SOMEWHERE OVER THE RAINBOW

How to Make Effective Use of Colors in Meteorological Visualizations

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This paper offers a perception-based color space alternative to the well-known red–green–blue (RGB) color space and several tools to more effectively convey graphical information to viewers.

One of the many challenges associated with atmospheric sciences is the analysis and utilization of large, usually very complex datasets. One way to gather the information and to better understand it is to visualize it graphically. Visualizations may be as simple as one-dimensional plots (e.g., time series plots) or as complex as multidimensional charts (e.g., from numerical weather prediction model output). As a scientist, an important part of daily work is to create plots and graphs that visualize results and outcomes earned through weeks and possibly months of work. The key feature of visualization is helping the reader to capture the information as simply and quickly as possible. This reader can be a colleague, a customer, or even you.

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The term "visualization" encompasses many aspects. Much work has been carried out during the last century to investigate the human perception and the influence of different aspects on how to best convey information. Initially, fundamental research was done in physics, biology, and medicine (see Miles 1943; Stevens 1966; Carswell and Wickens 1990), but with the advent of the computer industry this focus expanded into how to deal with the new technological achievements in different disciplines, including three-dimensional (3D) graphics, interactive visualization, and animation (Smith 1978; Ware 1988; BAMS 1993; Rogowitz and Treinish 1996; Light and Bartlein 2004; Hagh-Shenas et al. 2007). Today, the ubiquitous availability of computers and software enables everyone to create graphics for all different devices. We will focus on only one aspect: how to make effective use of color for visualization. Therefore, we are using relatively "simple" spatial plots to illustrate the guidelines and typical user tasks in atmospheric science.

Color is a good instrument to improve graphics, but carelessly applied color schemes can result in figures that are less effective than grayscale ones (Light and Bartlein 2004). For large parts of our vision, hue is irrelevant in comparison to shading. Color does not help us measure distances, discern shapes, detect motion, or identify small objects over long distances. Hue is useful for labeling and categorization but less effective for representing (fine) spatial data or shape. However, if used effectively, colors are a powerful tool to improve (highly) complex visualizations. Therefore, it is important to know how color perception works and how we can make use of it to improve visualization (Ware 2004). Most common software packages supply methods to create different types of plots with different color maps (or color palettes). Nevertheless, because most plotting functions are rather generic it is impossible for the software developers to provide adequate color schemes for all applications.

The default color map is often a red–green–blue (RGB) rainbow palette. This is probably the most known color map and consequently many people use it uncritically as the default for their visualization, even though it has been shown to be difficult or even harmful (Brewer 1997; Borland and Taylor 2007). In addition to the rainbow scheme, other color maps defined in the RGB color space also exhibit similar problems and have to be handled with care, because the RGB color space has some critical disadvantages (Rogowitz and Treinish 1998; Light and Bartlein 2004). Vivid colors along the spectrum of the RGB color space strongly differ in their luminance, which can lead to artificial dark or bright bands that can obscure the information shown. Furthermore, the RGB color space is not a uniform color space, meaning that color pairs with the same distance within the color space do not show the same perceptual difference. Other prevalent color spaces, such as hue–saturation value (HSV) and hue–saturation–luminance (HSL), suffer from the same problems as the RGB color space (Smith 1978).

To avoid these disadvantages several transformations of the RGB color space have been developed. These transformations are approximations of the human color perception system, in that they, for example, allow for the fact that we have a logarithmic perception of luminance (Stevens 1966). The most profound work has been done by the Comission Internationale de l'Éclairage (CIE) in creating color spaces like the CIELUV or CIELAB color space, based on a standard observer (Ware 2004). Keep in mind that there is not "one omnipotent best" color model or color scheme. Depending on the user task or the medium, the most effective color models and palettes can differ. Even with extensive user testing there is always a number of different effective color maps for a given purpose. The work of Mahy et al. (1994) contains a good experiment-based comparison of many of the available color spaces. In this paper, we will focus on a perception-based color concept called hue–chroma–luminance (HCL), which is the CIELUV gamut in polar coordinates. Thus, the HCL color space is based on how humans perceive color, in contrast to the RGB color space, which is based on technical demands of TV and computer screens.

In this article, we will demonstrate the benefits of the HCL alternative, which is already becoming better known and more frequently used in other

HUMAN COLOR PERCEPTION

To choose the "best" (or at least a good) color scheme, one has to understand the characteristics of the receiver and processor. The human eye contains two classes of cells that are responsible for our visual perception: rod and cone cells. Rod cells serve vision at low luminance levels while cone cells are wavelength-sensitive. Three subclasses of cone cells are responsible for long, medium, and short wavelengths, respectively. Although most properly referred to as L, M, and S cones, respectively, the names R, G, and B cells are also frequently used, albeit somewhat misleadingly. The RGB annotation suggests that the cells refer to red, green, and blue, which is not the case. In fact, the LMS cones have broadly overlapping scopes. This design strongly differs from the "color separation" often built into physical imaging systems (Fairchild 2013b).

Under low luminance conditions, our visual system is limited to gather our surroundings by capturing differences in luminance using the rod cells only (monochromatic; scoptic view). Under moderate to high luminance conditions, the rod cells are fully saturated and our visual systems switch from a rod to a cone view (trichromat; photopic view). The spectral sensitivity also changes between these two views. Rod cells are more sensitive to shorter wavelengths. The appearance of two objects—say red and blue—changes under different luminance conditions. While they have the same lightness under high luminance conditions, the red one seems to look nearly black under low luminance conditions while the blue still looks quite light. This is caused by a lack of sensitivity to longer wavelengths (red) in the scoptic view. As one can see, the human perception is a complex system with different behaviors. All of these factors make it difficult, if not impossible, to represent colors that can be accurately perceived by humans in all settings/contexts.

Current theories describe that at least three dimensions are necessary to code a specific color. Typically, color models with three dimensions are employed (Knoblauch 2002), while one can argue that more dimensions would be required. For example, Fairchild (2013a) describes that five perceptual dimensions are necessary for a complete specification (brightness, lightness, colorfulness, saturation, and hue). However, typically only the relative appearance of the colors is of interest and not all five dimensions have to be known. Hence, the three perceptual dimensions—hue, chroma, and luminance—are typically sufficient for most purposes.

