Colormaps that Improve Perception of High-Resolution Ocean Data

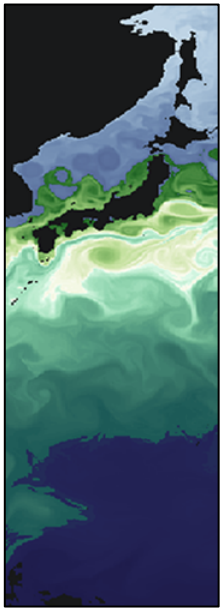

Figure 1. The Kuroshio Current and jet, highlighted by a nested colormap.
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Abstract
Scientists from the Climate, Ocean and Sea Ice Modeling Team (COSIM) at the Los Alamos National Laboratory (LANL) are interested in gaining a deeper understanding of three primary ocean currents: the Gulf Stream, the Kuroshio Current, and the Agulhas Current & Retroflection. To address these needs, visual artist Francesca Samsel teamed up with experts from the areas of computer science, climate science, statistics, and perceptual science. By engaging an artist specializing in color, we created colormaps that provide the ability to see greater detail in these high-resolution datasets. The new colormaps applied to the POP dataset enabled scientists to see areas of interest unclear using standard colormaps. Improvements in the perceptual range of color allowed scientists to highlight structures within specific ocean currents. Work with the COSIM team members drove development of *nested colormaps* which provide further detail to the scientists.

Author Keywords
Colormaps; color theory; color perception; climate science; scientific visualization; high-resolution datasets

ACM Classification Keywords
H.1.2 [User/Machine Systems]: Human Information Processing; H.5.2 [User Interfaces]: User Centered Design; I.3.m [Computer Graphics]: Misc -- Color

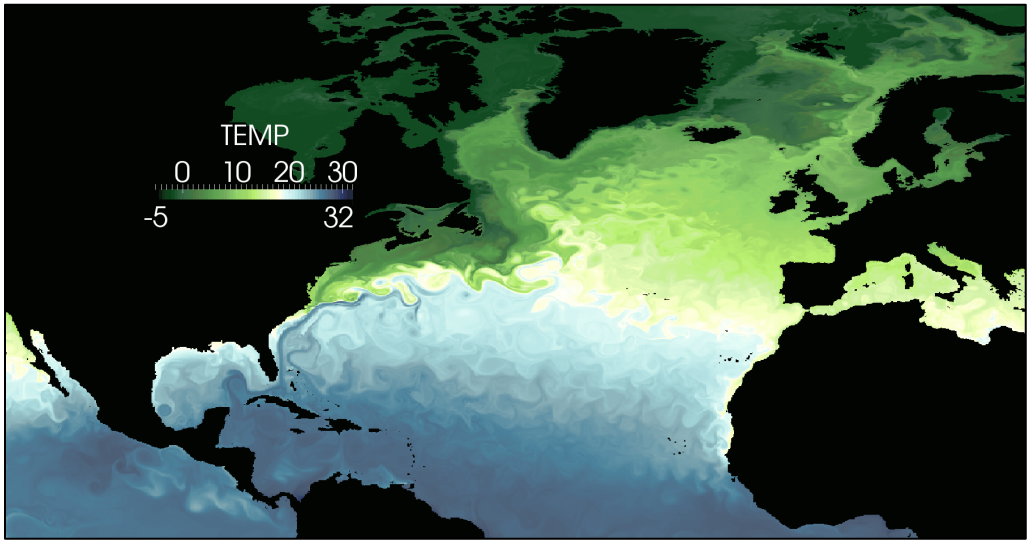

Figure 2. Mark Petersen describes the benefits of the newly developed colormaps as follows. "Within this colormap you can see detail of the structures over a wide range of temperatures to a greater degree than previously available. The ability to see this level of detail in the eddies and currents is essential to develop an intuition of the ocean dynamics. This intuition leads us to choose further analysis, which may then lead to quantifiable conclusions." ©Francesca Samsel 2014

Background

Climate change modeling scientists from COSIM, Climate, Ocean and Sea-Ice Model, at LANL, Los Alamos National Lab, are interested in the ability to understand the characteristics of three important ocean currents: the Gulf Stream, the Kuroshio current, and the Agulhas current retroflection.

