying inbound and outbound scatterers). Another criterion is that the mapping from the full-spectrum color space onto the CVD color spaces for deuteranomaly and protanomaly should be one-to-one. If achievable, colormaps should also be one-to-one to a gray-space colormap; however, this can be difficult. The two main radar moments that this article focuses on are: Ze in dBZ, and mean Doppler velocity (henceforth, velocity) in m s-1. Dual polarization moments co-polar correlation coefficient (ρHV) and depolarization ratio are also mentioned, but these moments are in the early stages of testing.

Ze has clear clusters corresponding to both microphysical processes and hydrometeors. Precipitating cloud returns are usually above -15 dBZ. In S-band radars, for example, drizzle occurs up to around 5 dBZ, transitioning to rain up to values around 60 dBZ where hail or very high rainfall rates cause elevated signals. Returns approaching 80 dBZ have been observed, usually aloft and caused by large and/or highly concentrated hail in supercellular storms or from miscalibration. For the transition between non-convection and convection, near 35 dBZ often is used as stated (e.g., Haberlie and Ashley 2018). With this in mind, the colormap can be developed to meet these different requirements. We do acknowledge that radars, such as the W-band (3 mm wavelength), have a maximum Ze for hydrometeors around 25-30 dBZ due to non-Rayleigh scattering effects, and colormaps should be adjusted to accommodate different frequency radars. Ze also is the product most commonly used by the general public. Forecasters need to issue warnings for severe thunderstorms due to hail, wind and more, while the public needs to see these dangers. For a professional, there needs to be a way to differentiate between different features in a radar scan. For the public, in general, the higher the Ze, the higher the chance of public impact. Therefore, higher values should be psychologically impactful. This is generally achieved with warmer hues like reds, pinks and purples.

Viewers of velocity imagery need to be able to quickly discern areas of incoming and outgoing velocities. Velocity varies between negative (toward the radar) to positive (away from the radar) when the values fall within the Nyquist interval, or a correction for aliasing has been done when outside the Nyquist interval. There are three requirements for velocity:

First, the value at zero m s-1 (the zero isodop) has a special significance due the transition in the flow direction along the radar transmission radial. Since the height of the radar sampling volume nearly always increases with range, the curve of the zero isodop broadly indicates the vertical wind shear profile. Therefore, there should be a change in hue around the zero isodop. Furthermore, it is essential to be able to visualize the impact of Doppler velocity aliasing (exceedance of Nyquist). Thus, the color at positive Nyquist should be highly contrasting with that at negative Nyquist. Therefore, the colors for negative and positive values need to have distinctively different properties like hue while maintaining CVD compatibility.

4. Creating perceptually uniform CVD friendly colormaps with Python

With the above criteria in mind, multiple colormaps for moments such as Ze and velocity were created for users with CVD using Python tools such as colorspacious and viscm (Smith et al. 2018). Colorspacious and viscm were used to visualize current colormaps as well as newly developed CVD colormaps in a CVD lens. The Python ARM Radar Toolkit (Py-ART) was utilized for reading the different datasets utilized in this work, as well as visualizing the radar data on a map (Helmus and Collis 2016). A mesoscale convective system (MCS; Jensen 2015), a pyrocumulonimbus storm (LaRoche and Lang 2017), and a winter storm (Feldman 2023) were used for testing newly developed colormaps for radar imagery. These comparisons were then provided to individuals in the community with CVD for input and feedback.

The first radar moment provided is Ze and the primary CVD colormap of focus will be the Chase spectral colormap. The Chase spectral colormap is a combination of the Python package Matplotlib spectral and magma colormaps (Hunter 2007), with values adjusted to achieve perceptual uniformity and order. A supplemental Jupyter notebook (Kluyver et al. 2016) is also available to show how the Chase spectral colormap was created. The new Chase spectral radar Ze colormap distinguishes light rain, heavy rain, and hail cores in a way that is interpretable by users with CVD (Fig. 2). The NWS Ze colormap is difficult for those with CVD to determine the difference between higher Ze convection areas (red) and areas of lighter rainfall (green), which is not the case for the Chase spectral colormap. We are also aware that different weather events might appear differently due to the colormap's constraints and care should be taken when setting the color scale minimum and maximum, especially with Ze. Due to this, testing was also done on a pyrocumulonimbus storm (Fig. 3) as well as a

winter storm (Fig. 4) to observe if the colormap still accomplishes the criteria previously set for these particular weather events. In both figures, it is apparent that the Chase spectral colormap is still able to highlight scientifically interesting data.