COLOR MAP DEFINITION

Most people are familiar with the coordinates of the RGB color space. Each of the three dimensions (red, green, and blue) can vary within the range from 0 up to 255. Table SB1 shows the coordinates for the HCL color maps used in this article. Choosing colors in the HCL space is similar to the RGB space, only the dimensions are different. The hue dimension (dominant wavelength) is circular starting with red (0), over green (120), to blue (240), and back to red (360 ≡ 0). The second dimension defines the chroma (colorfulness) and goes from 0 to 100. A chroma of 0 reduces the resulting color to a pure gray. The last dimension is luminance (brightness), which is also definable between 0 (black) and 100 (white). The transition between two values in each dimension should be monotonic but does not have to be linear (depends on the user task). For example, the luminance decrease in Figs. 4c,e follows a power function that allows us to highlight the areas with higher precipitation amounts (original value spacing in Fig. 4 is not linear either).

Table SB1. The coordinates for the HCL color maps used to create Figs. 1, 4, 5, and 6. The second column indicates the color followed by the coordinates for hue, chroma, and luminance. The first color indicates either the most left color (for horizontal color bars) or the bottom color (for vertical color bars). For the diverging scheme (Fig. 6b), the hue of the center value does not matter. It is exactly at the border for the two opposite hues, but its chroma is zero (gray).

Figure	Color	H	C	L
Fig. 1: Hue	1st	**0**	55	75
		*	*	*
	Last	**260**	55	75
Fig. 1: Chroma	1st	265	**0**	50
		*	*	*
	Last	265	**100**	50
Fig. 1: Luminance	1st	265	50	**15**
		*	*	*
	Last	265	50	**80**
Fig. 4c**	1st	80	20	92
		*	*	*
	Last	230	65	37
Fig. 4e**				92
	1st–4th	80	20	*
	5th–7th	130	35	*
	8th–10th	180	50	*
	11th–last	230	65	*
				37
Fig. 5d	1st (green)	150	76	98
	2nd (yellow)	92	82	81
	3rd (orange)	34	88	64
	4th (red)	–24	94	47
	5th (magenta)	–82	100	30
Fig. 6b**	1st (blue)	253	100	55
	Center (neutral)	—	0	95
	Last (red)	0	100	55

* Monotonically change along the dimension.

** Monotonic changes are nonlinear.

scientific fields (Zeileis et al. 2009; Silva et al. 2011). We argue that the use of misleading and distorting RGB color maps is not necessary, as alternative models are available and that changing to a perception-based color model can strongly improve the visual reception on graphical information with very little additional effort.

RGB VERSUS HCL COLOR SPACE. *HCL model.* The HCL color space is the polar transformation of the uniform CIELUV color space and forms a distorted double cone where each of the three dimensions directly controls one of the three major perceptual dimensions directly (additional information in the sidebars). The first one is hue, the dominant wavelength (defining the color); the second dimension is chroma, capturing colorfulness (color intensity compared to gray); and the third is luminance, pertaining to brightness ("amount" of gray). Figure 1 shows the three perceptual HCL dimensions. In each of the panels, one dimension changes linearly across the corresponding axis while the others are held constant. Hue changes the color while fixing the lightness and chroma level across colors. Increasing the chroma dimension increases the colorfulness compared to gray and the luminance dimension changes the colors from dark to light. Based on this concept, one can quickly define perception-based color maps for all kinds of tasks. Figure 2 shows a sample for HCL-based color maps. The qualitative schemes in Fig. 2a are constant in chroma and luminance (passing from H_1CL to H_2CL), leading to isoluminant color schemes. Figure 2b shows sequential schemes with constant hue but increasing luminance and chroma (passing from HC_1L_1 to HC_2L_2), leading to a color map with a perceptual linear change. If hue is not constant along the color map, we will get multihue sequential schemes (Fig. 2b). The multihue color maps are similar to the single-hue sequences but here all three dimensions are changing from left to right (starting at $H_1C_1L_1$ and ending at $H_2C_2L_2$). The last examples (Fig. 1d) are of diverging schemes. Such color maps work well for data with two extremes around a neutral center value. Diverging color maps combine qualitative schemes (each side has a specific hue) with single-hue sequential schemes. The center value has high luminance and low chroma (leading to gray/white) followed by a symmetric and monotone increase in luminance and chroma. Because the different color spaces are connected by some coordinate transformation functions, each color can be expressed in coordinates of any other color space. This allows us to pick colors in the HCL space and convert them into the RGB color space, with which all software packages can deal.

RGB model. Historically, the RGB model is based on how screens work. Cathode ray tube (CRT), light-emitting diode (LED), and plasma screens attached to TVs, computer monitors, and projectors all use the same technique: Images are created by additive color mixing. Each image consists of hundreds to thousands of pixels where each pixel emits a mixture of red, green, and blue light. Each single RGB color is defined by a triplet of intensities for those three primary colors. Appropriate mixing produces a wide range of colors. Three zero intensities result in black, while maximum intensities for all three primary colors yield white and, in between, all other colors can be defined. Two widespread simple transformations of the RGB color space are the HSV (hexcone model) and the HSL (triangle model). Although they have a slightly better behavior, the basic problems of the RGB color space cannot be solved.

Desaturation. To focus on the luminance dimension of a color palette, it can be desaturated, for example, by transforming to HCL space, removing all chroma (so that hue does not matter), and transforming back to the original color space. This just removes hue/chroma information but keeps luminance fixed. In HCL dimensions, changes in hue or chroma do not influence the underlying luminance information.

Comparison of HCL and RGB. Figure 3 shows a juxtaposition of the (in)famous RGB rainbow color map and an alternative HCL rainbow. Both rainbows go from red over green and blue back to red. Below the color wheel, the same color maps are shown as colorized and desaturated color bars, respectively. As shown in the desaturated version of the RGB rainbow, even the three primary colors, red, green, and blue, vary enormously in luminance: red has a luminance value of about 50, green is about 86, and blue is about 30 (100 would be white). This creates unwanted gradients throughout the whole RGB rainbow map. Furthermore, the RGB color map shows several artificial narrow bands most easily seen around yellow/cyan/magenta. What makes the RGB color spaces even worse is that the different colors of the spectrum are not uniformly distributed (the green sector looks wider than the red one), which creates an additional distortion. In contrast, the HCL version shows an isoluminant gray in the desaturated version. This is no surprise, because one of the three dimensions of the HCL color space directly controls the luminance. Nevertheless, many common software packages provide the RGB rainbow scheme as default. As Borland and Taylor (2007, 14) wrote, "the rainbow color map is prevalent in the visualization community" even if "the rainbow color map [is often] a poor choice." Because of its