These currents, or ocean jets, are part of the global thermohaline circulation, a large conveyor belt that transports heat, salt, and nutrients from equatorial waters towards the poles. Jets are fast and narrow (100km). With the newly developed colormaps, the currents are now easily visible as bands of warm water that penetrate into much colder water as they move poleward. The jets meander from north to south, pinching off eddies on either side, which move away from the jet but keep the same temperature. Oceanographers visualize surface temperature from models and satellite observations to gain intuition on the jet's behavior, and as a first step towards quantifying their transport characteristics.

It has been well established that, despite its ubiquitous use, the rainbow colormap is misleading and obscures detail [1,2,6,9]. The cool/warm divergent colormap, developed by Ken Moreland at Sandia National Lab, is a perceptual and cognitive improvement [5], but still does not provide the definition and color range scientists desired. We teamed up to investigate methods of creating colormaps able to reveal the detail within the high-resolution data contained in POP, Parallel Ocean Program. POP is an ocean model used to investigate the impacts of climate change. High-resolution simulations cover the globe with 0.1 degree horizontal grids (nominally 8 km) and 40 vertical levels, resulting in over 345 million data points per variable at an instant in time [10,11]. Simulations are very computing intensive: they run on thousands of processors, and proceed at 5 to 10 simulated years per day.

Development of Data-Driven Colormaps

Artists have been studying the properties of contrast for centuries. Understanding, controlling and allocating color contrasts enables painters to create complex, layered images with depth, perspective and harmony. Painters, having worked with color and color perception over

Hue, Saturation & Value

Hue is the actual "color", ranging from 0 to 360 degrees around the color wheel. Saturation refers to the purity of the color. Full saturation is the color at its most vibrant. As S levels lower, the color moves towards white. Value (luminance) describes the scale light to dark. HSV is the color space in which the human brain naturally resides. [2]

Divergent Colormaps

A divergent colormap is a colormap in which white is placed at a point of interest in the data and two color spectrums diverge from that center point as shown in Fig 2.

hundreds of years, have codified a set of principles that are now part of formal artistic training [7,8]. In order to address the scientist's needs, Samsel, a visual artist specializing in color, began developing colormaps based on these long-established principles of color contrast.

In order to manipulate color in alignment with color theory principles while equalizing for perception, a new tool was developed. This enabled the color control points to be specified in HSV (Hue, Saturation and Value) space with the fidelity required by the artist. However, the colormaps themselves are interpolations of the artist's HSV color control points using the CIELAB space to linearize the mapping in perception between control points. The authors have implemented a colormap editor, which produces colormaps for standard visualization tools.

Using this method, we created a set of colormaps that were presented to Mark Petersen, a research scientist in the COSIM team at LANL. His preference was a newly created blue/green asymmetrically-distributed divergent colormap, Figure 5. His selection is a variation on the widely used Moreland cool/warm shown in Fig. 3.

Figure 3. The cool/warm divergent colormap developed by Ken Moreland at Sandia National Lab.

Moreland's colormap uses a range of blues and reds. Given that green has the largest perceptual range of any color and red the smallest [2], we replaced the reds with greens. We also expanded the hue and saturation range of the blues. By varying two components of color, we create more readily identifiable contrast [2]. See Fig. 4.

To further expand the perceptual range, we increased the greens so that they span two-thirds of the colormap and the reduced the blues to one-third, Figure 5. This roughly equals the relationship between the range of perceivable color with greens and blues. While this method discards the useful property of placing the two color ranges away from a particular point of interest, it maximizes the number of perceivable levels across the entire data range.

Figure 4. A blue/green divergent colormap designed to increase the perceptual range.

Figure 5. An asymmetrical divergent colormap designed to maximize the range of perceivable data.

It is worth noting that while colormaps are usually built in CIELAB space [3,4] because it is the most perceptually uniform color space [2], it does not provide the ability to independently adjust the H, S, and V to the degree desired. Manipulating the HSV values by single degrees and percentages enables the creation of the artist constructed colormaps. Cognitive scientist, Colin Ware, acknowledges that, "Although they (CIELAB and other uniform color spaces) are useful, uniform color spaces provide, at best, only a rough first approximation of how color differences will be perceived." [2]

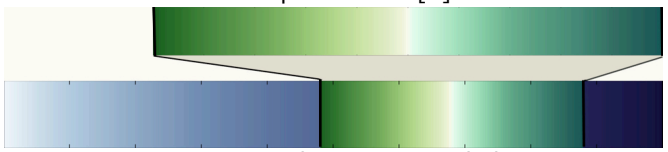

Figure 6. Nested colormap showing expanded inset range.