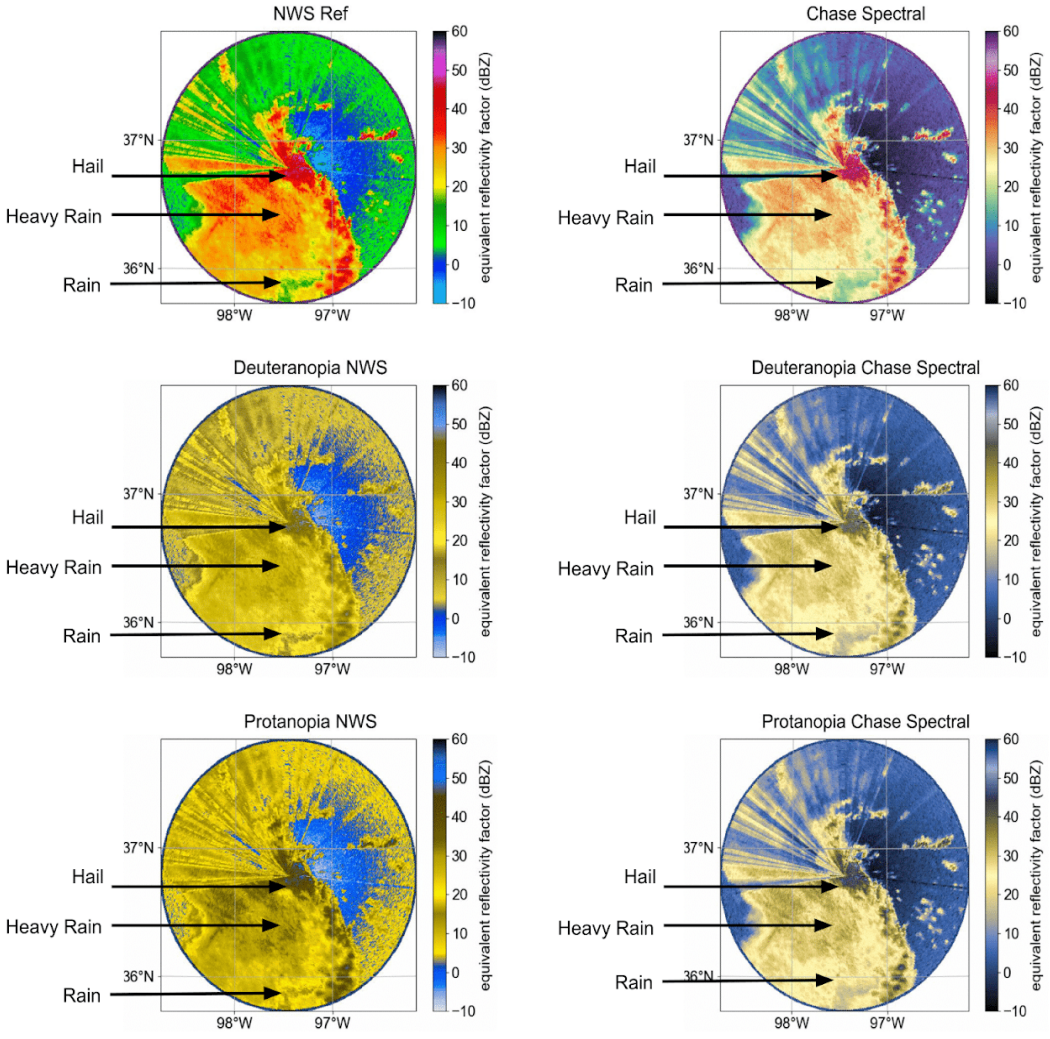

Fig. 2. Radar Plan Position Indicator (PPI) plots created by Py-ART and colorspacious showing the National Weather Service Ze colormap compared to the new Chase Spectral colormap through different CVD lenses for a convective system in Oklahoma observed by the ARM C-Band radar during the Midlatitude Continental Convective Clouds Experiment M3CE (Bharadwaj et al. 2023; Jensen et al. 2015).