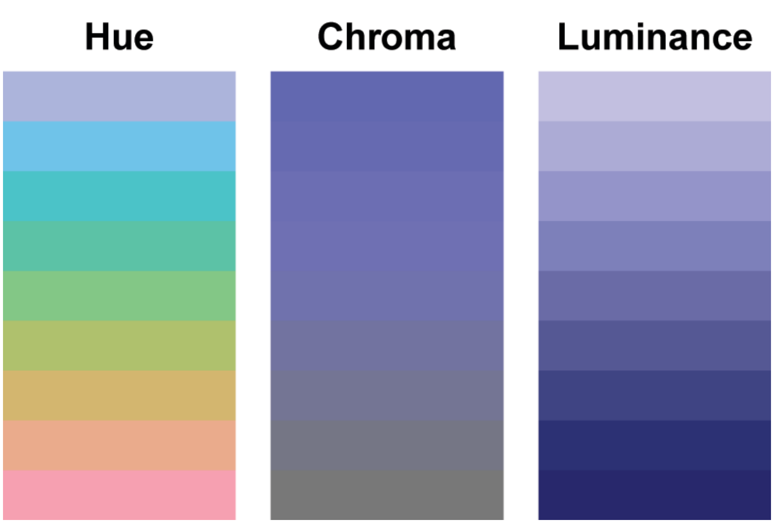

Fig. 1. The three dimensions of the HCL color model: hue, chroma, and luminance. In each panel, one dimension (see heading) changes linearly across the corresponding axis while the others are held constant.

lack of perceptual ordering, it not only confuses the reader but also obscures data through its inability to present small details and might even actively mislead the reader. As an exception from the rule Ware (1988, 49) suggested, "If you wish to read metric quantities using a color key, then a sequence that does not vary monotonically with the color opponent channels should be used. A good example is a spectrum approximation." However, considering the guidelines in the next section and the examples shown in this paper, one can see that for a wide range of purposes a spectral (rainbow) scheme is not the best choice.

GUIDELINES FOR EFFECTIVE COLOR MAPS. In recent years, several publications created guidelines for how to use colors effectively. Although those guidelines differ slightly, there are some cornerstones on how to create effective visualization. Before showing some real-world examples, it is worth introducing these rules (see Ware 2004; Rogowitz and Treinish 1996; Brewer 1997; Rogowitz and Treinish 1998; Treinish 1998; Light and Bartlein 2004; Hagh-Shenas et al. 2007):

Spatial frequency: High-frequency (detailed) data are best represented by monochromatic color maps that only differ in luminance (Mullen 1985).

Form: The human brain is extremely efficient in gathering the shape of an object. This information mainly comes from differences in luminance; therefore, form (e.g., terrain information) will be most effectively coded in the luminance dimension.

Number of colors: For classification tasks (search and distinguishing), only a small number of different hues can be processed with a low error rate. Healey (1996) showed only five to seven different hues can be found accurately and rapidly on a map. Furthermore, MacEachren (1995) wrote that, if the task is to precisely identify a certain color in a plot, the detection rate can plummet when the number of colors increases (detection rate for 10 colors: 98%; for 17 colors: 72%).

Data: Color should be seen more as an attribute of an object than as its primary feature. The human brain is more effective in capturing shape, form, position, lengths, or orientation than in gathering different colors. Therefore, plain plot types should be used if possible (e.g., line, bar, or box plots; see Carswell and Wickens 1990). Additional color can support the reader/analyst if the color matches the data. For continuous variables (e.g., temperature, total number of people in a region), sequential schemes are very effective (Figs. 2b,c). Isoluminant

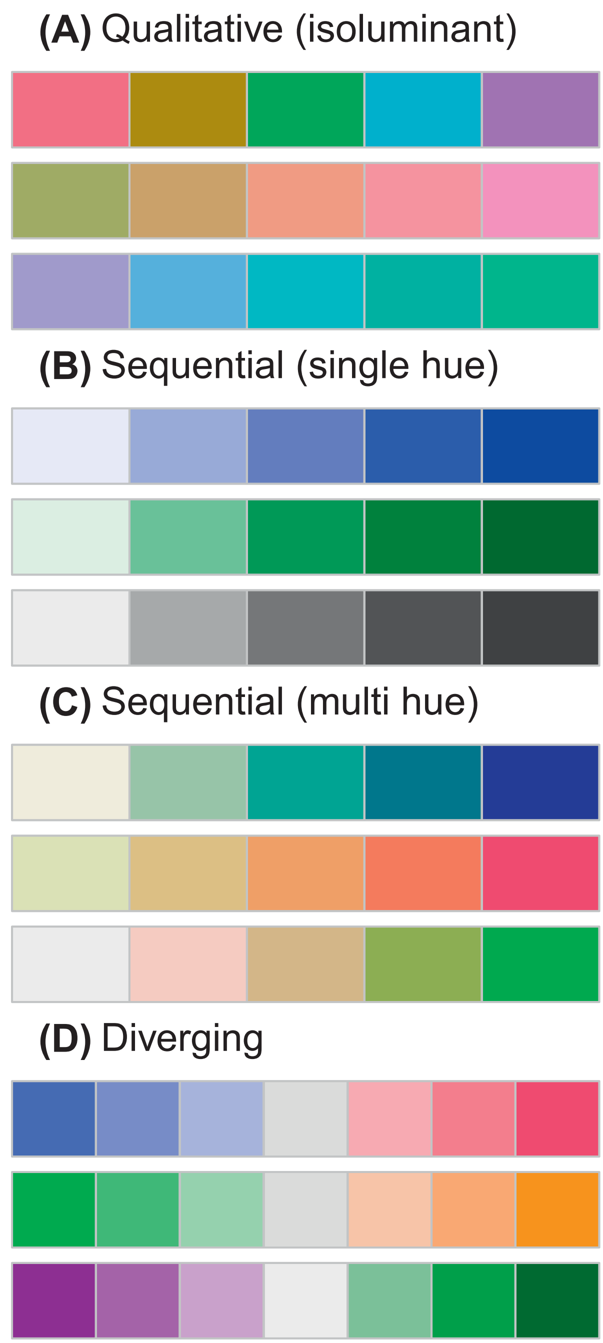

Fig. 2. Examples of different HCL color maps: (a) isoluminant qualitative schemes (e.g., for classification); (b),(c) sequential color maps (e.g., for continuous data: for either increasing or decreasing data with only one extreme); and (d) diverging schemes (e.g., for data with two extremes centered around a neutral value). Sequential schemes can contain one single hue or by passing from one to another trough the HCL color space along the hue dimension. The single-hue sequential color maps shown in (b) are all based on the identical luminance function. Even if they do have different/no hue, the grayscale representations of those three examples are exactly equal. Beside those main types, mixed/hybrid color maps are also possible.

