7th Framework Programme
ENV.2010.4.1.2-2
Integrating New Data Visualisation Approaches of Earth Systems into GEOSS Development

Project Nr: 265178

QUAlity aware VIsualisation for the Global Earth Observation system of systems

Deliverable D5.2
Visualisation of Quality Information Best Practice Report

Version 1.14

Due date of deliverable: 31/07/2012
Actual submission date: 06/08/2012

Document control page

Title		D5.2 Visualisation of Quality Information Best Practise Report		
Creator		Hansi Senaratne		
Editor		Hansi Senaratne, Daniel Nüst		
Description		Visualisation of Quality Information techniques and user preferences		
Publisher		GeoViQua Consortium		
Contributors		GeoViQua Partners		
Type		Text		
Format		MS-Word		
Language		EN-GB		
Creation date		17/01/2012		
Version number		1.14		
Version date		06/18/2012		
Last modified by		Daniel Nüst		
Rights		Copyright © 2012, GeoViQua Consortium		
Dissemination level	X	CO (confidential, only for members of the consortium)		
		PU (public)		
	X	PP (restricted to other programme participants)		
		RE (restricted to a group specified by the consortium)		
Nature	X	R (report)		
		P (prototype)		
		D (demonstrator)		
		O (other)		
Review status	X	Draft		*Where applicable:*
	X	WP leader accepted	X	Accepted by the PTB
		PMB quality controlled		Accepted by the PTB as public document
	X	Coordinator accepted		
Action requested		to be revised by all GeoViQua partners		
		for approval of the WP leader		
		for approval of the PMB		
		for approval of the Project Coordinator		
		for approval of the PTB		
Requested deadline		31/07/2012		

Revision history			
Version	Date	Modified by	Comments
0.1	17/01/2012	52N_HS	Initial Draft
6	13/07/2012	52N_DN	Second Draft
7	16/07/2012	52N_DN	Third Draft, circulated internally
8	30/07/2012	52N_DN	Included changes by FRAUN_ST, ASTON_VL, ASTON_JL
9	01/08/2012	52N_DN	Added missing scenario descriptions, executive summary, and conclusion. Version submitted to project coordinator.
9.01	01/08/2012	S&T_JS	Number of textual improvements, updating expert dataset intercomparison row in table in Section 3.2
10	02/08/2012	52N_DN	Integrating changes from S&T_JS and minor textual changes.
11	03/08/2012	52N_DN	Integrating changes from CEA_PE (edited table row for scenario, added visualisation method “colours and stippling”)
12	06/08/2012	CEA_PE	Changed figure 17’s description.
13	06/09_2012	52N_DN	Integrating changes by FRAUN_ST.

Institution	Contributors
52N_HS	52°North: Hansi Senaratne
52N_DN	52°North: Daniel Nüst
FRAUN_ST	Fraunhofer IGD: Simon Thum
ASTON_VL	Aston University: Victoria Lush
ASTON_JL	Aston University: Joanna Lumsden
S&T_JS	S&T: Joost Smeets
CEA_PE	Commissariat a l'Energie Atomique: Pascal Evano

Table of Contents

Executive Summary 6

1. Introduction 7

1.1 Scope of this Document and Relation to Other Deliverables 7

1.2 Data Quality in GeoViQua 7

1.3 Quality in Spatio-Temporal Data 7

1.4 Visualisation Methods 8

2. Quality Visualisation 11

2.1 State of the Art in Quality Visualisation 11

2.1.1 Coincident and Adjacent Visualisations 12
2.1.2 Classification of Visualisation methods 13

2.2 Review of Existing Visualisation Methods 14

2.2.1 Adjacent Maps 14
2.2.2 Animation 14
2.2.3 Hierarchical Spatial Data Structures 15
2.2.4 Colour schemes and colour legends 15
2.2.4.1 Colour legend construction schemes 16
2.2.5 Glyphs 18
2.2.6 Contouring 18
2.2.7 Focus Metaphors 19
2.2.8 Exceedance Probability Mapping 20
2.2.9 Statistical Dimension in a GIS 20
2.2.10 Error Bars and Intervals 21
2.2.11 Colours and Stripping for Model Comparison 21

2.3 Summary of Usability Studies 23

3. Visualisation Methods in GeoViQua 25

3.1 Iconic Visualisation: The GEO Label 25

3.2 Visualisation Methods for the GeoViQua Scenarios – a First Matching 26

3.2.1 GeoViQua Scenarios 26
3.2.2 Potential Visualisation Methods 27

4. Conclusion 30

5. References 31

Executive Summary

This document presents the current state of the art in quality visualisation. The review of existing best practices is based on the generic fundamentals of visualisation and data quality. The former is presented extensively in the introductory chapter of this document; the latter is merely described in short and left to other deliverables of the GeoViQua project. We discuss how the various definitions of spatio-temporal data quality have evolved over the years and review the evolvement of graphical variables and design principles, and how quality visualisation methods have been developed in compliance to these graphical variables and design principles.

The main chapter, Quality Visualisation, presents the state of the art in quality visualisation and contributes a review of existing visualisation methods. The existing usability studies for these methods are presented as well.

The final chapter makes a first connection of the quality visualisation methods to the use case scenarios of GeoViQua. The scenarios are shortly introduced and a table lists possible methods for each of them. A concise conclusion and collection of future work finishes this document. This report thereby lays the foundation for the application development with respect to the methods that are most suitable for the targeted platforms, users, and data.

1. Introduction

1.1 Scope of this Document and Relation to Other Deliverables

Visualisation of quality in spatio-temporal data is a complex procedure, due to reasons such as the heterogeneity of data, the spatial and temporal variation of data, different components of quality in data, and also the various abstract definitions of quality that is adapted to suit the context of data usage (Gerharz et al. 2012).

Together with the requirements collected in work package two (WP2), this document serves as a *guideline for the development of* original *visualisation methods* as well as the application of existing methods within GeoViQua. The document does not conduct a review of visualisations or software developed within the work packages four and five (WP4, WP5) of the project, though. The presentation of the prototypes and final components respectively is the subject of deliverables D4.2, D5.3 and D5.4.

This report further focusses on spatial visualisation, as the scenarios apply inherently spatio-temporal data, hence no investigation of information graphics, which come in a wide variety of plots, charts, diagrams, tables et cetera, were not taken into account, neither were textual methods for example side by side comparison.

The planned pieces of visualisation software will use data from several sources and of a variety of types, both structured and non-structured, as examined in work package three (WP3). This poses a great challenge to the tools and applied methods, which are eventually validated with real data and use cases within work package seven (WP7). A further dissemination of this work as a scientific publication is planned within work package eight (WP8).

1.2 Data Quality in GeoViQua

The definition of data quality for the matters of this report can be summarized as information which allows a user of spatio-temporal data to detect it’s fitness for a specific purpose or application. It can come in various forms, such as textual (metadata), meta-quality information (data about the metadata), and numerical quality information, which mostly is modelled as uncertainty. The latter is the focus of this report. Spatial visualisations typically require machine-readable and interpretable information, although glyphs present a counter example.