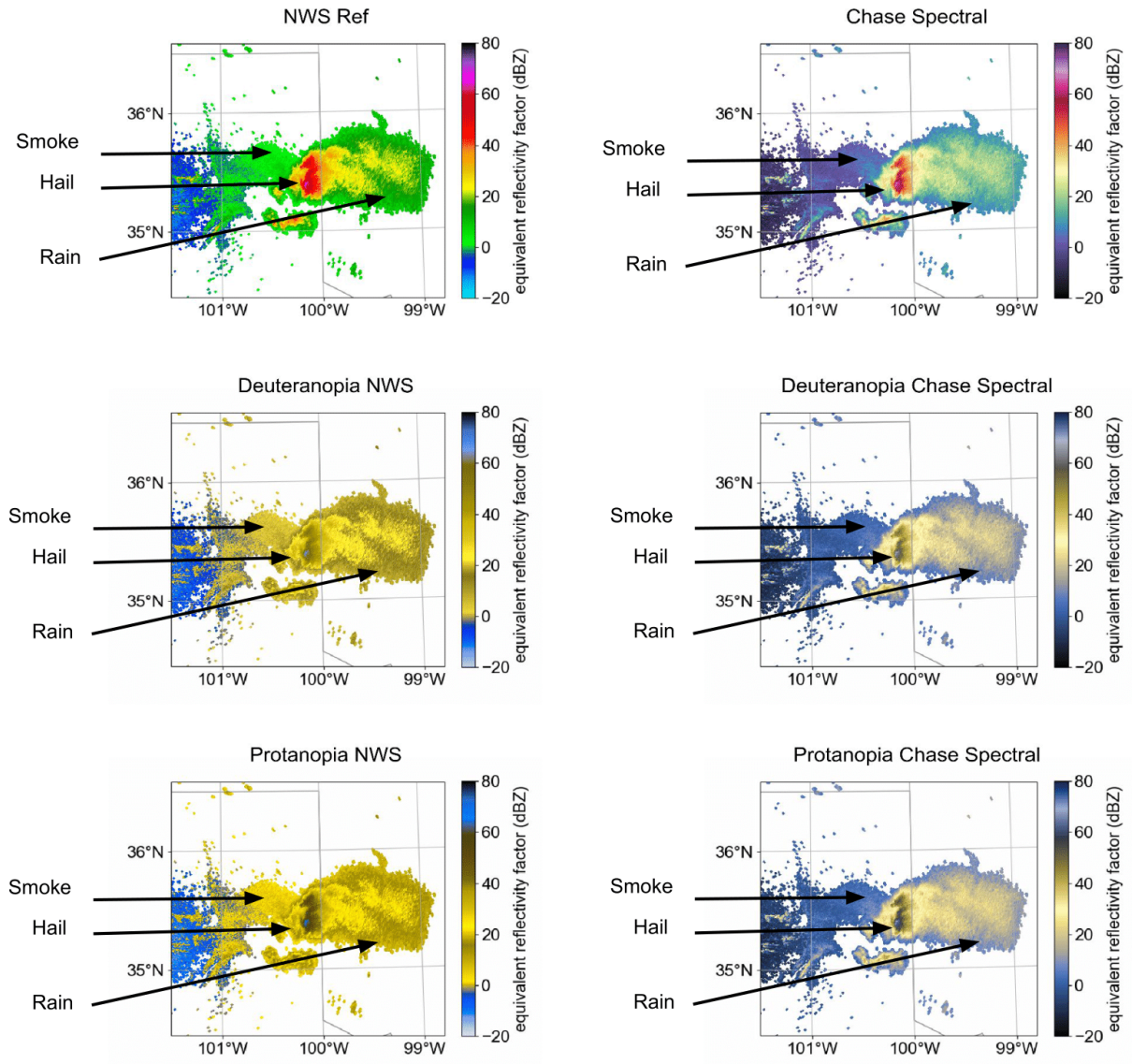

Fig. 3. Radar Plan Position Indicator (PPI) plots created by Py-ART showing the National Weather Service Ze colormap compared to the new Chase spectral colormap through different CVD lenses for a pyrocumulonimbus storm seen on a NEXRAD radar in Amarillo, Texas (NWS 2011).

These CVD colormaps are an original product of the focus group of radar researchers with CVD (including two of the authors). These individuals agreed that these colormaps are more interpretable than the default colormaps currently utilized in the community. Members of the focus group were able to distinguish between transitions of each of the colors and subsequently any changes in pattern in the examples provided. Additional CVD colormaps

for Ze and other radar variables can be seen in supplement Fig. S2.