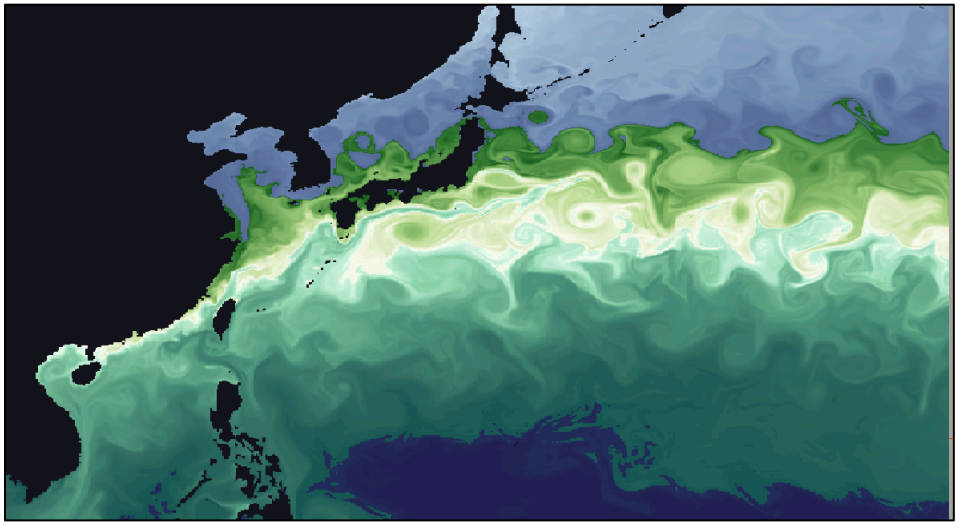

Figure 7. In the western Pacific, the Kuroshio Current is a narrow stream of warm water that sheds eddies as it departs eastward from Japan. The nested colormap was chosen to use light yellow at 22C at the center of the jet, highlighting cooler eddies to the north in green and warmer eddies to the south in teal. ©F. Samsel 2014

The color control points were specified in HSV space to align with the principles of color theory. The colormaps themselves are created from interpolations of the artist's HSV color control points using the CIELAB space to linearize the mapping in perception between control points.

This approach took advantage of a larger section of the color spectrum. One reason why this asymmetric colormap was selected by the domain scientist because of how it highlighted the Gulf Stream.

Specifically, it was useful to have the core of the Gulf Stream, Figure 2, stand out so that the eye easily follows its path across the Atlantic, from a narrow jet just off the U.S. to a wide current that extends north of the U.K. and Norway.

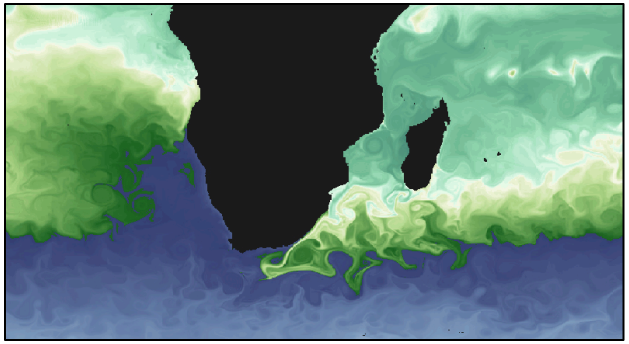

Figure 8. The Agulhas Current and Retroflection where warm waters move southward along the east coast of Africa, but then turn eastward at the southern tip of Africa. This retroflection is visible in the dark green of the nested colormap. ©F. Samsel 2014

In addition to being selected by the COSIM team, the effectiveness of the blue/green colormap was also tested and confirmed by a user study (see below). Asymmetric colormaps have a drawback. Typically, white is located at zero or at the mid-point of the data range. In an asymmetrical colormap the color is split based on the perceptual range of each color. However, it does have the advantage of exposing greater detail within the data and focusing attention on areas of interest.