A more precise definition is out of scope for this report and is provided by other project deliverables as well as in the project wiki[1]. As with respect to modelling of data quality, this is also best covered in the deliverables of WP6.

1.3 Quality in Spatio-Temporal Data

Quality in spatio-temporal data is subject to scepticism for reasons such as erroneous measurements in GIS, modelling spatial objects with inherent uncertainties, low resolution etc. Many sources have derived definitions for spatial and temporal data quality in the last two decades, in apt to various purposes. Chrisman (1983) outlined its definition from the USA-SDTS (Spatial Data Transfer Standards) draft as the “*fitness for use for a given purpose*”. The USA-SDTS established the guidelines for spatial data quality elements in 1997 (USGS 1997, p.15).

[1] http://twiki.geoviqua.org/twiki/bin/view/Quality

ISO (2002) defines spatial data quality as "*totality of characteristics of a product that bear on its ability to satisfy stated and implied needs*". ISO/TC 211 (International Standardisation Organisation/ Technical Committee), extending the standards from its predecessor CEN/TC 287 (Commité Europeen du Normes), developed a set of international standards for quality of geographic information that defines the elements of spatial data quality. As a part of the standard 19115 (Metadata), standard 19113 defines the quality principles, and 19114 defines quality evaluation procedures. The standard 19138 defines quality measures for spatial data quality elements (ISO 2002; Kresse & Fadaie, 2004; van Oort, 2005). Within GeoViQua, we have complied with the definitions and specification for spatial data quality as defined by ISO/TC 211. The quality elements as defined by ISO/TC 211 are: *completeness*, *logical consistency*, and *accuracy*.

Completeness describes the relationship between the represented objects and their conceptualisations. This can be measured as the absence of data and presence of excess data. Errors resulting from the absence of data are called errors of omission and errors that are the results of excess data are called errors of commission. *Consistency* is the logical coherence in the data structures of the digital spatial data. The errors resulting from the lack of it are indicated by (i) conceptual consistency: compliant to the rules of the conceptual schema, (ii) domain consistency: conformance of values to the value domain, (iii) format consistency: degree to which the data is stored in accordance to the physical structure of the dataset, (iv) topological consistency: correctness of the explicitly encoded topological characteristics of a dataset. *Accuracy* refers to the degree of closeness between a measurement of a quantity and the accepted true value of that quantity, and it is in the form of positional accuracy, temporal accuracy and attribute accuracy. Positional accuracy is indicated by (i) absolute or external accuracy: closeness of reported coordinate values to values that are accepted as being true, (ii) relative or internal accuracy: closeness of the relative positions of features in a dataset to their respective relative positions accepted as being true, (iii) gridded data position accuracy: closeness of gridded data position values to values accepted as being true. Attribute accuracy is indicated by (i) classification correctness: comparison of the classes assigned to features or their attributes to a ground truth or reference dataset, (ii) non-quantitative attribute correctness: correctness of non-quantitative attributes, (iii) quantitative attribute accuracy: accuracy of quantitative attributes. In both cases, the discrepancies can be numerically estimated. Temporal accuracy is indicated by (i) accuracy of a time measurement: correctness of the temporal references of an item, (ii) temporal consistency: correctness of ordered events or sequences, (iii) temporal validity: validity of data with regard to time. (van Oort, 2005; ISO, 2002).

1.4 Visualisation Methods

Spatial data quality components can be communicated to the user through various visual variables. Bertin (1983) Introduced a framework for graphic systems through eight visual variables; *location (x, y)*, *size*, *value*, *colour (hue)*, *shape*, *orientation* and *texture*. For any location in the plane (x, y), the remaining six variables can be used to represent a given object. These variables, as reprinted by Krygier & Wood (2005) are presented in Figure 1. They show which of these graphical variables are most effective for showing qualitative or quantitative data.

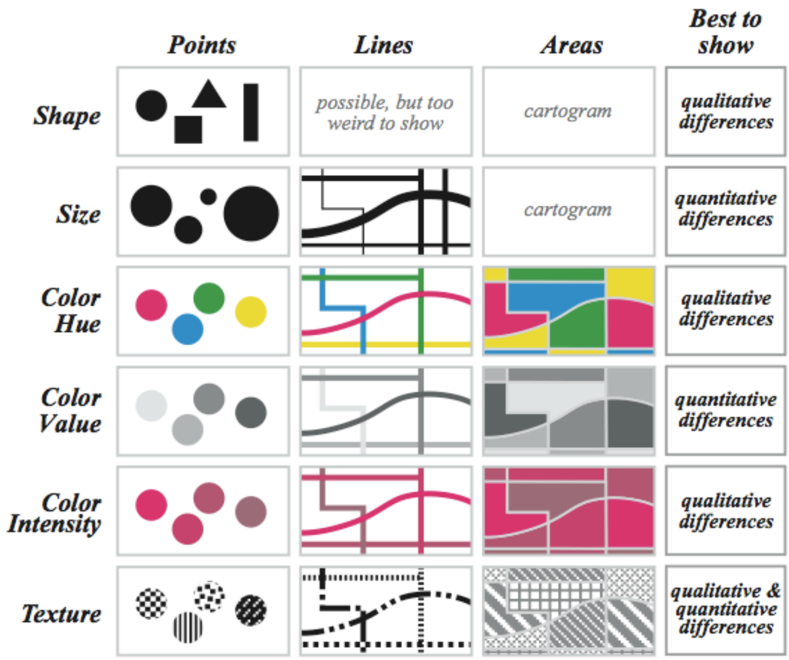


Figure 1. Bertin's graphical variables (Krygier & Wood, 2005)

There are many proposed changes or successors to Bertin's graphical variables, to cater for more variables available in non-print media or to ground Berin's work in other fields such as colour science or neuropsychology. One example is Green (1998), who notably adds "disparity" as a "retinal variable" (Bertin), i.e. stereo view depth as a perception to the model. He elaborates that depth might not be an independent "planar variable" (again Bertin), as could be assumed from the geometric point of view, but rather a quantitative retinal variable. This might be useful for designing unambiguous 3D quality visualizations, because in Bertin's model retinal variables are much more co-dependent than planar variables.

Tufte (2001) in his contributions to *graphical excellence* has provided six principles that can be followed in order to promote graphical integrity. These are; (i) graphics that represent numbers should be directly proportional to the quantities represented, (ii) clear and detailed text should be used wherever needed to avoid ambiguity, (iii) show data variation and not design variation, (iv) money in time series must be adjusted to inflation, (v) number of dimensions used to read data should not exceed the number of data dimensions that are being represented, (vi) do not show data out of context. Tufte further suggested that following these principles will overcome misinterpretation of representations of reality.