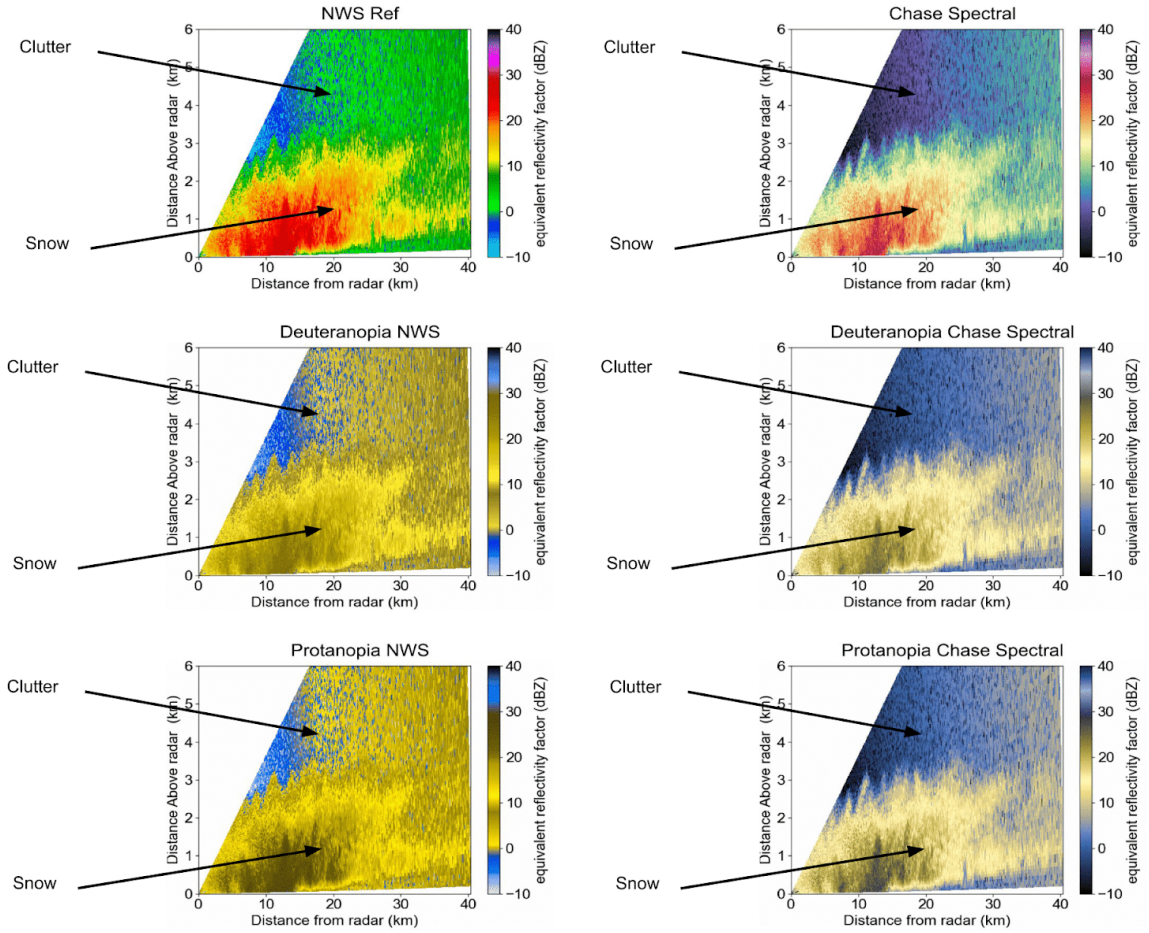

Fig. 4. Radar Range Height Indicator (RHI) plots created by Py-ART showing the National Weather Service Ze colormap compared to the new Chase spectral colormap through different CVD lenses for a winter storm in Crested Butte, Colorado observed by ARM's X-band radar (Chandrasekar 2023; Feldman et al. 2023).

Next, cmocean's balance, a CVD-friendly colormap, was tested for radar Doppler velocity. The cmocean balance colormap already exists in the oceanography community (Thyng et al. 2016); however, its applicability to weather radar has potential. Similar to Ze, the cmocean balance colormap was tested on the MCS (Jensen 2015) as seen in Fig. 5 (the same Ze example used in Fig. 2): which shows again, the difference in the NWS velocity colormap compared to the cmocean balance colormap through CVD lenses. There is a noticeable difference between the two colormaps. The NWS colormap is difficult for a user with CVD to differentiate between inbound and outbound scatterers and does not show regions of aliasing. The cmocean balance colormap shows clear definitions of aliasing as well

as the difference in scatterers.