Nested Colormaps

To maintain the detailed colormap but avoid the drawbacks of asymmetric maps, we developed a method for nesting colormaps. A second complete colormap was inset within the data range of interest, as shown in Figure 6. This led to the development of *nested colormaps*. Note that the inset, nested map, contains a full colorscale across a narrow range of data values of interest. This nested colormap, as shown in Figure 6, is set against neutral background colors for data values not in the range of interest. These maps can highlight specific features, provide significantly greater detail within areas of interest,

and enable scientists to easily explore all areas of the data with a microscopic-like focus.

Two types of nested colormaps were developed, one in which the value scale moved from light to dark, Figure 8, the other divergent with white in the center and dark values on either end of the value scale, Figure 7 and 9a.

Figures 9a, 9b and 9c are the same dataset from the Model of Prediction Across Scales project [14], differing only in the applied colormap. Figure 9a is a nested colormap, Figure 9b, the standard cool/warm colormap and Figure 9c uses our blue/green divergent colormap.

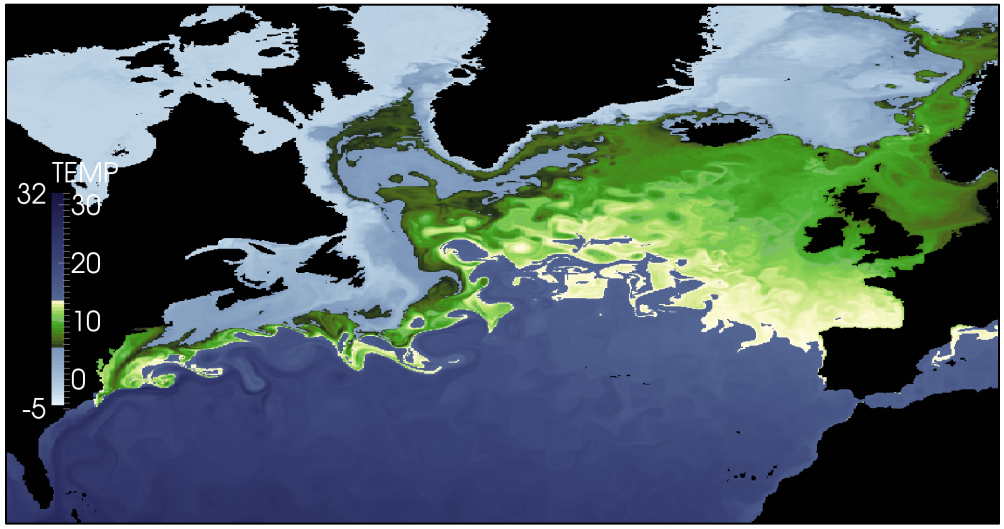

Figure 9a. Here one can clearly see the Gulf Stream as it departs the US coast at Cape Hatteras, NC, and turns left just south of Greenland, a feature known as the "Northwest Corner". The choice of nesting a large color range in a narrow window from 5-12C emphasizes the narrow width at the inception of the Gulf Stream, and the northward extent of relatively warm water along the coast of Norway. These characteristics are less obvious without nested colors (compare Fig. 9a and Fig. 9b/9c). ©F. Samsel 2014

Conclusions from the Domain Scientist

The addition of nested colormaps to highlight the range of temperatures in narrow jets allows ocean modelers to easily pick out the pathway and spatial features of these currents. At their inception, the currents have large temperature changes over short distances, which stands out with the colormaps discussed here and is an improvement over previous visualizations.