Agrawal et al (2011) presented a set of design principles for visual communication, in which they foremost described the importance of regarding human perception, cognition and communicative intent of visualisations in order to create meaningful designs. These principles were said to be used to either emphasize important information or de-emphasize irrelevant information. An early example of implementing these principles was the London underground map in 1933 by Harry Beck. In this he straightened the subway lines and spaced the stops evenly in order to meaningfully convey the sequence of stops to the viewer, such that they can cognitively perceive the underlying information. Thus, Agrawal et al. (2011) have developed a three stage approach for creating meaningful visualisation design systems. The first stage is to identify the *domain specific* design principles. Their aim is to create visualisations that cater to different information domains (e.g.

cartographic visualisation and technical illustrations) based on perception and cognition of these visualisations. The second stage is to implement these design principles by encoding them in to algorithms and interfaces, thereby creating the visualisation. The third stage involves the evaluation of these design principles by measuring their usefulness. This is achieved by getting qualitative user feedback, quantitative usage statistics and conducting formal usability studies. These procedures helped to assess how well the design principles serve the purposes of information processing, communication, decision making etc.

Ware (2004) as well, grounded his research on visual perception and comprehension in terms of physiological, perceptual and cognitive psychological theories. Following the *Gestalt Laws* (Koffka, 1935), Ware (2004) explained that properties such as proximity, similarity, continuity, symmetry, closure, connectedness and relative size substantially influence the perception of patterns, and that they can be used as basic design principles to create visualisations. Extending Tufte's graphical excellence principle of integrating text descriptions with a graphic, Ware (2004) further emphasised that text might prevail over images when it comes to presenting abstract ideas, logic, and conditional information.

Andrienko et al. (2008) discussed three approaches to analytical and exploratory visualisation. These were: (i) direct depiction: user identifies the patterns of measured phenomena through interacting with the visualisation that *directly depict* the measurements recorded in their data, (ii) summarisation: user identifies the patterns of measured phenomena through visualisations of data *summaries* that are computed from the original data measurements, (iii) pattern extraction: the computer identifies data *patterns* or summaries and represent these visually to be interpreted by the user.

Cartography has been a root in scientific visualisation which has now evolved and branched out in too many disciplines including spatial decision support and virtual reality environments. MacEachren & Kraak (1997) defined scientific visualisation as "the use of sophisticated computing technology to create visual displays" with an aim to assist the users in (spatial) thinking and problem solving through *knowledge construction*. The typical element of scientific visualisation, with regard to spatial information processing were said to be "spatial analysis" and "spatial simulation" according to Rimbert (1993). (MacEachren and Kraak, 1997)

These theories were adopted and modified in various application scenarios to depict the quality of spatio-temporal data through different visual variables. An excerpt on its application is rendered in Chapter 2. Beard et al. (1994) discussed that visualisation should primarily accomplish detection, notice, identification and quantification of spatial data quality, taking in to account also legal and psychological connotations of these terms. Further, emphasised the advantages of *visualising* spatial data quality as, speed of pattern recognition, motion detection, change detection, seeing the intangible (e.g. remote sensed data, molecular structures) etc. They also discussed that visualising *meta data* surpass the barriers of language, reduce cultural bias, and recover hidden structure in the pattern of data quality.

2. Quality Visualisation

2.1 State of the Art in Quality Visualisation

Quality visualisation aims at presenting the various components of quality in data in a visual context. Many visualisation methods, which vary from static and dynamic to interactive in nature, have been developed over the past couple of decades in various spatio-temporal settings, to communicate these components of quality. This chapter, first in 2.1 discusses the state of the art in quality visualisation and how these have evolved from basic static maps to today's more sophisticated tools. Chapter 2.2 reviews a number of well-established visualisation methods that are used today to convey one or more of the quality components. Following this, Chapter 2.3 takes a look in to several usability studies that have been conducted on some of the reviewed quality visualisation methods.

Various visual variables as discussed in Chapter 1.2 have been applied in the science of Geospatial analysis. According to MacEachren (1995), vision can be considered as an information processing system, and graphics to that matter is the main *language* applicable to this information processing. Hence, with this notion, information can be considered as the content and the graphics can be considered the container of the subjected content (Bertin 1983). Furthermore, Marr (1982) expressed *vision* as the "process of discovering from images what is present in the world, and where it is". This practise has been immensely attributed in the field of spatial decision support, information derivation etc.

Jaques Bertin, the French cartographer/graphic theorist influenced many in the field of cartographic symbolisation. Amongst many early discussions on quality visualisation, MacEachren (1992), Beard & Buttenfield (1991), Fisher (1994), van der Wel et al. (1994), MacEachren (1995) etc., were prominent in grounding the visualisation of quality concepts. Buttenfield & Weibel (1988) was among the first to present a framework for categorising the different components of data quality with a focus on how they can be cartographically presented with respect to the measurement scale of the data (Figure2.). Their approach focused on the five categories of data quality and three types of data; categorical (area features represented by categories or attributes represented by classes), discrete (point and line features), and continuous (surfaces and volume). The resulting matrix helps one to realise which visual variables are most appropriate to be used in representing a respective category. Buttenfield & Beard (1994) extended this framework by including also location, attribute, time and resolution components.

Data Type / Data Quality	Positional Accuracy	Attribute Accuracy	Logical Consistency	Completeness	Lineage
Discrete Points and Lines	Size Shape (Error ellipses) (Epsilon bands)	Value Color Saturation (Feature code checks)	Color mixing Redundancy by overprinting Slivers by solid fills (Topological cleaning)	Mapping Technique Density traces Marginalia Generalization algorithm Mapping tolerance Buffer size	Mapping Technique Minimum Bounding Rectangles
Categorical Aggregation & Overlay (Tesselation, tiling, Areal coverages)	Texture Value (Certainty of boundary location)	Color mixing (Attribute code checks) (Topographic classifier)	lack error models	Mapping Technique Missing values Logical adjacency surface Marginalia Discrete model weights	
Partitioning & Enumeration (Metric class breaks)	not meaningful	Size = height (Blanket of error)	Size = height (Maximum likelihood prism maps)	Mapping Technique Missing values Missclassification matrix Classing scheme OAL/TAI	Marginalia Source of data Scale/Resolution Date Geometry
Continuous Interpolation (Surfaces and volumes)	no clear distinction b/w the two Value Color Saturation (Continuous tone vignettes) (Continuous tone isopleths)		Size = line wt Color Shape = compactness (TIN links)	not possible by definition Mapping Technique Surface of search attenuation Marginalia Interpolation algorithm	
← Graphical Syntax →				← Graphical/Lexical Syntax →	

Figure 2 Buttenfield & Weibel's (1988) framework for categorising quality components with a focus on cartographic representation methods and different measurements scales

MacEachren (1992) took a slightly modified approach from Bertin (1983) and applied colour saturation to depict the spatial uncertainty of data, pure hues representing less uncertain information and unsaturated (grey) hues representing high uncertainty information. He introduced another variable, focus, in addition to Bertin's. Higher uncertainty can be depicted out of focus and lower uncertainties in focus. Further extending the variable "focus", MacEachren (1992) manipulated it in to four metaphors; (i) Contour crispness - varying the crispness or fuzziness of the edges of the symbols used (Figure 3.), (ii) Fill clarity – manipulating fill clarity to depict high and low uncertainty (Figure 4.), (iii) Fog – using transparency to depict uncertainty (Figure 5.), (iv) Resolution – adjusting the resolution of geographic detail to convey varying uncertainty (Figure 6.).

