Hadley Centre Technical Note 81

An assessment of mapping techniques to visualise uncertainty in climate data
(includes discussion on colour theory and consideration for colour blindness)

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Summary

Over about the last decade climate modelling has progressed from single projections to ensemble-based approaches which explore uncertainties in the model projections. This has presented major challenges for the way in which the data are visualised and communicated.

This technical note examines advantages and disadvantages of various techniques for visualising uncertainties in mapped climate data. Precipitation changes from the IPCC AR4 multi-model ensemble of climate projections are used to illustrate different techniques for visualising uncertainty - including the percentage agreement between ensemble members and the signal to noise ratio - and how these combine with information on the magnitude of climate changes to represent both climate change and uncertainty information.

A novel mapping technique is proposed that provides clear representation of both the magnitude of climate variables and degree of uncertainty represented by ensembles of climate data. This technique adjusts the hue of a small palette of colours to show the mean or median of a climate variable and the saturation of the colour to illustrate the confidence in this value. Details and practical application of this technique are provided, including guidance and scripts for reproducing this technique using ArcGIS, and these are discussed with relevance to colour theory. It is demonstrated that striking illusions can occur with perception of the apparent lightness and hue of an object and because of contextual issues, and these can have impacts on the interpretation of the mapped information.

Specific guidance is provided on the limitations and suitability of colour maps for colour blind people. Colours that look different to people with normal colour vision may appear the same to those with colour blindness. A small qualitative study is described which elicits responses from colour blind people within the Met Office on their ability to interpret the maps created using different mapping techniques. Recommendations are given to 1) avoid green-red and blue-purple in the same legend, and 2) ensure a clear colour contrast between low and high values, and a description of how to create a colour-blind friendly legend is provided.

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Introduction

Understanding and communicating uncertainties in observation and model data are major challenges in climate science. Even though climate models are continually developing in complexity and their ability to simulate climate at different temporal and spatial scales, they are imperfect representations of reality. Projections of future climate change using such models are subject to many forms of uncertainty (see Collins et al., 2006), including: i) unknown future concentrations of greenhouse gases and other anthropogenic and natural forcing agents (e.g. injections of stratospheric aerosol from explosive volcanic eruptions); ii) natural climate variability, and iii) errors in the model representation of climate system processes.

This technical note examines advantages and disadvantages of various techniques for visualising uncertainties in climate data. A novel mapping technique is proposed that provides clear representation of both the magnitude of climate variables and degree of uncertainty represented by ensembles of climate data. Details and practical application of this technique are discussed with relevance to colour theory, and particular guidance is provided on the limitations and suitability of colour maps for colour blind people.

Visualisation of spatial uncertainties in climate projections

Background

Over about the last decade climate modelling has progressed from single projections to ensemble-based approaches which explore uncertainties in the model projections. This has presented additional challenges for the way in which the projections are visualised and communicated.

One simple way that has been used to assess spatial uncertainties in an ensemble of climate model projections is to calculate the percentage of models that agree in the sign of change for a particular climate variable. For example, for an ensemble with 20 members, if 10 project an increase in temperature and 10 a decrease, then only 50% of models agree (the worst case scenario). Whereas, if all 20 members show an increase/decrease in temperature then 100% of models agree (the best case scenario).

This is illustrated in Figure 1, which shows the percentage agreement in the sign of average temperature and precipitation changes between 1961-90 and 2071-2100 projected by 22 climate models used for the IPCC Fourth Assessment Report (AR4) – see http://www.ipcc.ch/ipccreports/ar4-wg1.htm. This figure shows that across most of the globe (except regions in the North Atlantic and Southern Ocean) all the AR4 ensemble members agree on the sign of average temperature change. But for precipitation, the reverse is true and most areas show less than 90% agreement in the sign of change.

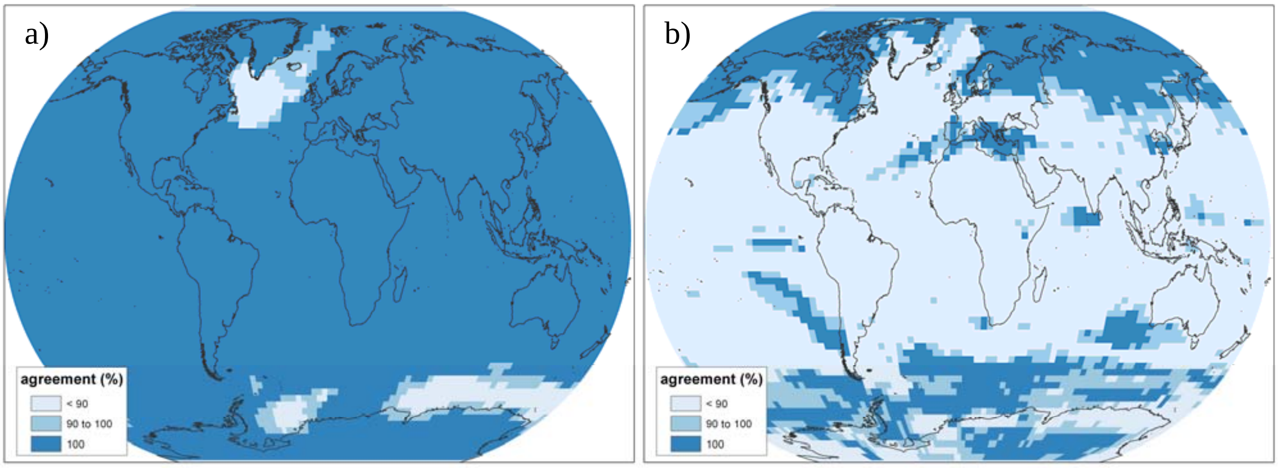


Figure 1 – Percentage agreement in the sign of change in a) average temperature and b) average precipitation between 1961-90 and 2071-2100 projected with an ensemble of 22 climate models for the AR4.

Another approach to visualise the level of confidence in an ensemble is the signal to noise ratio (see Figure 4). This is the mean of the ensemble members divided by their standard deviation, for example, a value below one means that the standard deviation or the "noise" is more than the mean, the "signal".

The maps in Figure 3 (same as figure 2 but on a different scale) and Figure 4 show both methods of measuring confidence for 2071-2100 precipitation minus 1961-1990 precipitation. Both maps give an indication of the degree of agreement across the AR4 ensemble and show broadly similar spatial patterns:

- South America, the Sahel, Southern USA, Central Europe, Australia and India have a low ensemble agreement percentage (< 70%) and a low signal to noise ratio (< 1)
- The Mediterranean, Canada and Northern Asia have a higher signal to noise (>1) and high ensemble agreement percentage (>90%)

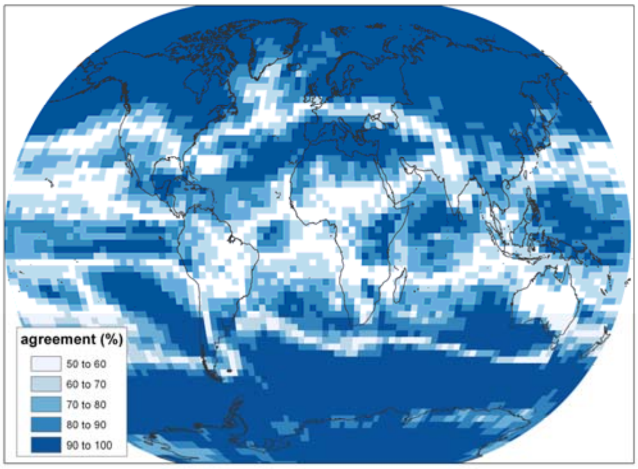


Figure 3 – Ensemble agreement for precipitation change.

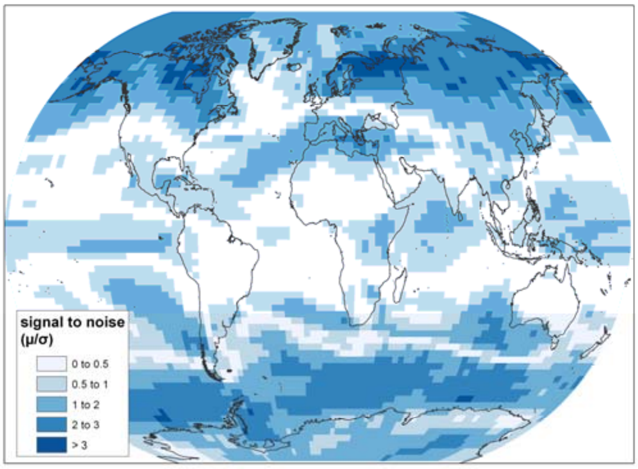


Figure 4 – Signal to noise for precipitation change.

While the techniques described above are useful to indicate the level of agreement across ensembles of climate data, they do not tell us any information on the sign or magnitude of change - for example, is the Mediterranean getting wetter or drier? This information is typically provided using maps of the ensemble median or mean.

In IPCC AR4, maps were included that illustrated both the ensemble-average climate change and the level of agreement in the direction of the change across a multi-model ensemble (Figure 5).

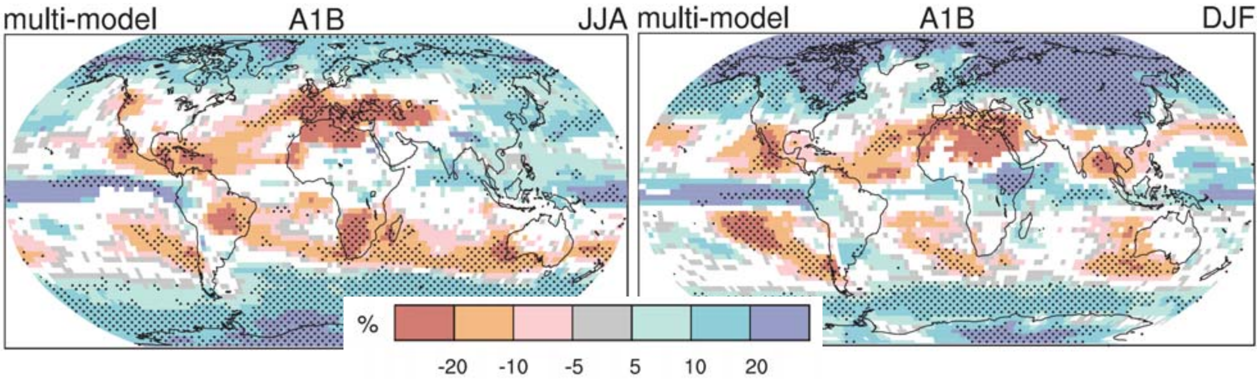


Figure 5 – Maps used in the AR4 to illustrate the multi-model ensemble average precipitation change (%) for the June-August (JJA) and December-February (DJF seasons between the 1980s and 2090s forced by the A1B scenario. Whiteout and stippling highlight, respectively, areas where less than 66% and greater than 90% of the ensemble members agree on the direction of change.