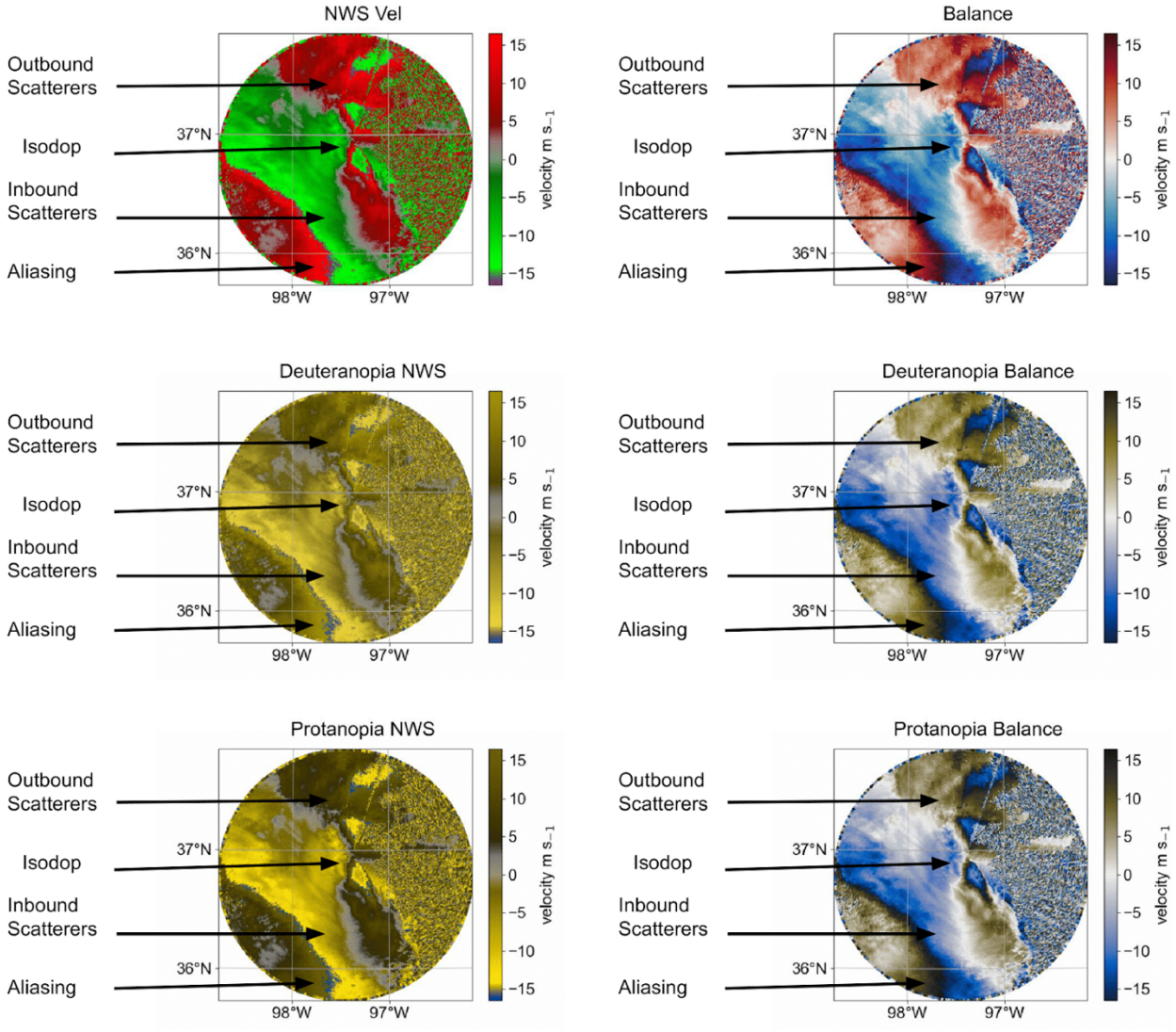

Fig. 5. Radar Plan Position Indicator (PPI) plots created by Py-ART and colorspacious showing the National Weather Service velocity colormap compared to the cmocean balance colormap (Thyng et al. 2016) through different CVD lenses for a convective system in Oklahoma observed by the ARM C-Band radar during the Midlatitude Continental Convective Clouds Experiment MC3E (Bharadwaj et al. 2023; Jensen et al. 2015).