2.1.1 Coincident and Adjacent Visualisations

MacEachren et al. (1998) further asserted that importance should not only be given to the visual syntactics with which quality measures are matched with visual variables, but also to the way data and data quality are linked and represented. The basic representations were proposed to be (i) coincident, where data and metadata depicted coincide on one map, and (ii) adjacent, where data and its quality are depicted adjacent to each other on two maps. The coincident method was further classified in to two based on the forms of representation. These are *visually separable* components and *visually integral components*. The visually separable form is where the user has the option of ignoring one layer of data while focusing on another. E.g. is the toggling method, where data and data quality are presented on two layers with the capability to toggle between the two layers. The visually integral form is where the user can view the data and data quality as one unit. E.g. is the use of a colour scheme to represent the data and its quality through varying saturations. Different methods belonging to these three forms are further discussed in Chapter 2.2.

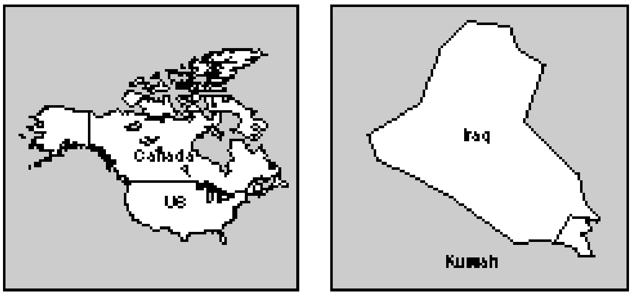


Figure 3 MacEachren (1992) showing the focus metaphor of contour crispness. Us - Canada are showing more certain borders as compared to Iraqui- Kuwait border

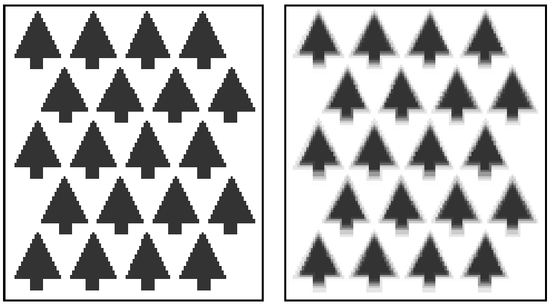


Figure 4 MacEachren (1992) showing the focus metaphor of fill clarity through certain and uncertain version of a land cover type

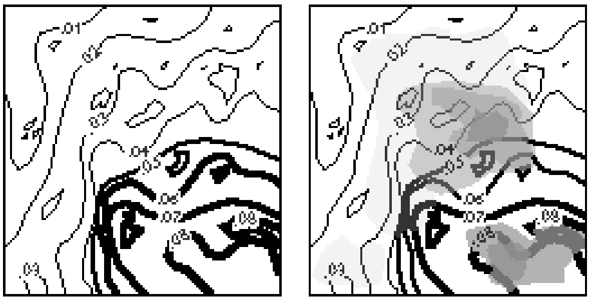


Figure 5 MacEachren (1992) showing on the left ecological risk areas due to Ozone and on the right the focus metaphor of fog with varying thickness to represent varying levels of uncertainty

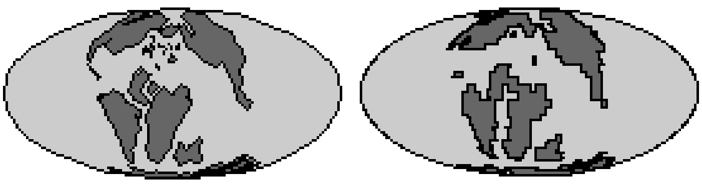


Figure 6 MacEachren (1992) showing the focus metaphor of resolution to represent the uncertainty in mid-cretaceous ocean flows

2.1.2 Classification of Visualisation methods

Pang et al. (1997) emphasised the importance of classifying visualisation methods in order for users to select appropriate methods for a given visualisation task. Many have also contributed to the classification of visualisation methods according to various parameters. Carswell (1992) and Cleveland & McGill (1985) said fundamental parameters such as length, area, ratios etc., describe and determine effectiveness of visualisation. Hesselink et al. (1994) classified existing visualisation techniques according to the order of data (scalar, vector or tensor), and domain (point, surface or volume). Brodlie et al (1992) classified visualisation methods according to dimensionality of entity being visualised. Extending from these previous work Pang et al. (1997) classified the visualisation techniques in respect to the value (scalar, vector or multivariate), the dimensionality (1D, 2D, 3D and time as another dimension), data extent (continuous and discrete) and visualisation extent (surface, volume, point etc.). Furthermore, Senaratne & Gerharz (2011) classified a number of selected uncertainty visualisation techniques according to the data extent (continuous, categorical), data format (raster, vector) and uncertainty type (positional, attribute). Andrienko et al. (2010) emphasised on the visual analytics for temporal dimension of data. They described a categorisation of visual methods according to the time characteristics that these methods were developed for. These are: (i) linear time versus cyclic time, (ii) time points versus time intervals, and (iii) ordered time versus branching time versus time with multiple perspectives.

2.2 Review of Existing Visualisation Methods

Following is a review of some of the well-established visualisation methods that have been developed over the years to visualise various components of data quality. Senaratne et al. (2011) reviewed and categorised selected visualisation methods based on several parameters (data type, uncertainty type etc.). We utilised these resources to reassess these visualisation methods within the requirements of GeoViQua.

2.2.1 Adjacent Maps

This method presents data and data uncertainty on two separate maps adjacent to each other. Through comparing the two maps, the degree of uncertainty at different points can be comprehended. A colour scheme can be used to represent the data and the saturation variations can be used to represent uncertainty (MacEachren et al. 1998). As seen in figure 7, the left side map shows the high and low concentration of PM10 with dark and light variations of red. On the right side map, high and low uncertainties of PM10 are shown through dark and light variations of the colour blue.