The AR4 maps shown in Figure 5 use stippling to highlight areas of high agreement (>90%) among ensemble members, and a whiteout shows areas of low agreement (<66%). Here, we describe a novel technique that builds on this AR4 mapping technique by replacing the uncertainty indicator provided by the stippling with several levels of colour saturation – using measures such as signal to noise or ensemble agreement to define the saturation levels. Figure 6 shows maps of precipitation change using this technique that are equivalent (with a different colour scale) to the AR4 maps shown in Figure 5.

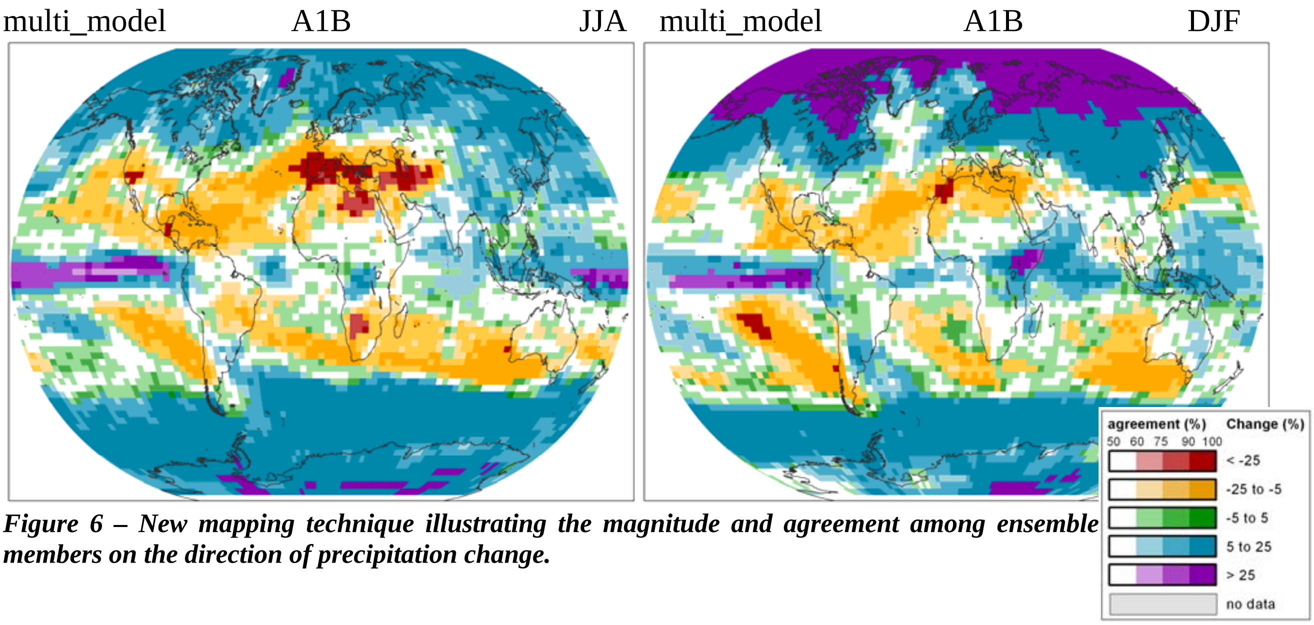


Figure 6 – New mapping technique illustrating the magnitude and agreement among ensemble members on the direction of precipitation change.

Method to create maps

The software product ArcGIS is used to create the maps and majority of figures used in this technical note (see http://www.esri.com/software/arcgis/arcview/index.html).

In order to create the maps in figure 6, two datasets are required:

- An ensemble mean or median of a climate variable
- An indication of confidence e.g. signal to noise or ensemble agreement percentage

These datasets are combined to create a composite of colour hue (see colour theory section later) and saturation/transparency. To demonstrate how the composite works, percentage of agreement in the direction of change across the ensemble members is used to define the saturation levels. Figure 7 shows the impact of varying the saturation (based on the ensemble agreement percentage) of a solid white layer overlaying a solid black layer. For ensemble member agreement levels between 50 and 60 percent white is displayed with 0% transparency (completely white). Whereas, for percentages between 60 and 75, white is displayed with 33% transparency, obscuring 66% of the colour underneath (in Figure 7b this creates a light grey). For percentages between 75 and 90, the white is displayed with 66% transparency, obscuring 33% of the colour underneath (leaving dark grey). Finally, when the ensemble agreement percentage is above 90 the transparency is set to 100% meaning that all the colour underneath is showing (pure black).

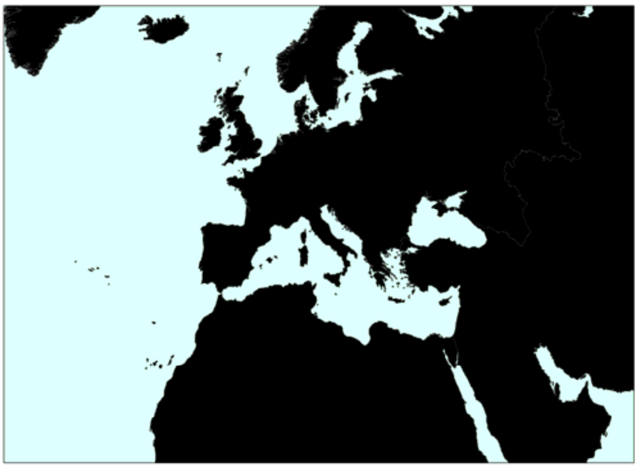


Figure 7a – Solid black layer

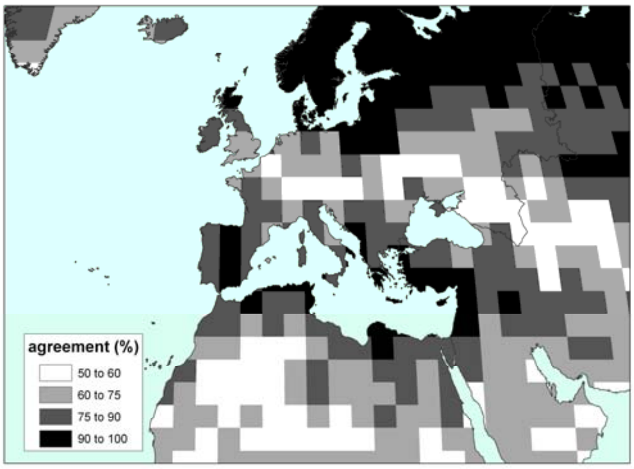


Figure 7b – Applying white transparencies

This approach is then applied to a layer where more colours are added to illustrate a climate variable, for example, figure 8a shows precipitation change (%) between 1961-1990 and 2041-2070 (for the AR4 multi-model ensemble mean).

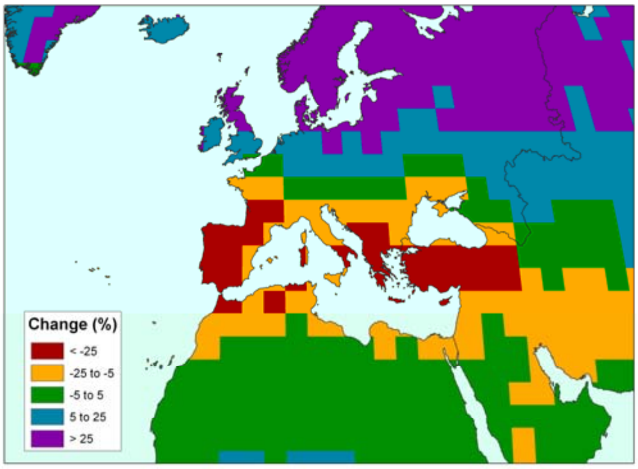


Figure 8a – The raw colours

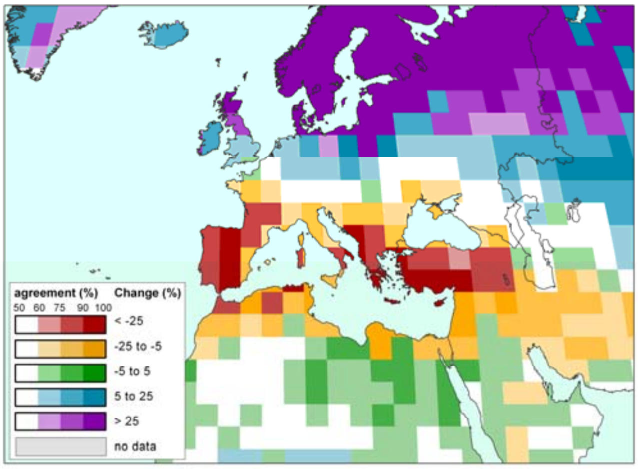


Figure 8b - Applying the transparencies

Figure 8b shows the addition of a saturation layer to demonstrate the level of agreement among the AR4 ensemble members. This figure shows that there is strong agreement on an increase in precipitation in Scandinavia (intense purple) and on a decrease in precipitation in the Mediterranean region (intense red and orange). However, areas such as the Sahara and central Europe have less certainty in the sign of change, highlighted by the paler colours in these areas.

The code required to create the different levels of transparency was written using the proprietary language Visual Basic for Applications (VBA) and these are described in Appendix A. The legend that appears with the map is made manually in ArcGIS by creating rectangles and using a gradient fill symbol to fill them with an appropriate colour with varying saturation.

General colour theory

A challenge for creating any multi-colour maps is choosing colours that allow interpretation of both the value and uncertainty of the information. Berlin and Kay (1969) performed a linguistic study which concluded there are 11 basic colour distinctions that fall into three classes:

- achromatic colour terms: black, grey, white
- primary colour terms: red, green, blue, yellow
- secondary colour terms: brown, orange, purple, pink

Several sources (Halsey and Chapanis, 1951; Kaiser and Boynton, 1989) have used the limited existing data combined with some theory to estimate that under best conditions, the eye can distinguish one million colours (http://www.visualexpert.com/FAQ/Part2/cfaqPart2.html). Clearly, there are plenty of colours available for map production. For the purpose of this technical note, colour will be defined with 3 attributes, all of which can be varied to create a wide range of colours.

- **Hue**: The property of colours by which they can be perceived as ranging from red through yellow, green, and blue.
- **Lightness**: a property of a colour, or a dimension of a colour space, that is defined in a way to reflect the subjective brightness perception of a colour for humans along a lightness–darkness axis. So for example a particular hue of yellow can have lightness adjusted so that it becomes brown.
- **Saturation**: is the amount of white apparently mixed with a pure colour. For example red can have white added to create pink.