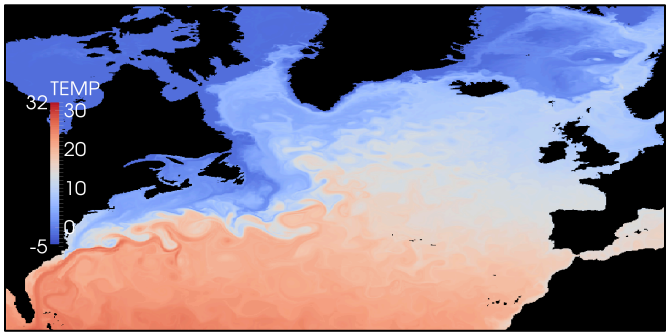

Figure 9b. Gulf Stream using standard cool/warm colormap. ©F. Samsel 2014

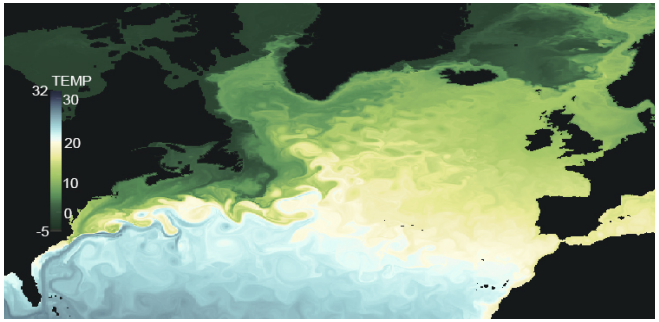

Figure 9c. Gulf Stream using blue/green colormap. ©F. Samsel 2014

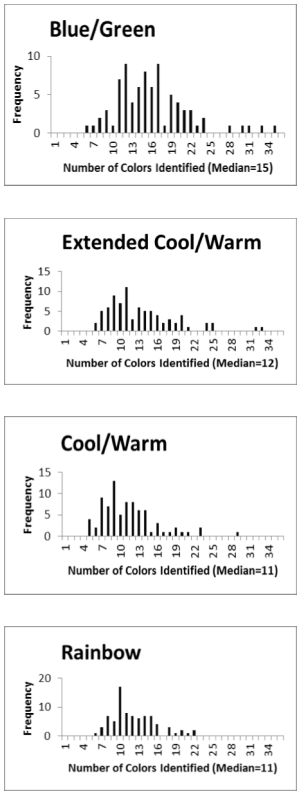

Figure 11. Histograms of the number of colors identified by participants in the Phase 2 user study.

User Study Methods and Results

While the COSIM team members found value in the newly developed colormaps, we wanted to assess whether the new colormaps provided a perceptual advantage for a more general audience. We conducted an informal survey with scientists at LANL and then a more formal user study described as Phase Two, below. Our hypothesis was that there would be a greater number of perceivable colors in our new colormaps than in the commonly used rainbow, cool/warm or heat map. More perceivable colors would translate to more perceptual steps when viewing data.

In the first casual study with LANL scientists, we tested the traditional colormaps against three of the new colormaps which included the blue/green colormap and the extended cool/warm. These colormaps were presented to scientists at LANL, all of whom are familiar with the traditional maps. Each participant was given 30 seconds to identify as many distinct colors as possible in each color panel. In this informal study, the scientists were able to identify the most colors in the extended cool/warm colormap. The blue/green was next followed by a tie between the remaining four. This first pilot study was very limited in scope and conclusions and the statistics were not sufficient to distinguish between all colormaps. However, it clearly indicated that, to a domain scientist, the extended cool/warm and the blue/green colormaps gave a more detailed view of the data.

Phase two of the user study involved an online Qualtrics study to obtain a larger range of participants from the general public. In this study, eight color panels were used: the three traditional colormaps, four of the new colormaps, the blue/green, the extended cool/warm, one using gold/grey, one using autumn colors and a "validation" panel as shown in Figure 10. The validation panel had an easily identifiable, fixed number of colors that enabled us to weed out results from participants who either did not understand the task or were not attentive. The color panels were presented in a random order to prevent a learning bias and the timing requirement used in the pilot study was removed.

Participants in this study were obtained through email solicitation and through the University of Texas Department of Psychology PSY301 Subject Pool. The data was culled to those with good validity (+-2 of the correct number of colors in the validation panel), lowering the number of subjects from 102 to 81. The standard colormaps with the highest median number of colors identified are the rainbow and the cool/warm. The highest median for our new colormaps was the blue/green. See Figure 11. Histograms of the number of colors identified in the colormaps of interest can be seen in the sidebar.

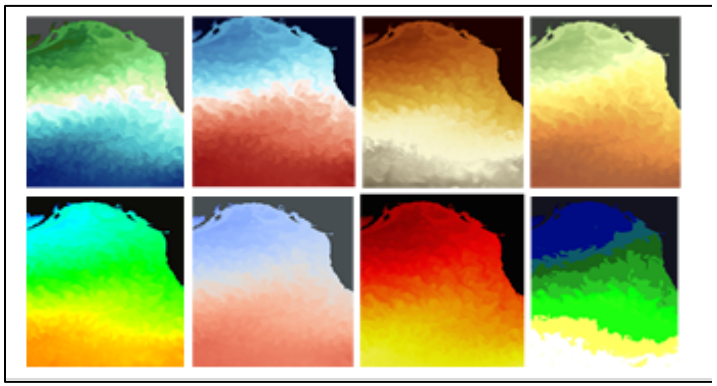

Figure 10. Above are the eight colormaps used in the Phase 2 Qualtrics study. In the top row are the blue/green divergent, the extended cool/warm, the gold/grey and the autumn (top, left to right). In the bottom row are the widely used rainbow, cool/warm, the heat map and the validation panel (bottom, left to right). The blue/green divergent was selected by the domain scientists as showing more detail and was found by the Qualtrics study to have more distinct colors identified than any of the other colormaps. ©F. Samsel 2014