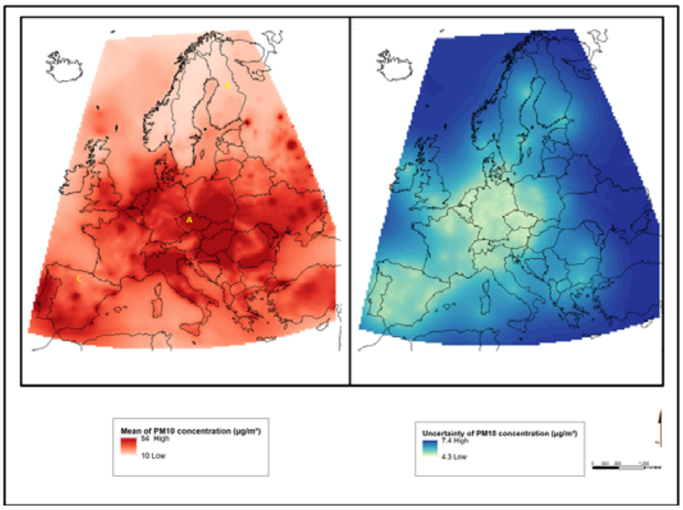


Figure 7. Adjacent Maps. Colour saturation is used to convey high/low PM10 values and high/low attribute uncertaintiesof PM10 (Image from Senaratne et al. 2012)

2.2.2 Animation

Animation is a presentation technique which can be used for different methods, and is the integral part of three visualisation methods. The first is an *Animation* of different realisations of the uncertain attribute in 2D to emphasise the uncertainty (Ehlschlaeger et al. 1997). In the second method called *Blinking Regions*, the two layers of attribute data and uncertainty data, are identified by their legends of varying classes of data and uncertainty respectively. These two images are overlaid on top of one another and alternately displayed (Kardos et al. 2006). In the third method, *Blinking Pixels*, the categorical data in each grid cell of a map is represented by colour. The colour remains stable for pixels with less uncertain classifications and changes continuously proportional to the uncertainty in the data creating a flickering environment (Fisher 1993).

2.2.3 Hierarchical Spatial Data Structures

Hierarchical data structures (Quadtrees) are used as a transparent tessellated layer on top of the data to represent the amount of associated uncertainty following the level of detail metaphor (Kardos et al. 2003). An example is presented in Figure 8 in which, finer tessellations represent lower uncertainty and coarser tessellations represent higher uncertainties (Kardos et al. 2004).

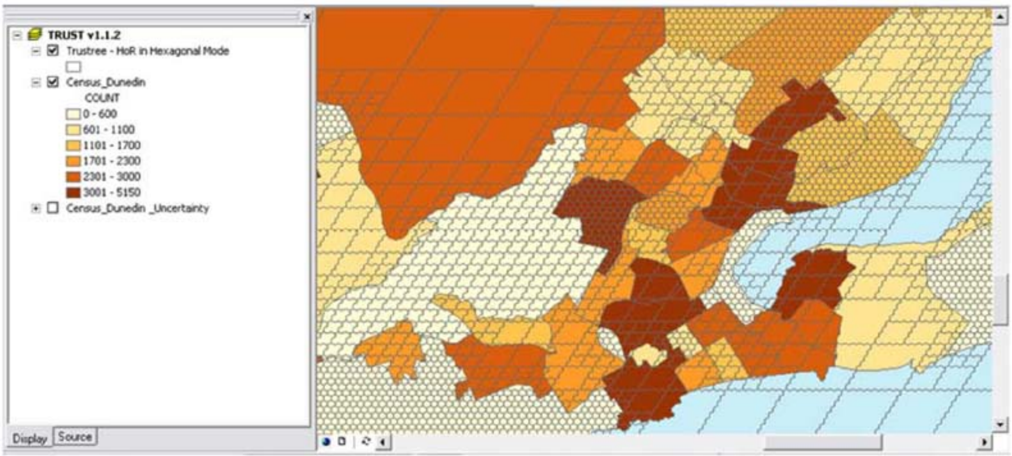


Figure 8. Hierarchical spatial data structures. Coarser tesselations represent higher uncertainty attribute uncertainty and finer tesselations represent lower attribute uncertainties (Image from Kardos et al. 2004).

2.2.4 Colour schemes and colour legends

Colour legends are well established in the geo sciences to display nominal, ordinal and quantitative distributions or data points. Colour discrimination is a relatively easy process for most humans and inclusion of ambient knowledge about landscape colours can greatly enhance the intuitive usability of a map product. For combined display of a value and its quality in a colour scheme (here: shorthand for a colour legend construction method), however, additional requirements become important.

About the evaluation of colour legend construction

In such a bivariate value-quality scenario, Tufte’s “do no harm” principle implies that colours should be calculated so the perceived distance in colour appearance matches the distance in value and quality (perceptually uniform/proportional). This requires the use of sophisticated colour models such as CIECAM02 (CIE 159:2004 - ISBN 978 3 901906 29 9) or one of its (inferior) predecessors. Without such a model, proportionality can only be achieved in the numerical, but not the visual colour representation. This is not to say it does not work – it just works less efficiently than it could, because it does not have the desirable property of perceptual uniformity (Stone, 2004).).

Moreover, perceptual uniform colour spaces are quite odd in shape – as odd as the human visual system one might say – but information visualisation requires an easily addressable space. This is readily available for device-dependent colour spaces such as RGB (sRGB), but those make the algorithm depend on device characteristics – it will be hard e.g. to apply an RGB-based "on-screen" algorithm to printed maps. The general solution is to use appropriate sub-spaces determined by intersecting the desired device and information spaces.

None of the publications reviewed here makes believable efforts to ensure visual proportionality or another of the aforementioned concerns. Since the claim of proportionality is made by some, this should be taken with a grain of salt. Similarly, a procedure sounding as simple as "mixing two colours" to obtain intermediates can be carried out in two well-defined ways: Using a perceptual colour model, or aligning to natural light mixing. Any ad-hoc way of mixing colours numerically, such as "whitening", is very likely not well-defined as device-specific non-linearities influence the results. More on this see Poynton, 1998

Thus the performance of techniques not performed in a well-defined colour space will be portrayed differently here than you might read in the papers. The results are considered accurate enough to validate the approaches, but not their performance.

2.2.4.1 Colour legend construction schemes

In the first method presented by Hengl et al. 2002 an *HSI colour scheme* is used. HSI is a transform of RGB approximating hue, saturation and intensity that has various definitions, one of which is chosen by Hengl et al. The scheme maps uncertainty to the saturation and intensity channels and uses hue to display the corresponding scale, leaving out some hues to avoid similarity in high and low values (Hengl et al. 2002; MacEachren et al. 2005). In the second scheme, Colourwheel, is used where the colour hue is used to represent a continuous taxonomic (ordinal) space and the saturation-intensity (whiteness) is used to represent the associated uncertainty. A setup for continuous predicted variables is also discussed where the amount of white colour, numerically proportional (see above) to the uncertainty, is mixed in with the hue which represents the prediction [i.e. base value] (Hengl 2003). A similar result is obtained by the technique of pixel mixing in which uncertainty is represented by adding amounts of white pixels proportional to the normalised prediction error (Hengl & Toomanian 2006). This technique is nearly equivalent except that mixing pixels, unlike HSI, implies natural light mixing and is thus well-defined. An example is presented in Figure 9 where, the data is represented by the colour hue and uncertainty is represented by the intensity of colour (whiteness).