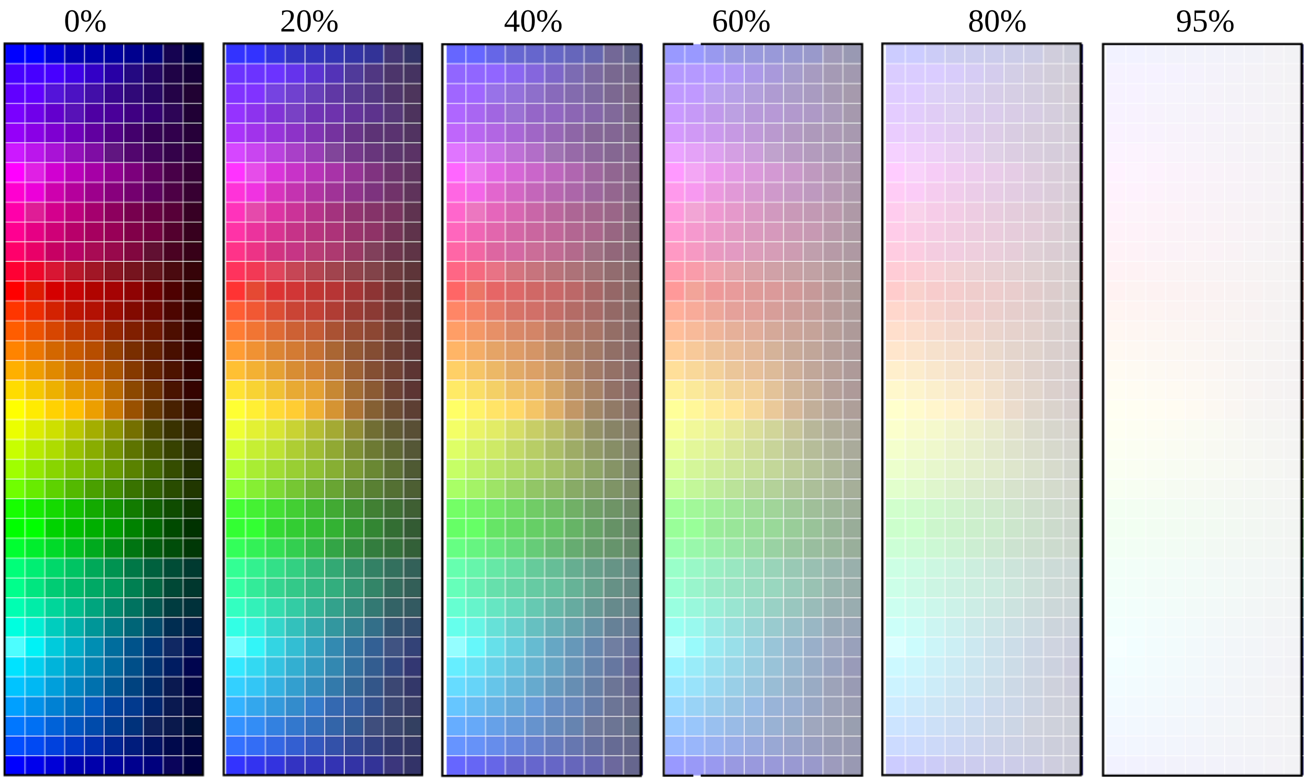
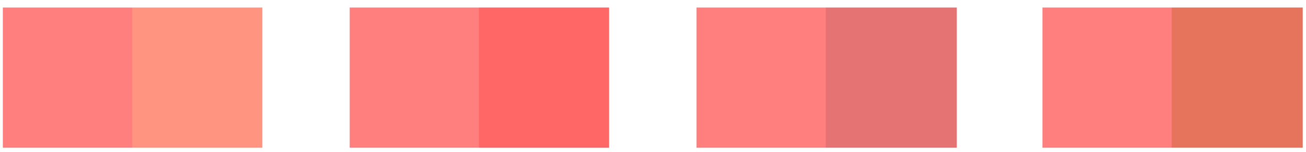


Figure 9 – Colour palettes with hue varying in the vertical axis, lightness in the horizontal and saturation (white added) given by percentage above palette.

Figure 9 shows a wide range of colours that can be created by varying the hue, saturation and lightness. However, there are many factors influencing a persons' ability to interpret colours that need to be considered when creating a map which incorporates wide colour ranges. These are described briefly and illustrated below:

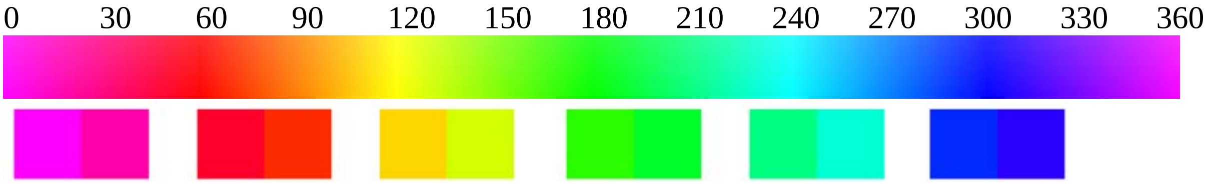
Spatial separation: Colour discrimination is much poorer when the samples are separated so that they don't form a border. The greater the separation, the worse the discrimination:

Number of dimensions: Colours will be easier to distinguish if they differ in hue, saturation and lightness than if they differ in only 1 or 2 dimensions:



Varying Hue   Varying Saturation   Varying Lightness   Varying all three

Spectral location: Hue discrimination varies across the spectrum. Normal viewers are most sensitive to hue changes around yellow and at the border between blue and green. Colour discrimination is poorest for colours from the edges of the spectrum, red and violets. Using a scale from 0 to 360 (magenta back to magenta) each of the coloured boxes is separated by 20 positions (e.g. the reds are at position 50 and 70, the yellows at position 100 and 120). It is very clear that some coloured pairs are much easier to distinguish between that others:



Size: Discrimination is poorer for small objects. Hue, saturation and lightness/brightness discrimination all decrease. The effect is greatest for yellow and blue. This really applies more appropriately over larger areas, for example when comparing small colour swatches to whole walls when decorating at home.

Saturation: Hue discrimination becomes worse as colours become less saturated:

Lightness: Hue discrimination declines at lower lightness:

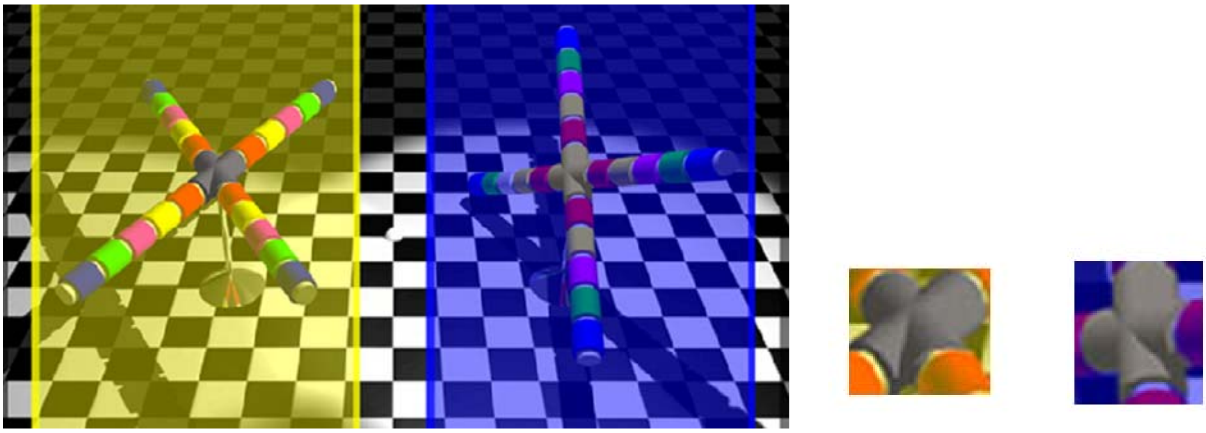


Figure 10 – Colour illusion (central joiners are the same colour but can appear to be different depending on the light under which it is viewed).

It is possible for colour perception to change given the context. So for example in Figure 10 (from http://www.lottolab.org/articles/illusionsoflight.asp) the central joiners of the coloured tubes are the same shade of grey, but the perception is that the one in the right is closer in hue to yellow. This illusion can be dispelled with the close ups to the right, they also show that the surrounding "reds" are in fact closer to magenta and orange.

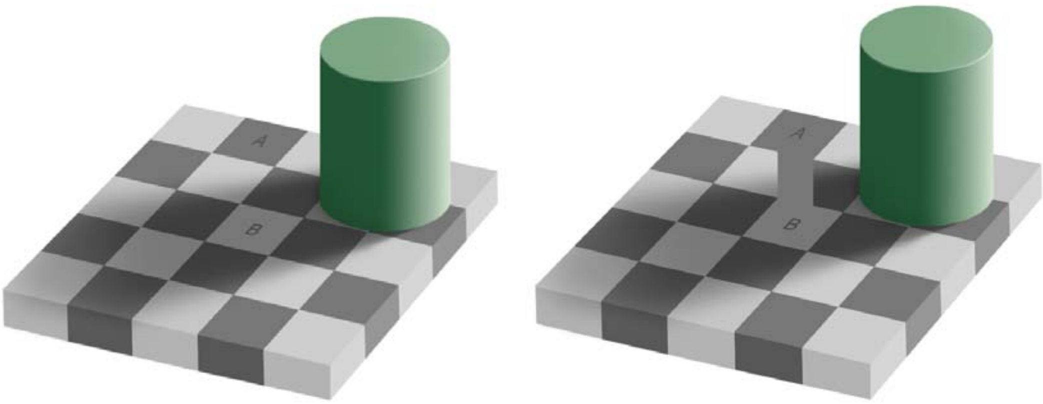


Figure 11 – Shadow illusion

Striking illusions can also be created on the apparent lightness of an object, Figure 11 (http://web.mit.edu/persci/people/adelson/checkershadow_illusion.html) demonstrates this. The squares labeled A and B are the same shade of gray. This can be verified by joining the squares marked A and B with a vertical stripe of the same shade of grey (image editing software shows both greys to be RGB 120,120,120). An explanation of this effect can be found at (http://web.mit.edu/persci/people/adelson/checkershadow_description.html).

A far milder form of this can be seen with perception of colours on maps. Figure 12 shows this, both pixels highlighted are in the same 1 to 2 category, but it appears that the one on the left is darker than the one on the right. It can be resolved by looking carefully but at first glance seems quite ambiguous.