Finally, we wanted to determine which of the colormaps show perceptually more colors than others. In keeping

Supporting Materials

User study details and statistical analysis as well as further examples of the colormaps and programs can be found at http://datascience.lanl.gov/ColorStudyOne

with the discrete integer nature of the data, we chose to use a nonparametric procedure called the *sign test* to assess differences between pairs of color panels. Comparing the blue/green divergent colormap to each of the other colormaps, the sign test revealed that the blue/green divergent colormap had more colors identified than any of the other colormaps ($p<0.0001$ or $p<0.00001$ in all cases) by examining the number of pairs with more colors identified by the blue/green colormap, and demonstrating that this frequency was very unlikely to have occurred simply by chance if the number of colors perceived was equal. Within the three standard colormaps, the rainbow colormap had statistically more colors identified than cool/warm ($p<0.001$) or heat map ($p<0.00001$). The extended cool/warm also outperformed the traditional cool/warm and heat map ($p<0.00001$). Since multiple tests were conducted, some care must be taken in interpreting these results, but because the p values for the statistically significant tests were extremely small, the effect of multiple comparisons is not thought to be an issue here. The z scores and p values from the (two-tailed) sign tests are summarized in Table 1.

Color1.0: Email & PSY301 Subject Pool						
BlueGreen vs:	**GoldGrey**	**Autumn**	**ExtCoolWarm**	**HeatMap**	**Rainbow**	**CoolWarm**
z-score	4.129	6.037	5.738	7.907	6.490	7.167
p-value	p<0.0001	p<0.00001	p<0.00001	p<0.00001	p<0.00001	p<0.00001
ExtCoolWarm vs:	**GoldGrey**	**Autumn**	**HeatMap**	**Rainbow**	**CoolWarm**	
z-score	1.039	0.465	5.812	0.232	4.672	
p-value	0.229	0.642	p<0.00001	0.817	p<0.00001	
GoldGrey vs:	**Autumn**	**HeatMap**	**Rainbow**	**CoolWarm**		
z-score	1.376	6.114	2.656	5.277		
p-value	0.169	p<0.00001	0.00791	p<0.00001		
Autumn vs:	**HeatMap**	**Rainbow**	**CoolWarm**			
z-score	4.359	0.232	3.022			
p-value	<0.001	0.817	p<0.00001			
Rainbow vs:	**HeatMap**	**CoolWarm**				
z-score	5.128	3.533				
p-value	p<0.00001	0.000411				

Table 1: Z scores and p values from the sign test pairwise comparison of number of distinct colors seen in the various pairs of colormaps. This was a two-tailed test with alpha=0.01 and splitting zeros between the two panels.

This study was repeated using Amazon Mechanical Turk (AMT), an online crowdsourcing site frequently used to solicit research subjects in the social and behavioral sciences [12, 13]. We obtained 100 participants via AMT which was culled to 83 after applying the validity requirement. A pairwise comparison of each pair of colormaps was again performed using the sign test. The results from analysis of the AMT data were in excellent agreement with the study above which solicited subjects through email and the psychology student pool. The blue/green divergent colormap again had more colors identified than any other colormap ($p<0.00001$ in all cases). Of the three traditional colormaps, the rainbow had statistically more colors identified than cool/warm or heat map ($p<0.0001$ in both cases).

Conclusion

Our continuous interaction between the disciplines enabled us to build colormaps of quantifiable value to the scientists. Discussions between the COSIM team members and Samsel spurred development of the nested colormaps. Specific plans are being laid to assist scientists in better understanding the currents and eddies that drive climate change. This collaboration was, in many ways, a test run. Its success has created interest from all parties to see how we can apply these new colormaps and techniques, in particular the nested colormaps, to more difficult and critical scientific issues necessary for building the next generation of climate change models.

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