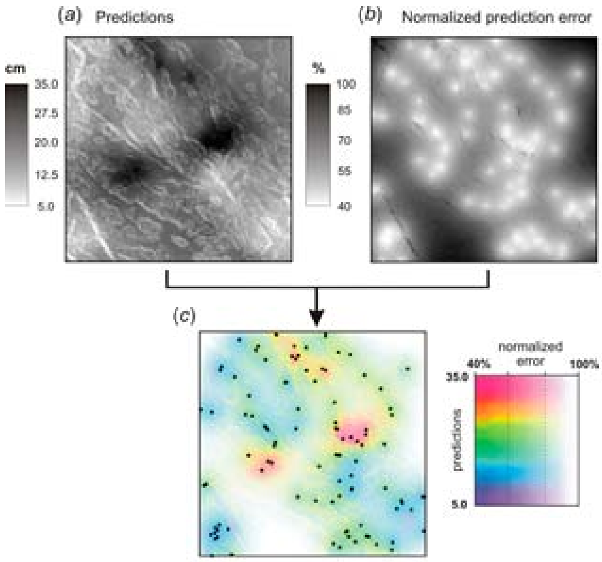


Figure 9. Whitening. Colour hue reperesents top soil thickness data and the saturated intensity represents the uncertainty of top soil thickness (Image from Hengl & Toomanian, 2006).

In a paper by Teuling et al. (J. Teuling, R. Stöckli, und S. I. Seneviratne, „Bivariate colour maps for visualizing climate data“, *International Journal of Climatology*, Bd. 31, Nr. 9, S. 1408–1412, 2011.) another approach is presented. Based on ad-hoc values-to-RGB transforms Teuling et al. make interesting use of psychological properties of colour. Again they use a bivariate colour legend which features co-called “warm” and “cold” colours to represent temperature. The other axis, also mainly differing in hue, represents humidity but that could be substituted for uncertainty in other contexts. As they concede, a perceptual colour model could improve their results, but also using independent visual channels (i.e. not just hue) could likely do so. Is an example for Teuling’s method[2].

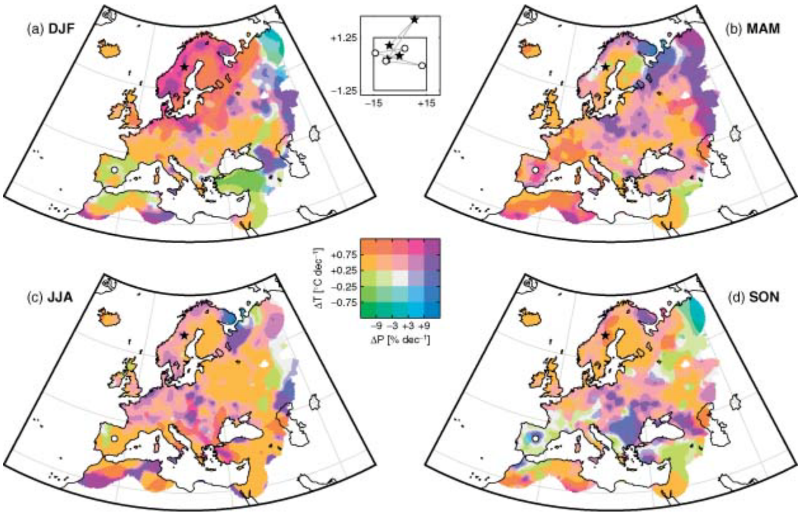


Figure 10. “Recent trends in Europe's climate as diagnosed by observed temperature (T) and precipitation (P) over the 30-year period 1979–2008. [...]Colours along the southern and eastern boundaries might be affected by interpolation.” (Teuling et al., 2011)
Precipitation varies from green to blue and orange to purple (horizontal axis in the centered color legend), temperature varies from green to orange and blug to purple, respectivily depending on the other variables value.

[2] Request for permission to reproduce is pending, please contact author before ciculating this report out of the consortium.

2.2.5 Glyphs

This method represents uncertainty and data in an integral depiction through pictorial symbols, known as Glyphs. For example, Pang (2001) demonstrated this in a use case where angular uncertainty such as for wind direction needs to be depicted in vector fields, Glyphs in the form of arrow plots were utilised. The width of the arrow head represents the angular uncertainty and the magnitude of the vector field is depicted through the length of the arrow plot (Pang 2001; Cliburn et al. 2002) Glyphs are also referred to as *Symbols* (Figure 10.).

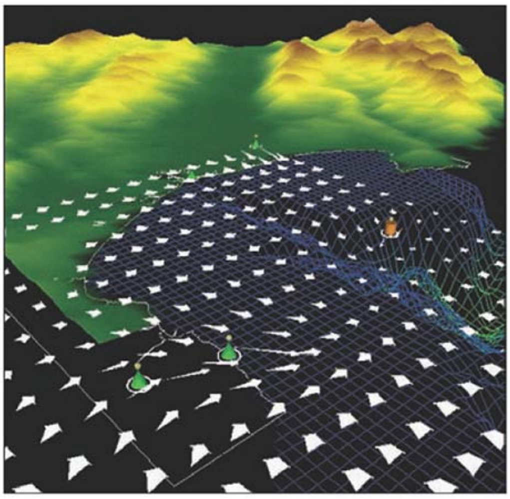


Figure 11. Glyphs. Wind velocity data is depicted through the length of the arrow plot and its angular uncertainty through width of the arrow head. These pictorial symbols are known as glyphs (Image taken from Pang, 2001).

Glyphs can be used to portray several dimensions by varying the glyph in specific ways. This technique is elaborated in Lie, 2009 and is also evaluated in a 3D, though not a mapping, context. Although it is often easy to overload a scene with glyphs, the individual characteristics of a glyph remain discernible. This makes glyphs a feasible option for multivariate mapping environments.

2.2.6 Contouring

This method is used to visualise uncertainty through contour lines. In a multivariate mapping environment, contour lines of different colours are used to distinguish between different variables and their uncertainties with the intensity of colour. Similarly, contours of varying thicknesses are used to represent uncertainty in an integral depiction where the thickness is proportional to the uncertainty (Figure 11.). Likewise, positional uncertainty can be depicted through gap widths in the dots of dotted contour lines where higher uncertainty leads to wider gaps (Dutton 1992; Osorio & Brodlie 2008). The concept of contouring or isolines can also be used in an animated environment. This approach is named, *Animated Isolines*[3] (Fauerbach et al. 1996).