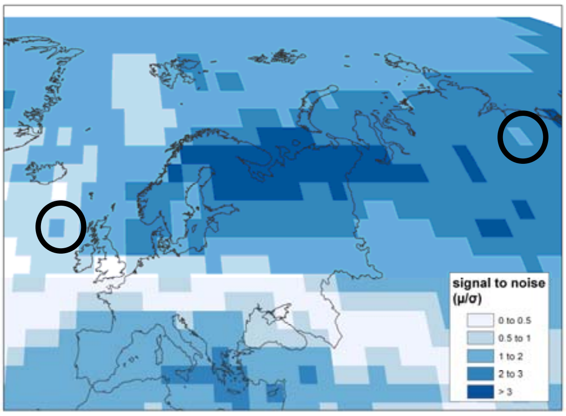


Figure 12 – Contrast issues with maps.

There are clearly many factors that affect ability to distinguish colours, all of which could be useful for map creation. The next section looks at approaches to creating maps that have maximum contrasting colours.

Guidance for creating an appropriate Legend

A common way of choosing colours in computer software is to use the RGB colour model. This is an additive colour model in which red, green, and blue light are added together in various ways to reproduce a broad array of colours. The name of the model comes from the initials of the three additive primary colours, red, green, and blue (http://en.wikipedia.org/wiki/RGB_color_model).

Red	Green	Blue
255	255	0
255	0	0
255	0	255
0	0	255
0	255	255
0	255	0

Red	Green	Blue
255	128	0
255	0	128
128	0	255
0	128	255
0	255	128
128	255	0

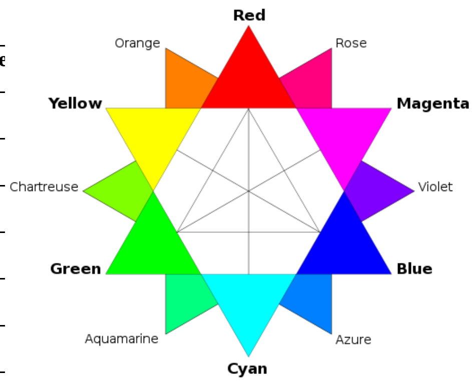
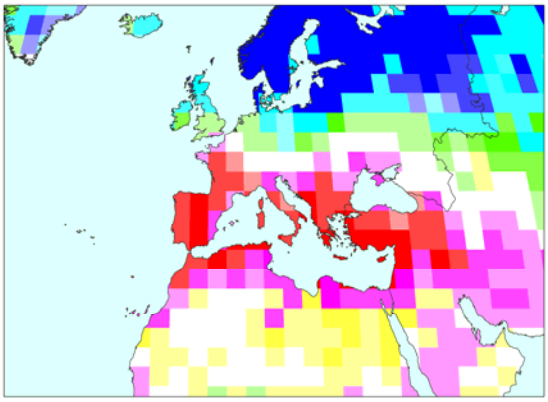


Figure 13 – Primary, secondary and tertiary colours tables (values for full saturation)

Using the RGB colour model it is potentially possible to create over 16 million colours (256^3). This is by combining 256 different levels of red green and blue. However, the eye cannot discriminate this number of colours though and a monitor certainly can't reproduce them.

The chart in Figure 13 shows the proportions of colour that are used to create the primary and secondary colours and the tertiary colours. It would be possible to approach colour selection by taking spectrally different hues. For example, a palette can be created using just primary and secondary colours. This potentially maximises the difference between the colours, but when looking at a map created in these colours (Figure 14a) is clearly not cartographically appealing.



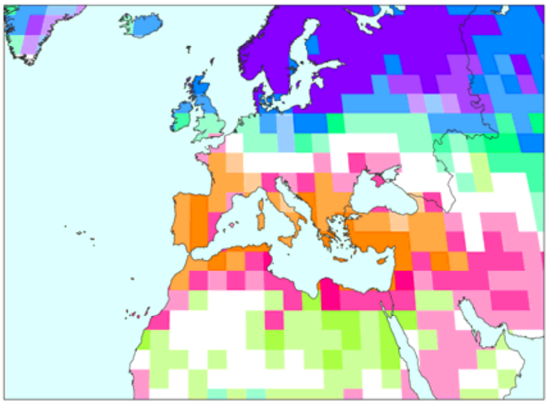


Figure 14a – Primary colour map ***Figure 14b – Tertiary colour map***

The tertiary colours are a combination of the primary and secondary ones e.g. orange is red + yellow, violet is magenta + blue. The map produced (Figure 14b) is slightly less garish, but there is still a clash between the rose and orange.

In previous work which looked at the Köppen climate classification, the author created a map with 27 categories (http://koeppen-geiger.vu-wien.ac.at/pdf/metz_15_3_0259_0263_kottek_wm.pdf) as shown in Figure 15. This used different colours to delineate different climate classes. Yellow shades are used for arid areas, red shades for equatorial, green and brown shades for warm temperate, purple and pink shades for snow areas and blues for polar zones. This map probably demonstrates about the maximum number of colours that could be used effectively on a map.

It helps to have the context to work out what some of the colours mean. For example, looking at point 1 on Figure 15, it can be seen that this is a pale pinkish colour that could be confused with the Aw equatorial category, but knowledge would tell us that it must be class Dsb as it is not in an equatorial zone. Point 2 demonstrates that there is clearly some similarity between the dark yellows in the arid category and the browns in the warm temperate one. Also point 3 shows the shades of green in the warm temperate categories are quite similar, thus it might be difficult to interpret the green at point 3 as Cfb as opposed to the green in the south-east USA which represents Cfa. Some interpretation can be helped by knowledge of the environment, but these contextual clues may not be available in many cases.

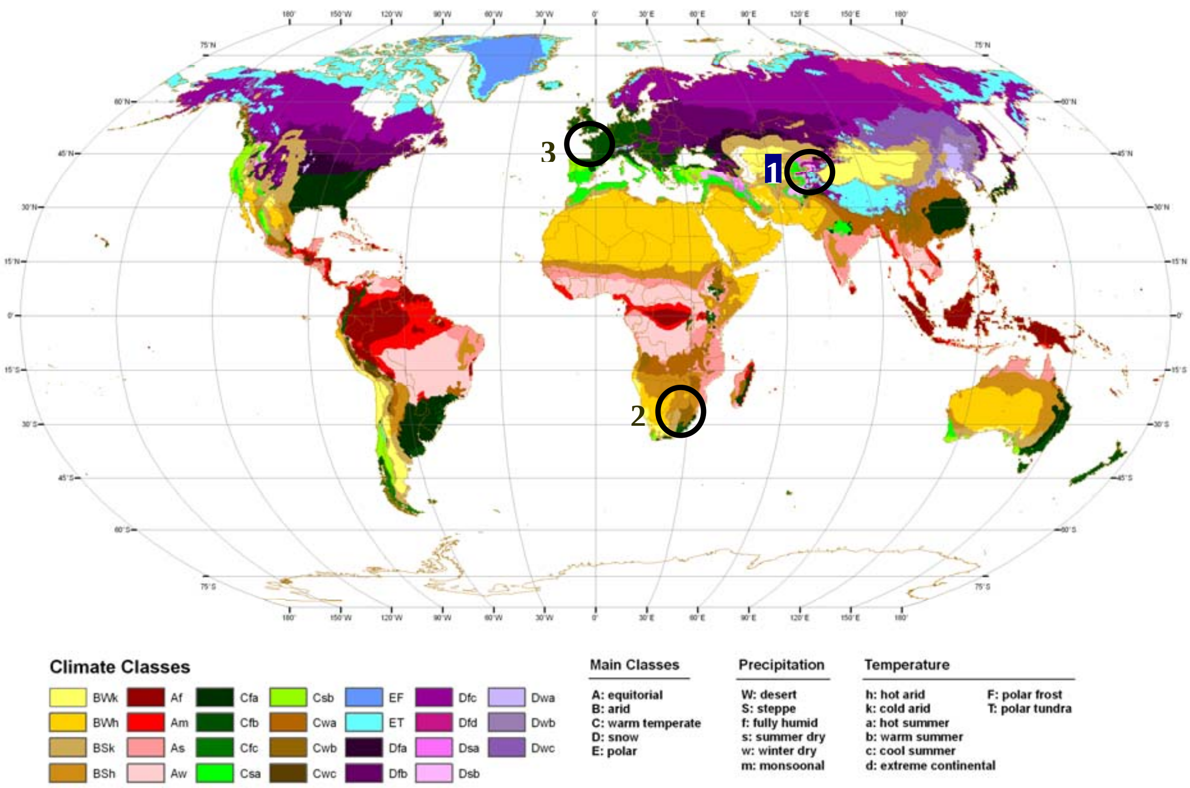


Figure 15 – Köppen climate classification employing 27 categories

It is clearly possible to create an almost unlimited range of colours using the RGB model. Using the selection available in ArcView makes it easier. Figure 16a shows the standard palette available to the user. From this palette, 12 colours have been selected, as can be seen in Figure 16b. The most obvious difference from the colours in Figure 13 is that none of them are pure spectral colours. These are very rarely used over large areas and more likely to be used for point and line symbology that needs to stand out (for example towns, roads and cities).

Figure 16a – ArcGIS palette

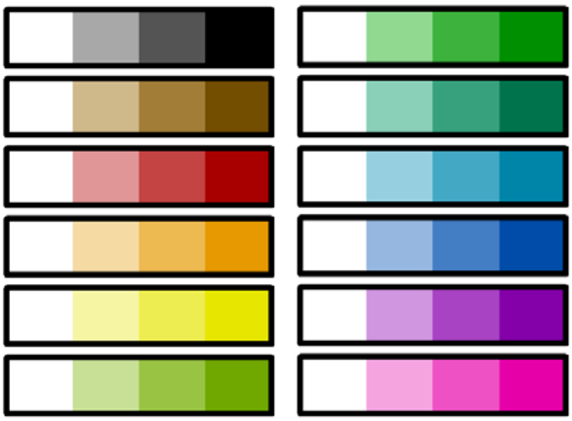


Figure 16b – Possible palette of colours

Choosing the number of saturations of colour

Starting at white and going out to a pure spectral colour, there are gradations in apparent saturation. However, some hues appear inherently more saturated than others. The most saturated yellow still appears pale compared to saturated red, saturated green and especially saturated blue. (http://www.visualexpert.com). Figure 17 shows primary, secondary and tertiary colours (from the colour wheel in figure 13) with 10 different levels of saturation, from white to the pure colour. It is clear the number of distinguishable saturation levels varies throughout the spectrum and is particularly strong in violet and weak in yellow.