With regards to dual polarization moments, Michelson et al. (2020) experimented with Crameri's colormaps directly and in modified form to display radar Ze, radial wind, and some polarization data. Fig. 6 illustrates how this was achieved based on a case of widespread rain combined with a large bird migration that took place in the spring of 2019, seen with the Canadian weather radar at Radisson, Saskatchewan. The fine structures and relative differences in Ze and radial wind velocity data are revealed using the sequential and perceptually uniform Hawaii (Fig. 6a) and diverging gradients of the Vik (Fig. 6c) colormaps,

respectively. Co-polar correlation coefficient (ρHV) is visualized using the plasmidis colormap (Fig. 6b), where the warmer hues are compressed and the cooler hues extended, as this radar variable's meteorologically relevant content is represented at the higher (warmer) end. In their study, Michelson et al. (2020) applied Crameri's multisequential Oleron colormap directly to represent differential reflectivity (ZDR). However, when combining ρHV and ZDR to produce depolarization ratio, a modified Oleron colormap was found suitable (CM_depol, Fig. 6d) to discriminate between meteorological (extended blue tones) and non-meteorological echoes (compressed Earth tones). We also examined the NWS correlation coefficient (pHV) colormap through a CVD lens for the MCS (Jensen 2015) in supplement Fig. S7. The NWS pHV colormap still performs well, even for those with CVD, because it does not spend much dynamic range in green colors, which avoids red/green contrast lost to CVD users. Plasmidis is an attempt to improve on the NWS pHV colormap, but the NWS pHV colormap currently, is one of the better options as it still maintains a form of CVD friendliness.