[3] http://www.geovista.psu.edu/sites/icavis/icavis/febm/sdhbivar.html

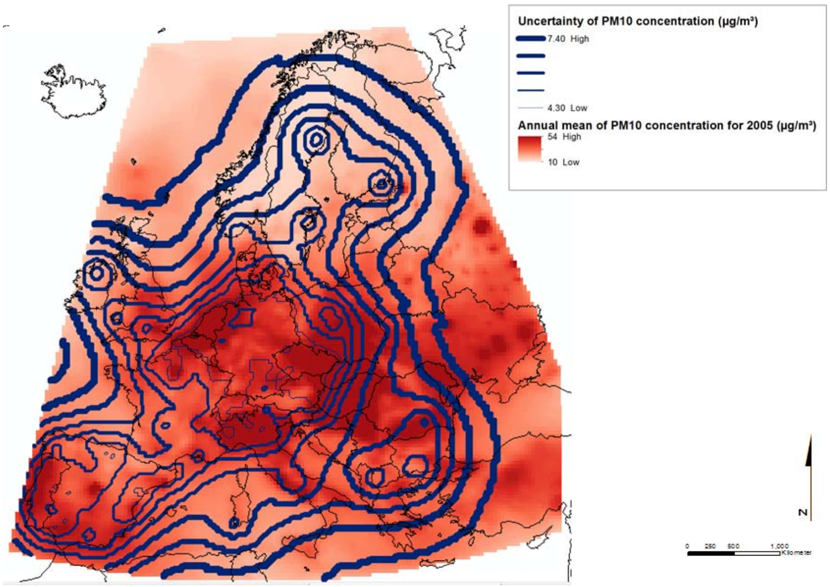
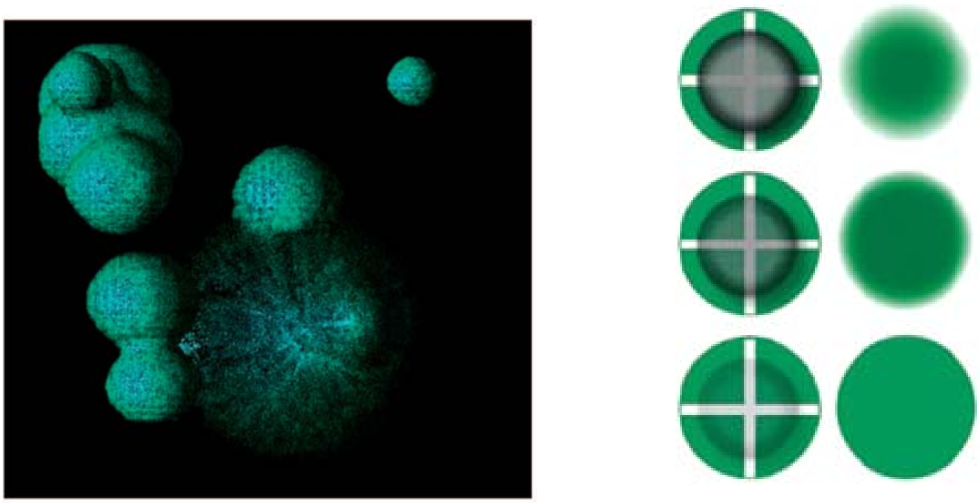


Figure 12. Contouring. PM10 concentration data is shown in the background with darker variations of red corresponding to higher concentration and lighter variations corresponding to lower concentration. The attribute uncertainty of PM10 concentration is shown in the foreground with thickening contour lines. Thicker contours corresponds to higher uncertainty and thinner contours to lower uncertainty in PM10 concentration (Image taken from Senaratne et al. 2012).

2.2.7 Focus Metaphors

The focus metaphor is based on the human perception of focussed and non-focused (blurred) views. Uncertain data is depicted out of focus, making it less precisely visible, e.g. foggy. More certain data is depicted in focus, e.g. crisp boundaries. Another metaphor of the Focus method is the *Opacity* method where less uncertain data is seen less opaque and more uncertain data is more opaque (MacEachren et al. 2005; Prassni et al. 2010). This concept can also be used in reverse where uncertain data is shown more transparently (Drecki 2002). An example in Figure 12 a) represents the spread of a brain tumour modelled by point opacity modulation. More opaque regions show lower uncertainty and less opaque regions (more transparent) shows higher uncertainty (Grigoryan & Rheingans 2004).



a) b)

Figure 13. Focus metaphors. a) the uncertainty of the spread of a brain tumor is represented by transparency. higher transparency conforming to higher uncertainty. b) The same concept is used to show uncertainty through transparency and edge crispness (Image a) taken from Grigoryan & Rheingans, 2004; image b) taken from MacEachren et al. 2005).

2.2.8 Exceedance Probability Mapping

Exceedance probability is used to depict the probability of exceeding a threshold in a certain pixel or area. This method is commonly used for environmental concentration maps where the exceedance of concentration thresholds are mapped (Van de Kassteele & Velders 2006). A similar concept is giving confidence intervals. An example for this method is shown in Figure 14. Exceedance probability of NO2 beyond a threshold.. In this figure, the exceedance probability of NO2 beyond the threshold of 40 μg/m³ near Rotterdam is presented. The IPCC (Intergovernmental Panel on Climate Change) terminology is utilised to communicate these probabilities (Van de Kassteele & Velders 2006).

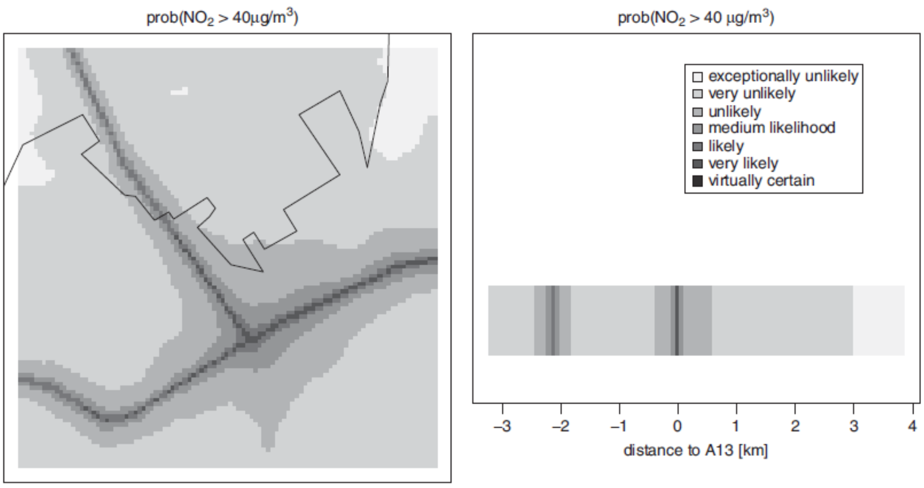


Figure 14. Exceedance probability of NO2 beyond a threshold.

2.2.9 Statistical Dimension in a GIS

The uncertainty of the data is represented by the cumulative probability functions for each pixel or vector object. Depending on the chosen quantile or threshold value, the map colour scale shows the associated value or probability (Pebesma et al. 2007). PDF graphs can also be generated for the exceedance probability of threshold values. By analysing these, associated uncertainties can be concluded. The *Aguila* tool is an implementation of this method.