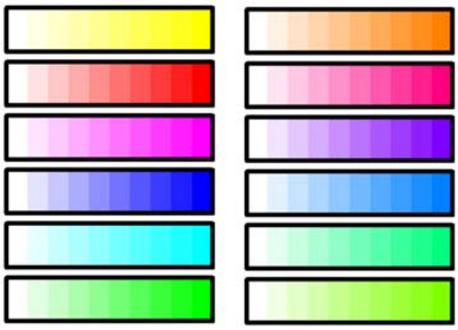


Figure 17 – Ten Levels of saturation for 12 most basic spectral colours with black and white equivalent.

Initially, when developing this mapping approach, 10 gradations of colours were used. This produced a smoother looking map but not one in which the legend could be related to the map. By testing various numbers of categories between 3 and 10 (Figure 18) it was decided that 4 categories provided the optimum number for map legibility whilst still providing useful information of the uncertainty in the data. Looking at Figure 19a, although it is easy to see the white at point 1 it is only by context that the darkest red is interpretable at point 2. It is almost impossible to work out that point 3 is the 8^{th} level of red. Figure 19b in contrast is far easier to interpret in most situations.

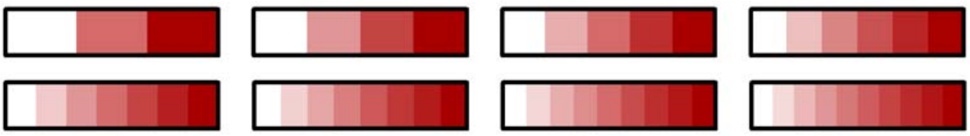
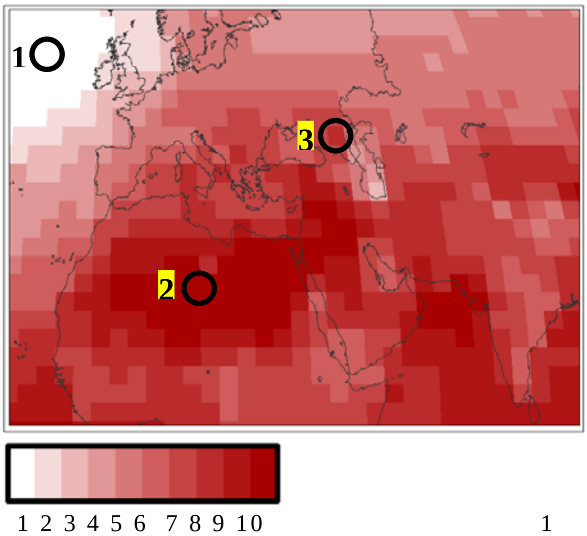


Figure 18 – Various saturations of red



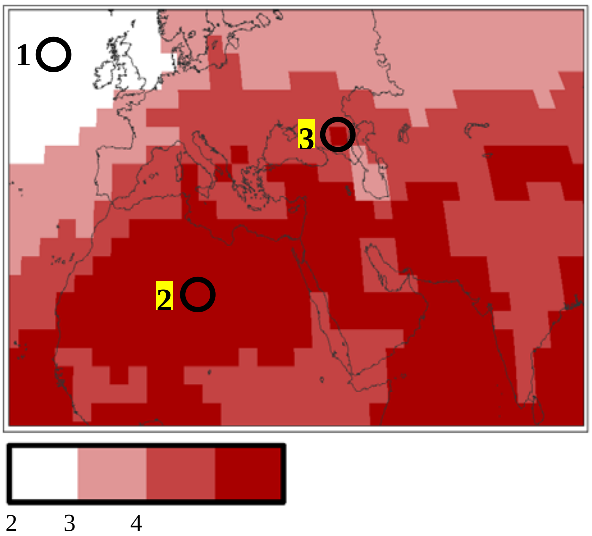


Figure 19a – A map with 10 categories *Figure 19b – A map with 4 categories*

Unfortunately the contrast illusion (from figure 13) still exists with 4 colours as can be seen in figure 21 with the circled pixels being the same tints of red. However this will probably not be such a problem because the maps created will include multiple hues with which to distinguish them.

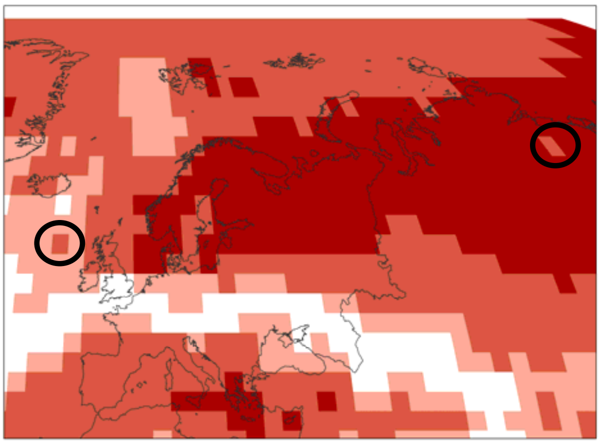


Figure 20 – Colour illusion on 4 colour map

Choosing the number of hues

The final stage is choosing the number of colour categories that can be interpreted from the map. The maps in figures 21 to 24 show 3, 5, 6 and 7 colours being used to illustrate precipitation change. Looking at figure 21 it is easy to perceive the differences in colour for the 3 categories. The disadvantage of this map is that there is a limited amount of information about the degree of change i.e. there is a reduction in precipitation, an increase in precipitation or the sign is about the same.

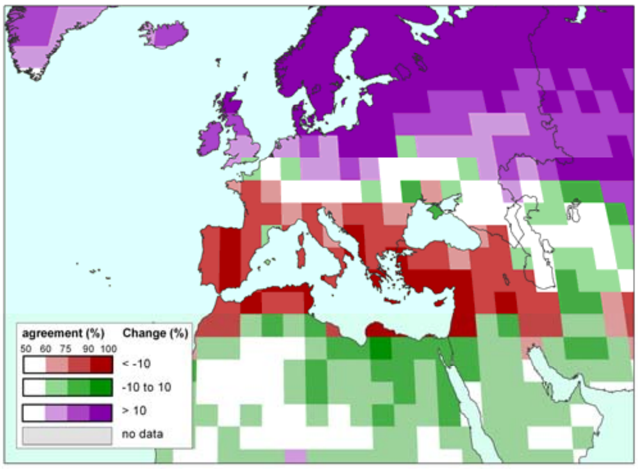


Figure 21 – 3 colour map

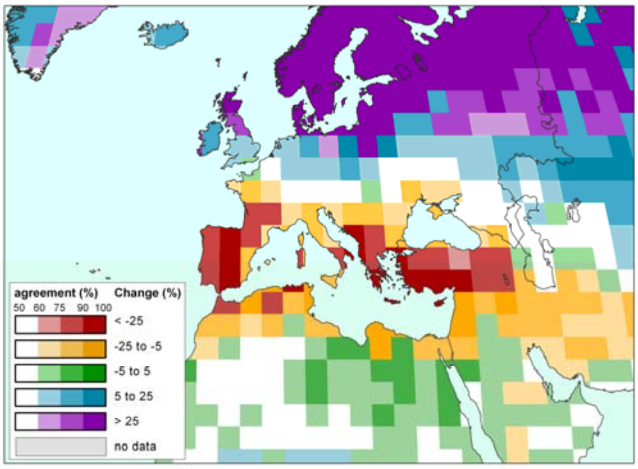


Figure 22 – 5 colour map

Figure 22 shows a map with 5 colours. This map has more distinction in the magnitude of the change, this means it is possible to identify that Scandinavia is getting wetter than northern Germany and that Spain is drier than Italy (not possible in the 3 colour map). Figure 23 shows a map with 7 categories. This allows even more distinction in the amount of change, but it is perhaps more difficult to interpret as the shades of the 5 to 20 category may be confused with the green or blue on either side of it. This is particularly true for the paler versions of the colour, an adjustment to the colours may help to resolve this but it is beginning to get too busy with information.

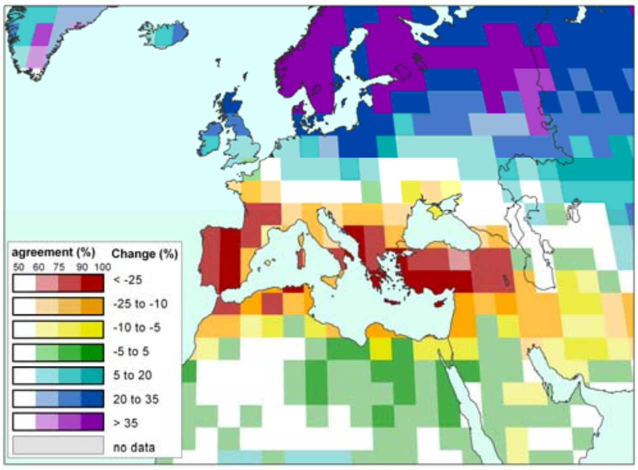


Figure 23 – 7 colour map

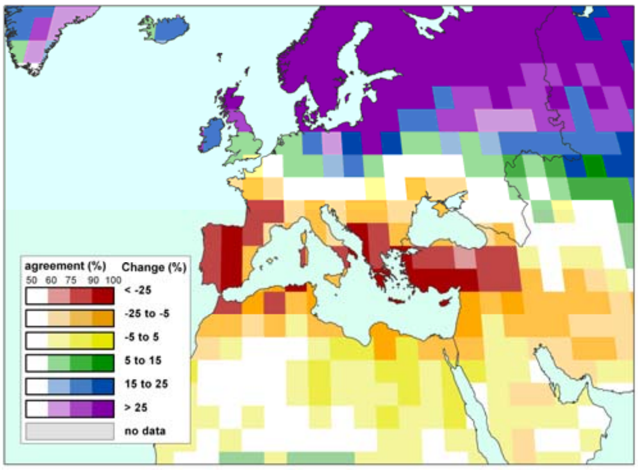


Figure 24 – 6 colour map

A possible compromise between legibility and showing the contrasts in magnitude of the change is to use a 6 category map. This could incorporate an extra category in the direction of the bias of the data i.e. positive or negative. So in Figure 24 above the difference between northern and southern Britain is highlighted.

Further work could be done to look at other climatic variables, regions and spatial scales to assess the impact on map interpretability.