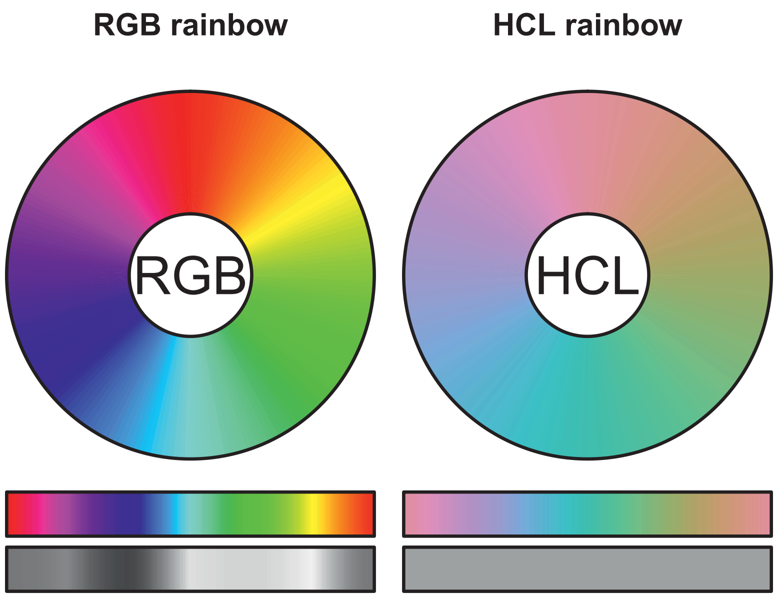

Fig. 3. Juxtaposition of the RGB rainbow color map and an HCL-based rainbow. Below the color wheel, the same palette is shown as a color bar in the colorized version and the corresponding desaturated version, respectively. The RGB rainbow creates unwanted variations in luminance, while the HCL rainbow is fully isoluminant.

qualitative schemes (Fig. 2a) work best for classification because they do not add perceptional distortion to the data. For data with a well-defined neutral value (e.g., precipitation anomalies, balance data), a diverging color scheme with a neutral color around this center point works well (Fig. 2d).

Unique hues: The opponent color theory describes six colors where two colors build an opponent pair at a time. Those pairs are black–white, green–red, and blue–yellow. Our visual system is very efficient at separating opponent colors. If only two different colors are necessary, a pair of opponent colors might be a good choice. For figures that are just containing symbols or markers and just a small set of colors, the six colors of the opponent color theory might work well. However, note that for people with a color deficiency this task can get impossible (cf. "Meteorological examples: Dealing with visual constraints" section).

Contrast: Objects and distinct shapes are easier to identify if there is a clear boundary between them and the surroundings. If necessary, this can be achieved by adding additional contours with a high contrast to the colors of the pattern at the boundary.

Background: The objects (the information) and the background should clearly differ in luminance. Furthermore, the background color should be neutral (white, light gray, or black) not to skew the colors.

Heterogeneity: An object will stand out as a distinct figure if there is a difference in the background.

Conventions: If there are conventions, they should be taken into account (e.g., hot = red, cold = blue, high alert level = red, etc.). However, such conventions are not available for all different purposes and they can strongly differ between cultures.

User task: One of the most important issues is to be aware of the purpose of the user of the visualization: who the end users are (e.g., professional scientists, residents of a country, or decision makers like a civil protection service), what prior knowledge they possess, and what their requirements are. The second driving factor is the type of information that should be transmitted. The most effective color palettes can differ completely—whether we have to communicate thresholds, continuous data, or an abstract or detailed representation of the environment. Some examples are discussed later in the article.

To summarize. As the guidelines show, effective colors have to fulfill a variety of requirements. Although those requirements are rather guidelines than rigorous rules, breaking them can rapidly diminish the effectiveness of the corresponding display. The content of most visualizations is complex enough. Colors should not amplify that. Sometimes it can be a benefit that highly saturated vivid colors shine out; on the other hand, they can produce a lot of "colorjunk" (Tufte 1990). A figure with countless colors and needless luminance gradients makes it harder to gather the important information. The major task of color mapping is to guide the reader and to capture her/his interest. Not losing the reader with unappealing colors is an advantage and should be one of the aims. Furthermore, the task of the user strongly affects the choice of colors, and it is self-evident that figures for a scientific article and a popular product for an Internet platform can have different demands. A final important controlling feature is the medium on which the visualization will be transported (color representation and resolution). In an ideal case, the colors should work everywhere including screens, data projectors, and printers (grayscale and colorized).

METEOROLOGICAL EXAMPLES. With the conceptual understanding of how the HCL color model works and the guidelines shown above we can now discuss some common meteorological products and plot types to demonstrate the benefits of a more perceptional color concept. The first one is about increasing continuous data: forecasted precipitation amounts. The second example deals with categorical data: a severe weather advisory. The third has multiple contents and is a map used for air mass and frontal analysis.

What can go wrong with inefficient color maps? Let us start with Fig. 4, showing a 5-day accumulated precipitation forecast over the East Coast of the United States during the landfall of Hurricane Sandy in 2012. Figure 4a shows the original figure as provided by the National Oceanic and Atmospheric Administration (NOAA) on its public website.

If one is already familiar with this special type of product, one can quickly identify regions with low precipitation amounts (vivid green colors) and those with high amounts of precipitation (reddish colors), but it is hard to grasp the message of the whole figure at once. For all those not familiar with the colors, it is even harder. One has to scan the entire image and compare the map with the color bar to get an idea of the information shown. The reason, therefore, is the vigorous varying underlying luminance and the high number of different mostly fully saturated colors and very strong color gradients (see box/marker a). Both features actively mislead the reader and make it difficult to capture the entire information. Figure 4b shows the desaturated representation of the original figure. The way luminance changes does not support the visual construction of the data as a form or virtual surface. Furthermore, one can see that the color