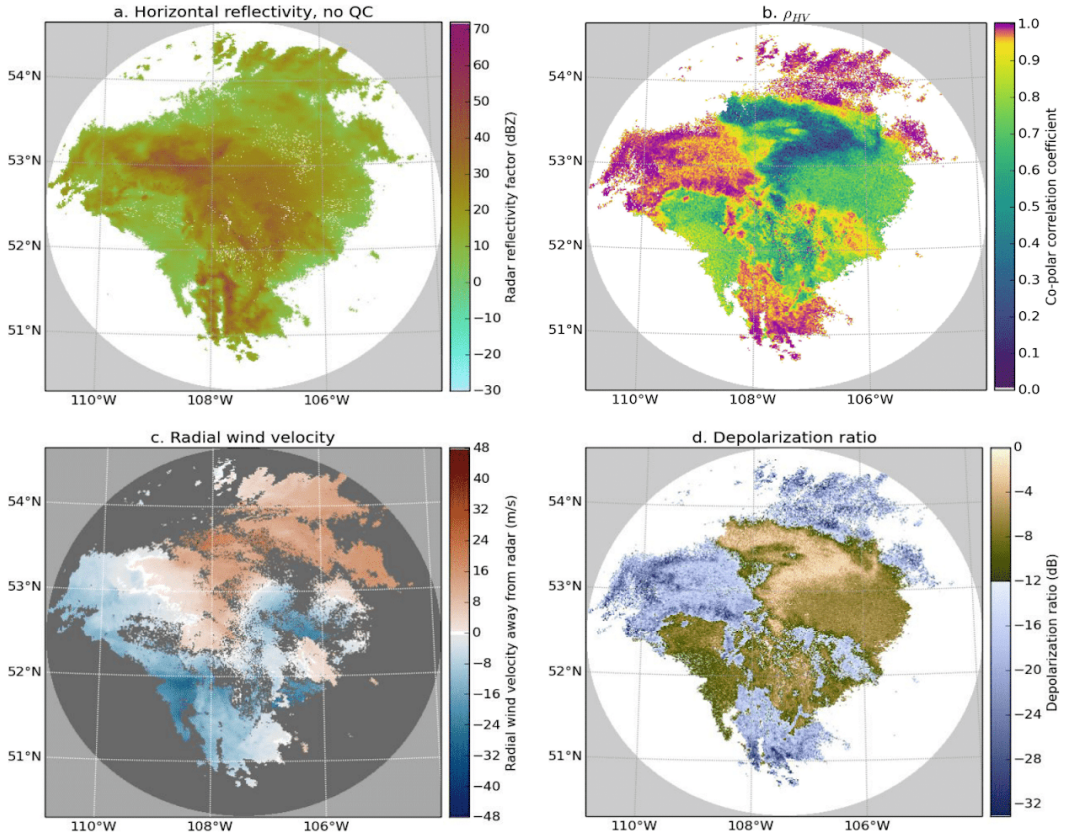

Fig. 6. Case of widespread rain combined with a large bird migration that took place on May 15, 2019, at 09:00 UTC, seen with the Canadian weather radar at Radisson, Saskatchewan (Michelson et al., 2020). Crameri's and new colormaps have been used "as is" and in modified form: a. Hawaii, b. Plasmidis, c.

Vik, and d. CM_depol. The application of these colormaps includes white and grey for representing areas outside radar coverage and radiated areas that produced no echoes.

4. Summary and lessons learned

It has been demonstrated that there can be colormaps that meet criteria such as the ability to highlight rain, frozen precipitation, non-meteorological targets, velocity-based items, be perceptually uniform, and accessible for those with CVD. This was possible by working with those in the CVD community as well as utilizing Python tools such as colorspacious and viscm (Smith et al. 2018). These CVD-friendly colormaps are now available in a GitHub repository at https://github.com/openradar/cmweather that is used by a variety of open-source radar software packages found in the open radar community (Heistermann 2015). For Ze moments, the Chase spectral colormap is excellent at showing detail in differing returns and is our recommended colormap for accessibility, however colormaps can be adjusted if a radar operator or user needs a specific criteria but the colormap should still maintain some form of perceptual uniformity. In Fig. S2, Fig. S3 and Fig. S4 (see supplement) we also highlight two improved colormaps for Ze: Homeyer rainbow and Lang rainbow. The Homeyer rainbow is also an excellent colormap that is similar to the Chase spectral colormap. The Lang Rainbow colormap is also an improvement compared to the NWS colormap on the higher end of dBZ for CVD individuals; however, it does not resolve as well the lower end of the spectrum.

For velocity, there were two visual targets: highlighting the zero isodop and ensuring a good perceptual contrast across the Nyquist interval. The NWS velocity colormap is inferior in both perceptual uniformity and in its projection into CVD spaces. The cmocean balance colormap is near perfect in perceptual uniformity and projects well into deuteranopia and protanopia space and is our recommended colormap for radial velocity. Supplemental materials Fig. S5 and Fig. S6 are also available for the blue orange red colormap (BuOrR14) and blue to red (bwr) colormaps, which shows that the BuOrR14 colormap performs well at conveying the range and structure of the radial velocity field and has good contrast to viewers without CVD, but is very poor in perceptual uniformity and has poor definition of the zero isodop. The bwr colormap is better in perceptual uniformity but is poor at highlighting the Nyquist jump.

While the NWS pHV, CM_depol, plasmidis and some of Crameri's colormaps can work for dual-polarization radar moments, future efforts should examine different CVD-

friendly colormaps in more detail for these variables. For example, it would be ideal to have a colormap to highlight regions around zero ZDR for calibration reasons. In addition, we are continuing to work with the radar community and those with CVD to improve on these colormaps while still highlighting scientifically interesting data (Crameri et al. 2020; Stauffer et al. 2015). We believe that testing these colormaps on cloud radars or adjusting them to have the ability to highlight drizzle and cloud drops (shallow cumulus and marine stratocumulus) is needed. We understand that the threshold for non-convection and convection may differ between studies, events, and meteorological regimes, so the colormaps will need flexibility or different forms to meet these different criteria.

The intent of these colormaps is for the radar community to have access to colormaps that can be used to communicate their data accurately while being inclusive to the CVD community. These colormaps are available online in a variety of packages found in the open radar community. The Homeyer rainbow colormap also has been implemented in the weather radar application RadarScope.

Acknowledgments.

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Data Availability Statement.

Data used for testing these colormaps are provided by the ARM User Facility data discovery for the convective and winter systems (Bharadwaj et al. 2023; Feldman et al. 2023). The pyrocumulonimbus data can be found on the Amazon web service NEXRAD data network (NOAA 1991). Code used to produce these figures will be hosted at the repository on GitHub: https://github.com/EVS-ATMOS/CVD-colormaps/tree/main. Supplemental materials for other CVD colormaps in use are also available upon request, as well as figures showing other popular non-CVD friendly colormaps through CVD lenses.

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