Perception of maps for Colour Blind People

Colour-vision impairment, or "colour-blindness," affects over four percent of the population (for more detailed information on colour blindness consult Appendix B). Depending on the type and extent of this colour-blindness, colours that look different to people with normal colour vision may look the same to the colour-vision impaired. Using software available online at http://www.vischeck.com/vischeck/vischeckImage.php it is possible to simulate how different colours might appear to a colour blind person:

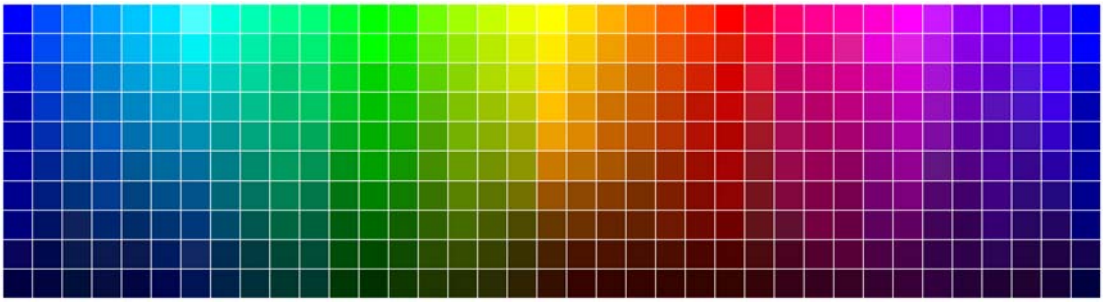


Figure 25 – Original colour palette

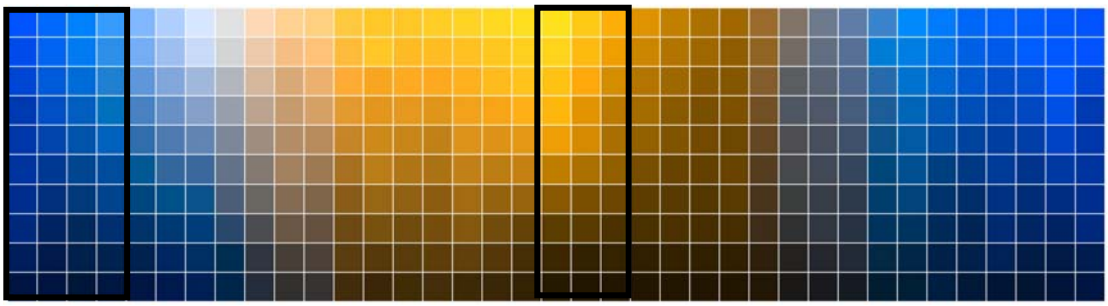


Figure 26 – Deuteranope colour simulation

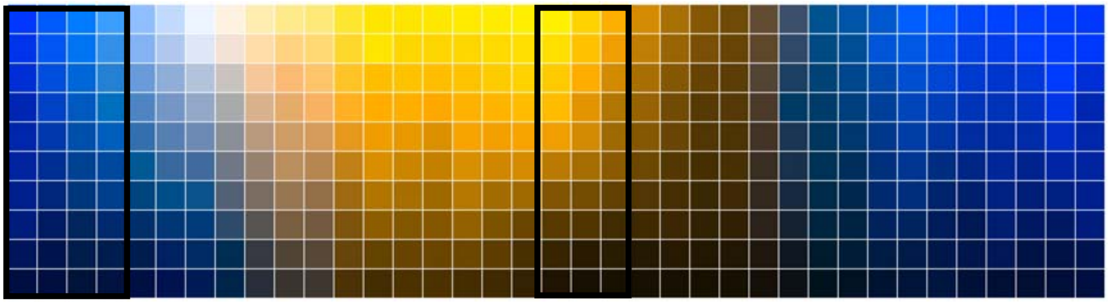


Figure 27 – Protanope colour simulation

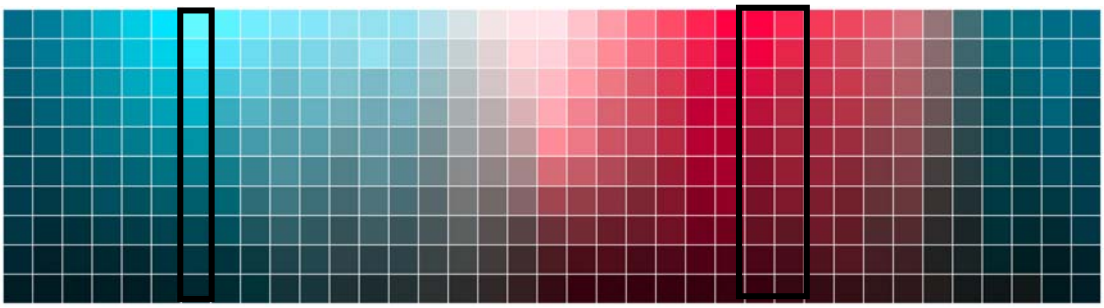


Figure 28 – Tritanope colour simulation

The colour palette in Figure 25 has 35 columns. Figures 26 and 27 show simulations given for Deuteranopia and Protanopia (types of red-green colour blindness), this shows that only 7 of the columns appear similar to the original set in Figure 28. For Tritanopia (a type of yellow-blue colour blindness) only 3 of the columns are quite similar in colour. This disparity in colour perception can clearly lead to problems understanding maps in which colour schemes are used to represent data (Gardner 2005).

By far the most common form of colour blindness (>99% of colour blinds) is one in which there is difficulty with discriminating red and green hues. It is impossible to know exactly how an individual perceives colour, but it is true this perception varies significantly for each individual. However, for the rest of this study, colour simulations will be for deuteranopes and the deuteranomalous as they account for about 70% of colour blind people and the effects are similar (compare Figures 26 and 27) to the protanopes who account for most of the rest.

Looking at Figures 29a and 29b the difficulty with map interpretation becomes clear. The reds in Spain are difficult to distinguish from the Greens in Egypt, also the blues and purples in Russia and Scandinavia are not easy to tell apart.

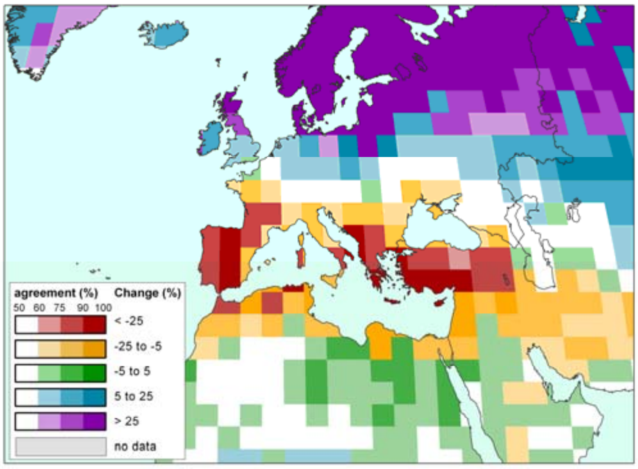


Figure 29a – Original map

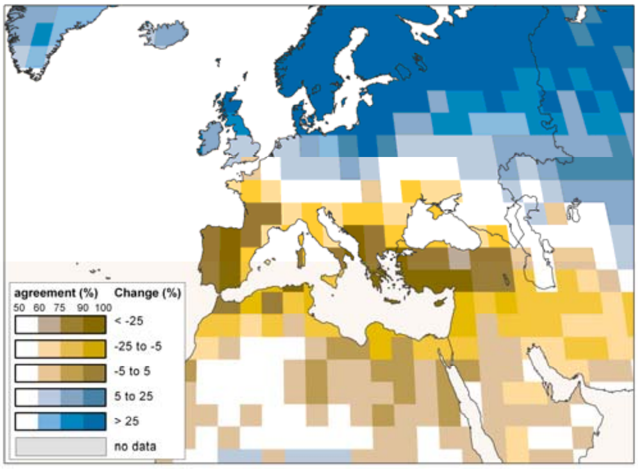


Figure 29b - Deuteranope colour simulation

The colour blind simulation in figure 29b is of course just a version of how someone with colour blindness might perceive the map in figure 29a. To gain more insight, a very small qualitative study was performed by posting a question to a Met Office internal newsgroup, the posting is shown below:

I am creating maps to display uncertainty in climate projections. From reading the literature it appears that about 4% of people are colour blind (95% of them men) and from using a piece of software called VisCheck http://www.vischeck.com/vischeck/vischeckImage.php I have discovered that the maps I am creating may be close to impossible to interpret by colour blind people. The legend I have created for my map is shown in figures 29a and 29b. The simulation clearly shows that the green and red categories are almost identical and the blue and the purple are very similar as well.

I would be interested to hear by email or return to this post from anyone who is colour blind, whether the Deuteranope simulation is a realistic approximation of how the legend appears to them, i.e. does the image on the left look similar to the one on the right (it is clearly very different if you are not colour blind)

This posting produced a response from 5 people (all men) and the responses are summarised below:

- The colours of the legends in figure 29a and 29b look the same
- The second rows for the legend in figure 29a and 29b are virtually identical
- The fourth rows for the legend in figure 29a and 29b are virtually identical

- Within the legend, rows 1 and 3 look similar
- Within the legend, rows 4 and 5 look similar
- The lowest two colours of -25 to -5 and -5 to 5 are the same
- The middle of 5 to 25 and the lower colour of >25 are more or less the same
- When colours are next to each other, they can be differentiated, when they are apart they cannot be differentiated
- Maps and plots are often ignored because the key cannot be related to the plot

For this small sample of colour blind people it clearly shows there is a difficulty interpreting maps. Taking the responses above into consideration, a legend was created (figure 30) where green is removed to try and avoid the red-green confusion and purple is removed to eradicate the purple-blue confusion. The agreement on the sign is given by varying the lightness and darkness of the colours blue and red.

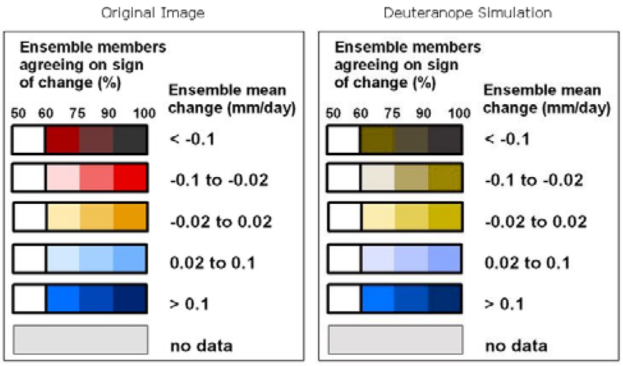


Figure 30 – Initial attempt at colour blind suitable legend.

This seemed to alleviate some of the problems with one user reporting that although the colour blind simulation looked the same as the original, there was a clear difference between the between the rows, unlike in the original. Of course this might not be the case for people with other types of colour blindness, another user still struggled with identifying differences between the colours on the top line. A further problem with the legend above is that it can't be created by varying the saturation of a specific colour and would not be compatible with the method developed.