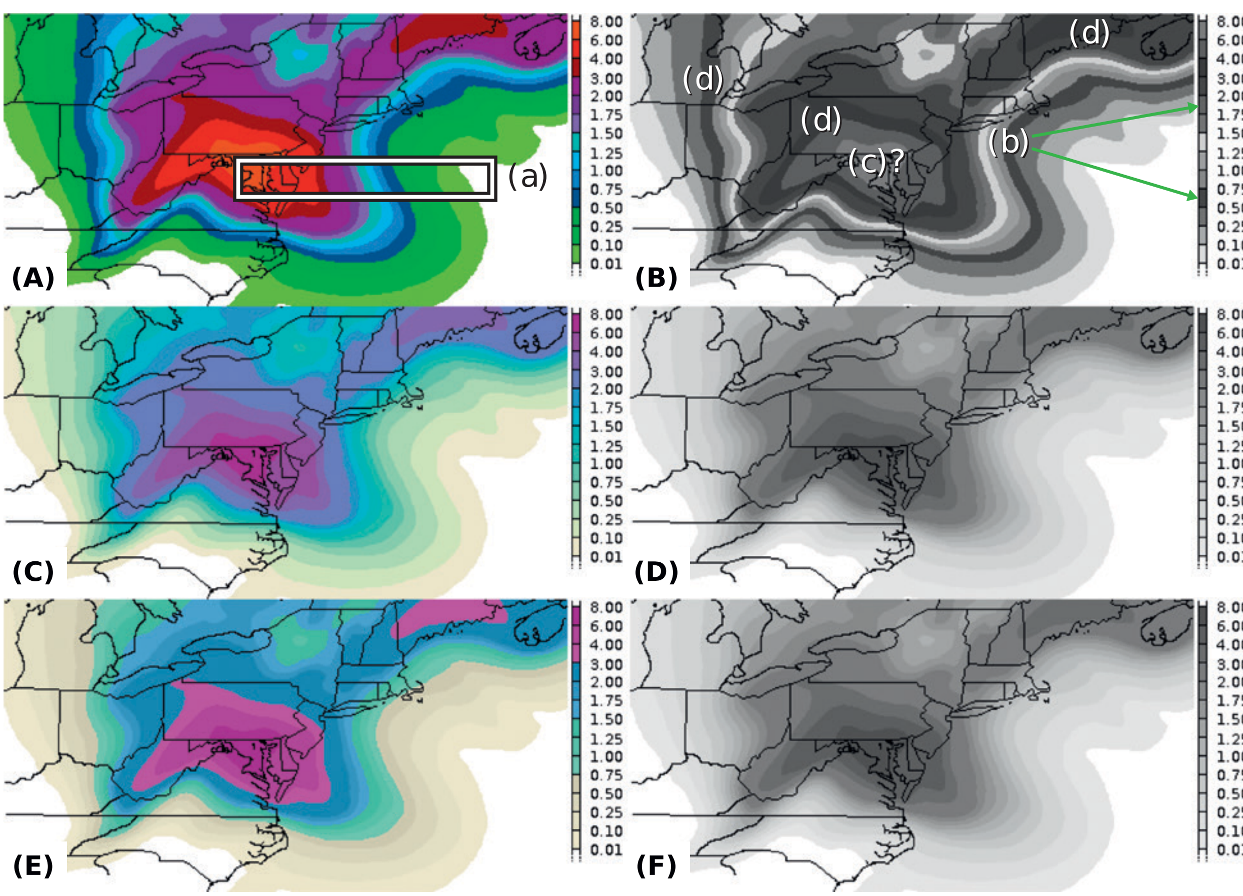

Fig. 4. A rainfall amount forecast during the landfall of Hurricane Sandy on 29 Oct 2012, over the U.S. East Coast. The data are shown in inches accumulated over 120 h: (left) the colorized version and (right) its grayscale representation. (a) The original version as provided by NOAA (www.noaa.gov/). (c),(e) Alternative color maps based on the HCL color concept. The reason for this color choice, the assumed user task, and markers a–d shown are discussed in the paper.

concept completely breaks down when displayed on a monochromatic medium (e.g., grayscale print). The allocation between gray tones and values is no longer unique (marker b in Fig. 4b), the maximum value is no more obvious (marker c), and the overall information gets strongly distorted. Readers are automatically focusing on the distinct dark bands (marker d).

But how can this be improved? Let us have a look at Fig. 4d. This is the desaturated version of an alternative HCL-based color scheme where the values are directly coded in the luminance dimension. Low values have a high luminance (toward white) while luminance monotonically decreases with increasing amounts of precipitation. In contrast to the version above, the human visual system can rapidly recognize the overall shape of the data. Furthermore, the most important parts of the map stand out. This helps the reader/analyst to identify the most important parts as quickly as possible, even without checking the color bar at the outset. The guidance is additionally supported by changing chroma and hue in Fig. 4c. Areas with low values—in this case the less important regions—fade out toward the white background while the regions of interest stand out in luminance, chroma, and hue (dark, colorful, and reddish). As the original figure, the new color map contains 13 different colors but now with a smooth transition from one side to another without creating unwanted distortions. The monotone transition in all three dimensions of the HCL color space creates the impression of a smooth and continuous form or surface. If you compare Figs. 4c and 4e, you can see that we modified how hue and chroma changes over the full palette. The reason is that we redefined the main user task in Fig. 4e. Local communities or civil defense organizations may be interested in some critical thresholds. The guidelines suggest that we can rapidly distinguish small numbers of different hues. Therefore, we combined two color map concepts. While the absolute values are still coded in the luminance dimension (to obtain the shape of the data), hue and chroma are now based on four different categories (gray/green/blue/reddish; stepwise increasing chroma and hue). The result is a hybrid color map as shown in Fig. 4e, a mixture between a qualitative and a sequential scheme. Our visual system can rapidly distinguish the areas indicated by the different hues and chromas, but we are still able to capture the overall shape or form of the data shown or to translate a specific color into its value if necessary. Because we have not changed the way how the luminance changes from low to high values the grayscale representation of both Figs. 4e and 4f is exactly the same. The example shows that the choice of the color map is strongly connected to the user task. However, taking care of some basic guidelines can help to improve the way the information is transported.

Dealing with visual constraints. Color blindness, or color vision deficiency, is another important aspect when choosing effective colors (Brettel et al. 1997; Harrower and Brewer 2003; Light and Bartlein 2004). In Europe, about 8% of the male population has visual constraints (slightly less in the United States; see Miles 1943; Wong 2011; Fairchild 2013b). Far more men than women are affected. Besides the relatively rare monochromacy (light/dark contrasts only), two main types of dichromacy or constrained trichomacy are observed among the male population: Either one of the cone cell subclasses is lacking entirely (about 2%) or it is anomalous (about 6%). The most frequent of these is the deuteranomaly, also known as red–green blindness caused by a cell anomaly. People with this type of anomaly are poor at discriminating small changes in hues in the red–yellow–green spectrum.

Again, we would like to show you a real-world example to illustrate what can happen if visual constraints of the end user are not considered. Figure 5 shows a warning map for Austria in 2013 for severe precipitation amounts. The left column shows the original image while the right column shows an alternative HCL-based color palette, both traversing from green via yellow, orange, and red to purple. The top row shows the colorized version followed by a desaturated version thereof and emulated deuteranope vision (red–green blindness) in the bottom row.

Let us start with the colorized version in Fig. 5a: Like in the example before, all colors are on maximum saturation to attract the attention of the reader. Warning maps, or warning products in general, are often colored similarly to replicate the colors of a traffic light (to regard conventions). The disadvantage of the chosen colors in Fig. 5a: it is hard to capture the most important areas. The vivid colors all over the color map coerce us to scan the whole image. As an alternative, we show an HCL-based color map. The data shown here are a mixture of qualitative data (classification) and continuous data with one extreme (highest alert level). Because only five different colors are necessary a multihue sequential scheme seems to be convenient with a decreasing luminance toward a one-sided extreme at higher alert levels. To take care of the traffic light concept we kept the hues going from green to magenta. To get an effective color map with a steady color change all colors have to lie on a path between the two anchor points within the HCL color space (light green on one side and dark magenta on the other). Because of the shape of the HCL color space, it is possible that the path lies beyond the boundaries of the HCL gamut. If this happens it is necessary to adjust the dimensions. In our case, luminance and chroma have to be tuned until all colors are well defined in HCL dimensions. Therefore, it is necessary to pick more "pastel" colors, which leads to the color map shown in Fig. 5d. In return, we can strongly improve the reader support and guidance of the product.

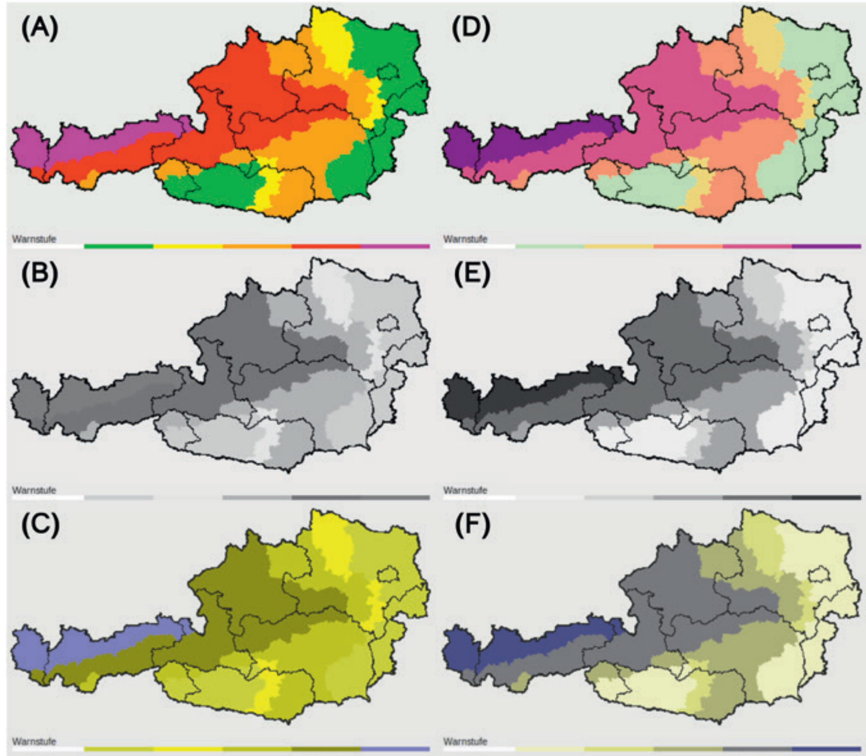

Fig. 5. A severe weather advisory for Austria published on 31 May 2013. (a) The original image as published by UBIMET GmbH (2013), slightly modified because of further postprocessing steps. (d) A modified version with HCL-based colors. (b),(e) As in (a),(d), but desaturated version. (c),(f) Simulation of the appearance for people with deuteranomaly (red–green weakness). Because of the lack of perceptual representation of the RGB color space, different distortions can be found in (a)–(c).

In the desaturated versions in Figs. 5b,e, while the HCL version still conveys the essential information, the desaturated RGB version shows something different. Yellow colors are rather light, which results in a higher luminance than the surrounding orange and green (which are barely distinguishable). An inappropriate representation of the warning levels is the result. Similarly with emulated deuteranope vision (Figs. 5c,f), while the interpretation of the original RGB version gets difficult or impossible, the HCL version preserves full readability. This aspect is very important for some fields of application. The example shown here warns the inhabitants of Austria of severe weather situations. Imagine that for 4 out of 100 people it can be very difficult to gather the information just because of inefficient colors. Using more appropriate color palettes can make it much easier for them to interpret the plots and to gain the important information. Clearly, it is important to think about for whom the product should be accessible and to tailor visualizations for the needs of end users.

Supporting and guiding the specialized user. To give a broader idea of how to make use of the HCL, we consider a somewhat more complex example where the user task is to identify fronts. Figure 6 shows an equivalent potential temperature analysis on 700 hPa from the European Centre for Medium-Range Weather Forecasts (ECMWF) as employed in the internal weather platform at the Institute of Meteorology and Geophysics in Innsbruck. Equivalent potential temperature is a conserved variable and widely used to identify different air masses and fronts. Fronts are found at regions of large gradients of equivalent potential temperature. Additionally, geopotential height is shown to appraise the movement of the air to identify the front types (Steinacker 1992).