Colour blind users were then asked how they created maps for themselves. One user suggested to get maps to work for him he had to create maps that to the non colour blind would look very unappealing. Other users supplied some useful hints to make maps easier to interpret:

- Make sure that there is a clear contrast between low and high values on a map, even if the ones in the middle are difficult to distinguish. This clarifies general patterns, even if the zones of transition aren't very clear.
- Try to use contrast cues to aid interpretation. Reduce the colour setting on the monitor and if you can distinguish a difference in contrast then most people with colour blindness will too.
- If the sign of the change is particularly important, then make sure the contrast either side of zero is large (same with exceedence/non-exceedence of any threshold).

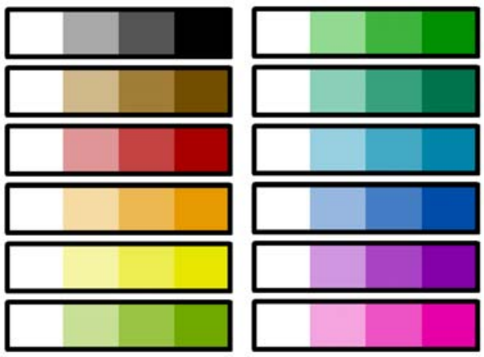


Figure 31a – Original palette

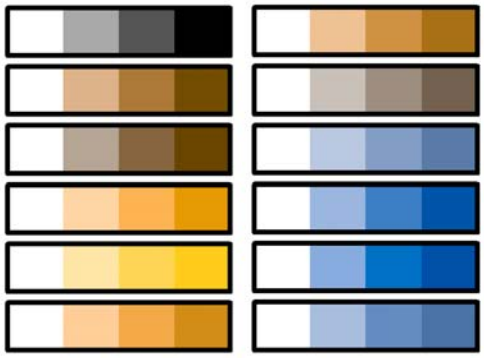


Figure 31b - Deuteranope colour simulation

Using the palettes in figures 31a and 31b in conjunction with the feedback received from colour blind people a legend has been created that is hopefully usable for colour blind people and also works with the technique developed. Figure 32a shows the legend developed and an interpretation of it with 2 types of colour blind simulation (figure 32b and 32c). This legend ensures:

- Values at either ends of the scale are the most distinguishable. Therefore, a dark blue and dark red is used for these.
- The next categories will be lighter but still be distinguishable. For these, orange and aquamarine is used.
- The middle category needs to be the palest and a yellow is used for this. Although this is not the clearest one to distinguish gradations of, in this context it is the least important category as it is in a transition zone.

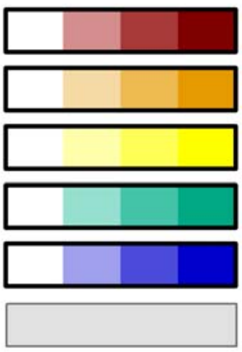


Figure 32a – Original Legend

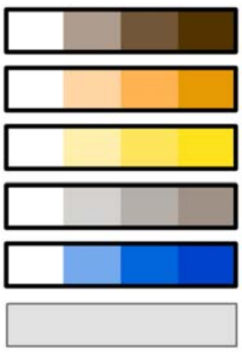


Figure32b - Deuteranope

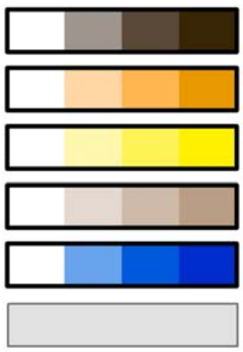


Figure 32c Protanope

A possible area of confusion may be the no-data value looking very similar to the palest aquamarine. However, making this colour either bluer or greener would cause confusion in other areas, so no data may need to be represented in a different way.

Following a number of iterations, the map created (figure 33) using the legend in figure 33a proved to be most effective for discrimination for colour blind people, whilst still remaining usable for people without a colour vision impairment.

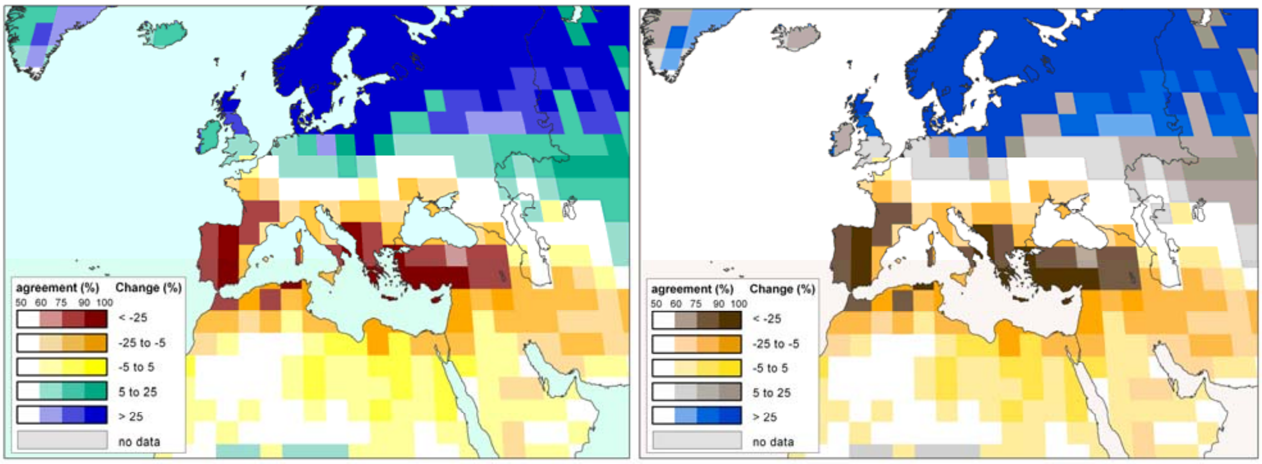


Figure 33 – Suitable legend for colour blind people.

Although this technique is based on a very small sample it is believed that the general concepts are sound. It is true that red-yellow-blue is often an effective scheme to use for colour blind individuals. It is probable that trialling these maps on a larger selection of colour blind individuals may demonstrate that different people perceive the maps in different ways.

Future work might include a more quantitative study on the information that can be gained from these maps in comparison to tables, graphs and a greater number of maps.

Acknowledgements

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APPENDIX A – Code used to create transparent white layer

To create the saturation layer, code is used to automate the process. It requires creating a string that is semicolon delimited by each value category, with each sub-value subsequently delimited by commas. The legend below is for ensemble agreement percentage:

```
strLegendString= "50,60,255,255,255,255;60,75,255,255,255,155;75,90,255,255,255,70;90,100,255,255,255,0"
```

so taking the first delimited part, the first 2 values are the upper and lower values of the ensemble agreement i.e. between 50 and 60 % agreement

50,60,255,255,255,255

Next is the RGB value of the colour in this case the value 255,255,255 is white

50,60,**255,255,255**,255

Finally the last value is the transparency (between 255 for no transparency to 0 for completely transparent). As this needs to appear completely white the value is set to 255

50,60,255,255,255,**255**

The next step is to set the layer that is getting the transparent white legend, shown below

```
Dim rl As IRasterLayer
Set rl = getLayerFromName("PrecAgree.tif")
```

Finally the legend is setup and applied using the code below:

```
setupUserDefinedLegend strLegendString, 1
applyRasterLegend rl, 1, 0
```