Figure 6a shows the product as it was provided over the last decade using a rainbow-type color map as found in many other meteorological websites and products. Because of the strong color gradients, especially between red and green (opponent colors), a large proportion of our less experienced students was misled and placed the fronts at color boundaries instead of at the strongest equivalent potential temperature gradients. Mostly, fronts were allocated to the areas where red and green encounter

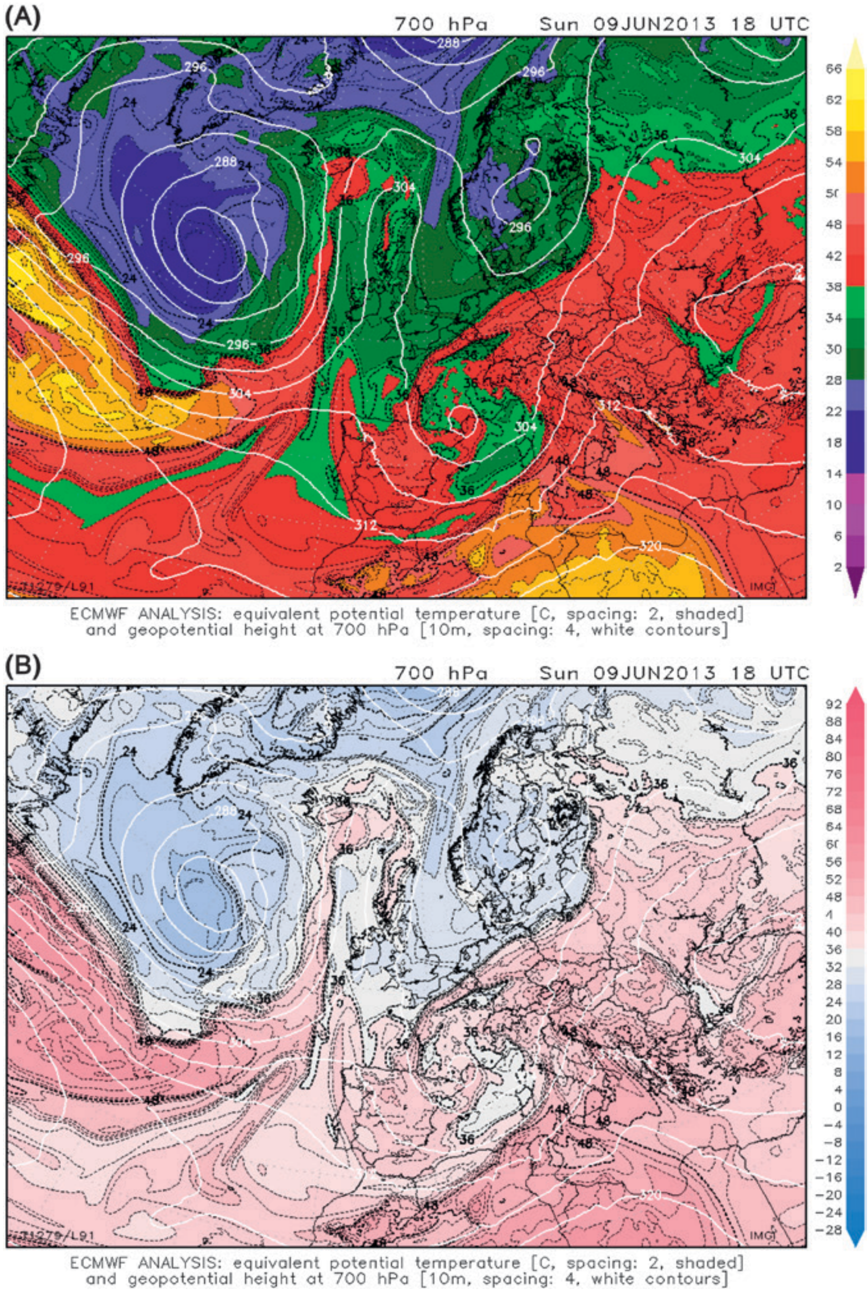

Fig. 6. ECMWF analysis of the equivalent potential temperature (°C) at 700 hPa over the Atlantic/Europe. (a) The old product based on highly saturated RGB rainbow colors. (b) The revamped product including an HCL-based color map.

each other because the color gradients obscured the physical gradients. The striking quantity of misinterpretations was the main motivation to redesign our products.

Figure 6b shows the new appearance of the same analysis field. Please remember that the main user task is to identify frontal zones. The exact absolute (metric) values of the equivalent potential temperature are not of interest. To get an overall idea of the air masses (cold/warm), we added a diverging color scheme using the conventional colors (red/blue) centered around the empirical model climate mean for the displayed area. The hue in Fig. 6b has to be seen as an additional attribute supporting the reader to capture the overall distribution of air masses and to identify the two extremes as quickly as possible. Additionally, three types of contour lines are shown. A high contrast (black) was used to code the important information: borders for the geographical orientation and the isentropes for the frontal analysis. As secondary information, geopotential height is shown in white contours. Because this information is less important on the first look, it is forced into the background.

The original RGB-based product is a good example how colors can actively mislead the reader. Since we removed this shortcoming, the number of misinterpretations decreased by roughly 50% (empirical value from the daily weather-briefing lecture at the Institute of Meteorology and Geophysics, University of Innsbruck; G. J. Mayr 2013, personal communication).

TOOLS AND FURTHER READING. We have selected three cases from among hundreds of meteorological products to demonstrate how to apply coloring guidelines and how to make use of color palettes derived from the HCL color space. Because a good concept is worth little without ease of use, we now make some suggestions of how to integrate the HCL color concept into your daily workflow. Even if visualization software does not provide the HCL scheme, it should be emphasized that each HCL color can be converted to the corresponding RGB coordinates with the corresponding hexadecimal representation. The authors use the colorspace package (Ihaka et al. 2013) written in R, but there are packages and sources for other established coding languages as well.

Online tool. We set up an online interface to create customized palettes. The tool "online HCL creator" is available online (www.hclwizard.org/). The interface offers some typical examples of statistical maps/graphics and some specifically meteorological chart types. You can easily modify the color palettes and tune them for your personal needs. Furthermore, the tool gives you the ability to emulate the appearance of the chosen colors under different visual constraints (e.g., for deuteranope viewers) or in a desaturated representation (e.g., on a grayscale printer). The interactive examples give a first impression of what the resulting color maps look like. Moreover, we developed some export functions for common software languages so that the HCL palettes can be comfortably applied to your own data in a familiar software environment.

Advanced users. One of the most powerful tools to create HCL palettes for all possible uses is the package colorspace (Ihaka et al. 2013), which provides various types of color space manipulations/transformations plus an intuitive graphical user interface (GUI) to pick color maps. The colorspace package is written in R (R Core Team 2013), an open-source programming language that has also been receiving increasing attention within our community. Our online interface mentioned above is based on this colorspace package, mimicking its choose_palette() graphical user interface. There are also modules for other languages such as Python (see colormath module; Taylor 2014) or MATLAB (see image processing toolbox or the colorspace transformation module; Getreuer 2011) that allow you to choose and transform color sequences in different color spaces.