The functions required are shown below:

```
---------------------------------------------------------------------------------------------

Public Type nameLegendItem
   dblRangeLower As Double
   dblRangeUpper As Double
   intFillRed As Integer
   intFillGreen As Integer
   intFillBlue As Integer
   intFillTransparency As Integer
   strLabel As String
End Type

Public Type nameLegend
   strFieldName As String
   legendItems() As nameLegendItem
End Type

Public currentNameLegend As nameLegend


Private Function getLayerFromName(strLayerName) As ILayer

Dim pMxDoc As IMxDocument
Set pMxDoc = ThisDocument

Dim pAV As IActiveView
Set pAV = pMxDoc.ActiveView


Dim pMap As IMap
Dim pLayer As ILayer
Dim pGroupLayer As IGroupLayer
Dim i As Integer

'get the document and map
Set pMxDoc = ThisDocument
Set pMap = pMxDoc.FocusMap


For i = 0 To pMap.LayerCount - 1
   Set pLayer = pMap.Layer(i)
```

```
   If pLayer.Name = strLayerName Then
      Set getLayerFromName = pLayer
   End If

Next i

End Function


Public Function setupUserDefinedLegend(strUserDefinedLegend As String, _
                                      dblMultiplyFactor As Double, _
                                     Optional strLogStepsLabels As String, _
                                     Optional strUnits As String) As Boolean

'-----------------
'DECLARE VARIABLES
'-----------------

Dim dblLogX As Double
Dim lngLogAboveMax As Long
Dim lngLogBelowMin As Long
Dim dblClassRangeUpper As Double
Dim dblClassRangeLower  As Double
Dim intClassCount As Integer
Dim intNumberOFClasses As Integer
Dim strLegendDetails As String

Dim dblClassRangeUpperRealWorld As Double
Dim dblClassRangeLowerRealWorld As Double
Dim strClassRangeUpperRealWorld As String
Dim strClassRangeLowerRealWorld As String
Dim strClassLabel As String

Dim arrLegendDetails() As String
intNumberOFClasses = UBound(Split(strUserDefinedLegend, ";")) + 1


ReDim Preserve currentNameLegend.legendItems(intNumberOFClasses - 1)

For intClassCount = 1 To intNumberOFClasses

    strLegendDetails = Split(strUserDefinedLegend, ";")(intNumberOFClasses - intClassCount)


    dblClassRangeLower = Split(strLegendDetails, ",")(0) * dblMultiplyFactor
    dblClassRangeUpper = Split(strLegendDetails, ",")(1) * dblMultiplyFactor

    currentNameLegend.legendItems(intClassCount - 1).intFillRed = Split(strLegendDetails, ",")(2)
    currentNameLegend.legendItems(intClassCount - 1).intFillGreen = Split(strLegendDetails, ",")(3)
    currentNameLegend.legendItems(intClassCount - 1).intFillBlue = Split(strLegendDetails, ",")(4)
    currentNameLegend.legendItems(intClassCount - 1).intFillTransparency = Split(strLegendDetails, ",")(5)


    currentNameLegend.legendItems(intClassCount - 1).dblRangeLower = dblClassRangeLower
    currentNameLegend.legendItems(intClassCount - 1).dblRangeUpper = dblClassRangeUpper


    dblClassRangeUpperRealWorld = dblClassRangeUpper / dblMultiplyFactor
    dblClassRangeLowerRealWorld = dblClassRangeLower / dblMultiplyFactor
    strClassLabel = Round(dblClassRangeLowerRealWorld, 1) & " to " & Round(dblClassRangeUpperRealWorld, 1)
& " " & strUnits

   '----------------------------------------------
   'APPLY THE CLASS LABEL TO THE CURRENT LEGEND ITEM
   '----------------------------------------------
    currentNameLegend.legendItems(intClassCount - 1).strLabel = strClassLabel

Next intClassCount

setupUserDefinedLegend = True

End Function


Public Sub applyRasterLegend(pInLayer As ILayer, intLayerType As Integer, intTransparency As Integer)

    Dim i As Long
    Dim strLegendItems() As String
    Dim strLegendColour As String
    Dim strLegendColourArray() As String
    Dim dblRangeLower As Double
    Dim dblRangeUpper As Double
    Dim intFillRed As Integer
    Dim intFillGreen As Integer
    Dim intFillBlue As Integer
    Dim intFillTransparency As Integer
```

```
Dim strRangeLabel As String
Dim pColor As IRgbColor
Dim pExclude As IRasterDataExclusion
Dim dblExcl(1) As Double
Dim intClassCount As Integer
Dim intDifCount As Integer

intClassCount = UBound(currentNameLegend.legendItems) '+ 1

Dim pRasterLayer As IRasterLayer
Set pRasterLayer = pInLayer

Dim pRaster As IRaster
Set pRaster = pRasterLayer.Raster


Dim pClassRen As IRasterClassifyColorRampRenderer
Set pClassRen = New RasterClassifyColorRampRenderer

Dim pRasRen As IRasterRenderer
Set pRasRen = pClassRen
Set pRasRen.Raster = pRaster


' Set raster classify renderer
pClassRen.ClassCount = intClassCount + 1
pClassRen.ClassField = "Value"
pRasRen.Update

'---------------------------------------------------------------------------------
' THIS HAS BEEN ADDED BECAUSE WHEN THERE ARE ONLY VERY FEW UNIQUE VALUES IN A GRID
' THE CLASS COUNT GETS RESET TO A DIFFERENT VALUE
'---------------------------------------------------------------------------------
intDifCount = (intClassCount + 1) - pClassRen.ClassCount
intDifCount = 0

'----------------------------------------------------------------------------
' LOOP THROUGH THE CLASSES AND CREATE A CLASS RENDERER TO APPLY TO THE RASTER
'----------------------------------------------------------------------------
For i = intDifCount To intClassCount


    dblRangeUpper = currentNameLegend.legendItems(i).dblRangeUpper
    dblRangeLower = currentNameLegend.legendItems(i).dblRangeLower
    intFillRed = currentNameLegend.legendItems(i).intFillRed
    intFillGreen = currentNameLegend.legendItems(i).intFillGreen
    intFillBlue = currentNameLegend.legendItems(i).intFillBlue
    intFillTransparency = currentNameLegend.legendItems(i).intFillTransparency
    strRangeLabel = currentNameLegend.legendItems(i).strLabel

    pClassRen.Break((intClassCount) - i) = dblRangeLower

    '---------------------------------------------------
    'CREATE A COLOR FROM RGB AND TRANSPARENCY COMPONENTS
    '---------------------------------------------------
    Set pColor = New RgbColor
    pColor.RGB = RGB(intFillRed, intFillGreen, intFillBlue)

    pColor.Transparency = intFillTransparency

    ' Create a color ramp to use
    Dim pRamp As IAlgorithmicColorRamp
    Set pRamp = New AlgorithmicColorRamp
    pRamp.Size = intClassCount
    pRamp.CreateRamp True

    ' Create symbol for the classes
    Dim pFSymbol As IFillSymbol
    Set pFSymbol = New SimpleFillSymbol

     ' Loop through the classes and apply the color and label
    pFSymbol.Color = pColor

    pClassRen.Symbol((intClassCount) - i) = pFSymbol
    pClassRen.Label((intClassCount) - i) = strRangeLabel

Next i

'-------------------------------------------------------
' APPLY THE RASTER RENDERER TO THE CURRENT RASTER LAYER
'-------------------------------------------------------

pRasRen.Update

Set pRasterLayer.Renderer = pRasRen ' pClassRen
pRasterLayer.Renderer.Update
```

```
    '---------------------------------
    ' SET THE TRANSPARENCY OF THE RASTER
    '---------------------------------
    Dim pRasterLayerEffects As ILayerEffects
    Set pRasterLayerEffects = pRasterLayer
    pRasterLayerEffects.Transparency = intTransparency

End Sub
```

Appendix B – Background information on colour blindness

The text below is a direct copy from the webpage "visual expert" and I believe it provides some useful background information about colour blindness http://www.visualexpert.com/FAQ/Part4/cfaqPart4.html. I have kept in the American spelling of colour…

How many people are color blind?

The term "color blindness" is too vague to be useful. There are 7 types of color deficiency due to cone abnormalities. In addition, the elderly see colors differently, but are not color blind in the usual sense of the term. Finally, brain damage can create a very rare condition called achromatopsia.

People with normal color vision are called "trichromats" because they require three primaries to match any arbitrary sample. The trichromatic eye has three cone types, each containing a photopigment which responds to a restricted range of wavelengths. The major color deficiencies are abnormalities in the way cone pigment is distributed in the cones. In all, there are three deficit classes:

Anomalous Trichromats

There is a subpopulation of trichromats, who still requires three primaries to match a sample, but whose matches are abnormal because they use one primary far more than would be expected.

While having all three cone types, one cone type is rarer, has a reduced amount of pigment, or has a pigment tuned to an unusual wavelength. These "anomalous trichromats" fall into three groups, based on the primary which they overuse:

Type	Cone	Male%	Female%
protoanomalous	"red"	1.0	.02
deuteranomalous	"green"	4.9	.38
tritananomalous	"blue"	~0	~0

They can see all hue categories, so they are not color blind in any real sense. But they may have difficulty is discriminating colors which a normal would easily distinguish. Anomalous trichromats, however, are a very heterogeneous group. Some are only slightly different from normals, some are almost dichromats and others fall somewhere in between.

People with congenitally weak "blue" cone response, anomalous tritanopes, are virtually nonexistent. However, some eye diseases, such as glaucoma, attack blue cones creating "acquired" anomalous tritanopia. The loss of blue cones is usually greatest in the periphery.

Dichromats

The second class of color abnormal is the dichromat, a person who requires only two primaries to match any sample. These people are missing one of the three cones types.

Type	Cone	Male%	Female%

protanope	"red"	1.0	.02
deuteranope	"green"	1.1	.01
tritanope	"blue"	.002	.002

Unlike color anomalous individuals, dichromats are true color blinds in the sense that there are some hues which they cannot perceive. Lights which would appear different to a trichromatic will be metamers (appear identical) if they create the same activation ratio in their remaining two cone classes. Protanopes and deuteranopes are red-green color blind and see only yellows and blues. The tritanope is analogously blue-yellow color blind.

However, there is evidence that at least some dichromats use rods to compensate for the lack of the third cone. Studies find that these dichromats can often discriminate colors along the red-green axis of color space.

Monochromats

Monochromats can match any light with a single primary. They generally have no cones and make all matches using rods. They are very rare, 1 in 10,000,000. With only a single receptor type, they can have no color vision and are truly color blind because they distinguish only brightness levels. Their vision is so generally poor that the color selection for visual design is the least of their problems.

Achromatopsia

Lastly, achromatopsia is a condition which arises from brain damage and not from cone abnormalities. These people see the world a having little or no saturation. Fortunately, the condition is very rare.

What do color blind people see?

Some theorists like to say things such as "a color which would look deep red to a normal, looks dark yellow or brown to a dichromat." This is speaking very loosely because it assumes a commonality of perceptual experience. Of course, it is impossible to know what color blind, or any other, people experience. Given this caveat, here is common lore.

Dichromats have a point on the spectrum called the "neutral point" where the lights appears achromatic. The point is about the same for both classes, 495 nm for protanopes and 500 nm for deuteranopes, wavelengths which would appear slightly bluish green to a normal (assuming aperture color).

All wavelengths below the neutral point appear blue while those at longer wavelengths appear yellow. In the first few nm. away from the neutral point, apparent saturation increases rapidly, so dichromats can easily discriminate colors. The rest of the blues then appear similar as do the rest of the yellows and only discrimination of brightness is possible. Toward very long wavelengths, protanopes experience lights as becoming darker, so a very red apple, as already mentioned, might look dark yellow or brown. Some people think that a protanope sees red as black on a CRT because he has no "red cones." This is false because CRT colors always have white content and because "green" cones are still slightly sensitive to relatively long wavelengths. However, deep red may appear dark. Tritanopes have a neutral point at 570 nm., a wavelength which appears yellow to a normal trichromatic. Higher wavelengths appear red while lower ones appear green.

The description of dichromatic color perception comes from both theory and from studies of a few people who were dichromatic only in one eye. However, it’s not absolutely conclusive. First, there is no guarantee that the "normal" eye of a unilateral dichromatic is really normal. Second, studies often find that dichromatic color vision is much better than that predicted by theory. The best guess is that rods activate the red component red-green opponent process to give dichromats a weak three-dimensional color space.

What colors do the color blind confuse?

Anomalous trichromats are such a diverse group that they are difficult to characterize. Dichromatic confusions, on the other hand are more homogeneous and predictable.

A technical answer requires looking at cone activity. Recall that color is initially determined by the relative activity of the three cone classes. Protanopes, who are missing "red" cones, cannot distinguish lights which produce equal ratios of activity in the "green" and "blue" cones. Similarly, a deuteranope, who is missing "green" cones, cannot distinguish lights that produce identical activity ratio between the "red" and "blue" cones. Experts often plot these as "confusion lines" on a CIE diagram.

For a more qualitative understanding, look at the location of the protanoptic and deuteranopic neutral points located in at the edge of the green range. It should be clear that protanopes and deuteranopes will confuse reds-yellows-greens on the one hand and blues on the other. They have little ability to distinguish saturation except around the neutral point, so a deeply saturated blue and bluish white will appear similar in color.

On the other hand, they can generally discriminate differences between blue and yellow and blue and red. Besides this, dichromats use brightness to make most of their discriminations. Protanopes and deuteranopes, however, differ in the colors which they confuse and discriminate.

Likewise, tritanopes would have trouble discriminating hues located above or below their neutral points. Purples would also be difficult to discriminate since they differ in their blue content.

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