Other tools. Harrower and Brewer (2003, 2011) developed the online tool ColorBrewer.org that provides predefined color palettes for various purposes with focus on map makers. While their palettes are not directly based on the HCL model, the guidelines used in their creation are very similar resulting in often similar sets of colors. Easy-to-use sets of colors are available in different coding languages (e.g., colorbrewer in Python, RColorBrewer in R, cbrewer in MATLAB). However, the disadvantage of ColorBrewer.org is that you can only pick from preset color schemes.

CONCLUSIONS. Visualizations are used regularly to communicate methods, data, and findings. The ubiquitous availability of computers and software enables everyone to create all possible types of visualizations and animations, yet creating effective plots and maps is not a trivial task. When colors are used, they are mostly derived from the famous red–green–blue (RGB) color space because most software offers easy access to RGB-based palettes and RGB-based color map designers. Consequently, a large proportion of the science community uses RGB-based color palettes uncritically (Borland and Taylor 2007; Light and Bartlein 2004; Rogowitz and Treinish 1998).

In this article, we offer basic guidelines on how to use color more effectively in visualizations. Therefore, we introduce the less well known hue–chroma–luminance (HCL) color concept as a toolbox to achieve this goal. In contrast to the technical RGB color model, the HCL color concept is based on how human color vision works (Zeileis et al. 2009; Silva et al. 2011). The HCL color model captures the three main perceptional dimensions—hue (dominant wavelength: defining the color), chroma (colorfulness: compared to gray), and luminance (brightness: amount of gray). With these three dimensions, a broad range of colors can be defined (Knoblauch 2002; Fairchild 2013a), facilitating specification of effective colors for various purposes.

To demonstrate the advantages of the HCL over the RGB color space we discussed three common visualization types from the meteorological field and demonstrated that the HCL color model can help to define effective color maps for all kinds of visualizations. The benefits are as follows: better readability; full functionality in grayscale/luminance; enhanced end user support; more effective conveyance of complex concepts; and enhanced accessibility for people with visual constraints. But any color model fails when the user task is not considered. It is probably the most crucial factor dictating how to choose the most effective colors for a given product. If the user task is unknown or not well defined, the effectiveness of a figure can get lost completely.

Additionally, the presented tools should help to easily adapt the proposed concepts for your own work. In particular, we provide a web interface to the R package colorspace where everyone can create personal HCL color maps and export them in different formats for several common software languages.

We have often experienced skepticism about changing familiar color maps when introducing potential users to the HCL colors. However, much more often than not, this skepticism turned into enthusiasm after a few days of using HCL-based products, especially with the availability of tools to ease implementation into one's own workflow.

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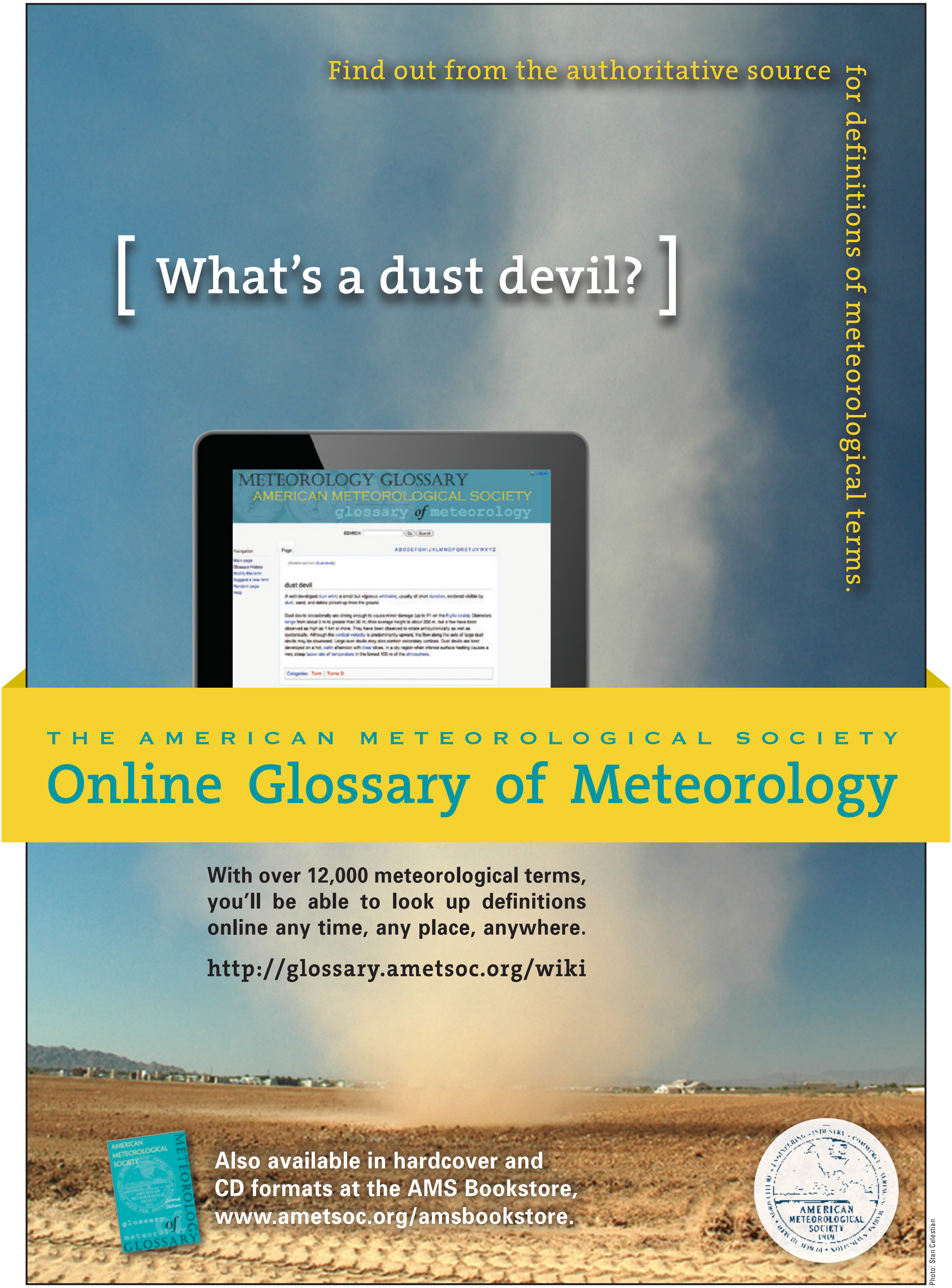

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