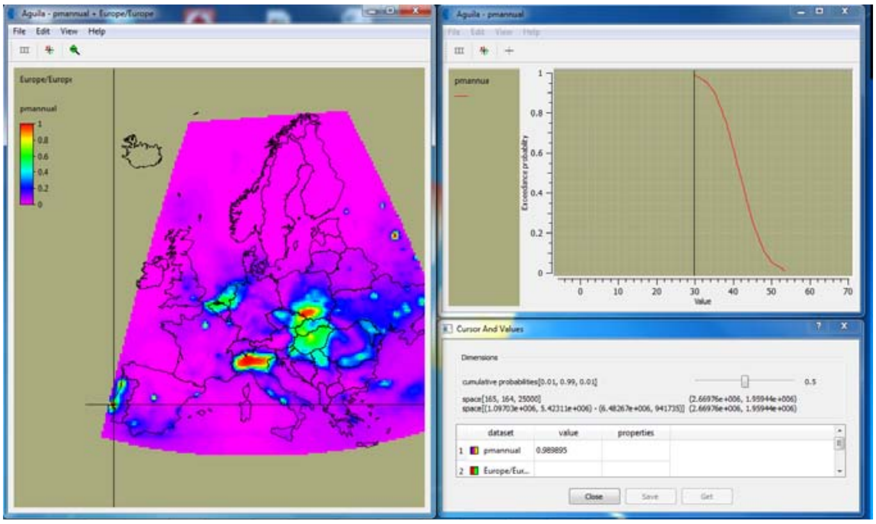


Figure 15. A screenshot of the software Aguila for interactive visualisation of uncertain spatio-temporal data (Pebesma et al., 2007)

2.2.10 Error Bars and Intervals

Error bars and intervals are a means to indicate uncertainties of data represented in charts and graphs, in proportion to the confidence intervals taken in to consideration. In the case of error bars, for each data value, the propagated uncertainty is represented through the length of the error bar. Further, in the case of intervals, for each data value, the propagated uncertainty is depicted through the width of the interval (Olston & Mackinlay 2002). An example for such a visualisation was developed in the UncertWeb project[4], which also integrates an interactive map (UncertWeb Deliverable 3.3, 2011).

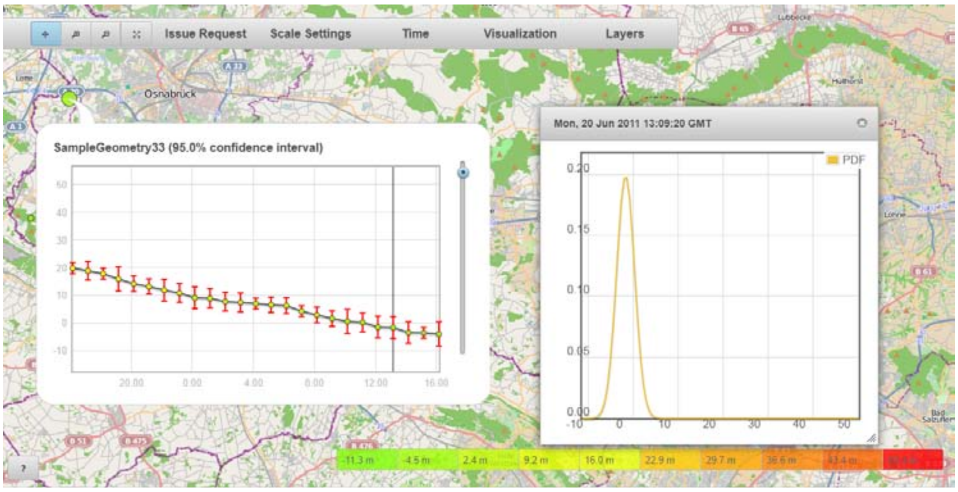


Figure 16. Screenshot of the web client for uncertainty visualisation from the UncertWeb project.

2.2.11 Colours and Stripping for Model Comparison

Tebaldi (Tebaldi et al. 2011) proposes a way to visualize uncertainty applied to comparison of climate models. It is based on the Summary for Policy Makers 7 (SPM7) of the IPCC[5] but introduces some changes.

Besides the information about the spread across models compared to the multi models mean response, this method gives information about the number of models agreeing on the sign of change. Furthermore the idea is that it is important to take into account the variability of each model (noise, internal uncertainty, or internal variability (IV)). Concretely, if two models give different results but the difference between models is inferior to the IV, one can't conclude that there is a really disagreement. A disagreement between models is only true in cases where there is a disagreement in the sign (above and below the mean).

> *The method thus uses the following steps, grid point by grid point: 1) Test for significant change in each of the models individually with a t-test comparing the mean of the reference and the future period, 2a) if less than X = 50% of the models show a significant change then show the multimodel mean change in color, 2b) if more than 50% of the models show significant change then test for agreement in sign by the following criteria, 3a) if less than Y = 80% of the significant models agree on the sign then show the grid point as white, 3b) if more than 80% agree on the sign show it in color with stippling. The*

[4] http://www.uncertweb.org
[5] http://www.ipcc.ch/

X and Y percentages are of course a subjective choice. They could be chosen differently depending on the desired level of confidence.

(Tebaldi et al. 2011)

An example of such visualization is shown in Figure 17.

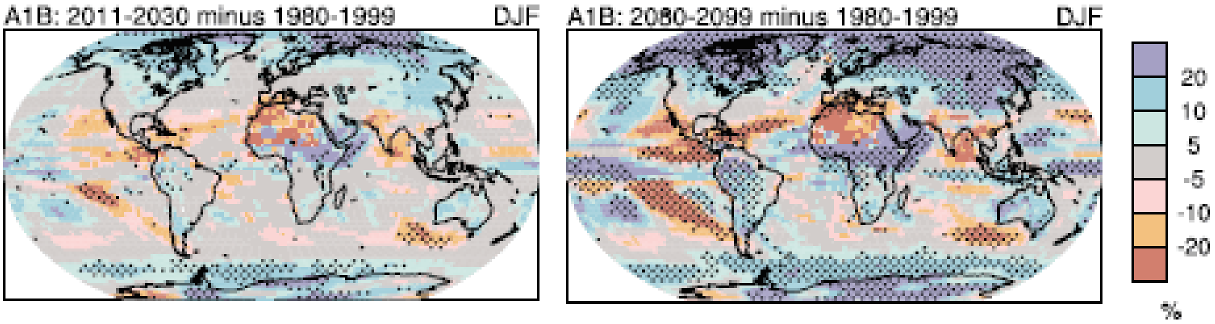


Figure 17. (left) Early (2020) and (right) late (2090) century projections of December to February precipitation change from eight initial condition ensemble members of the NCAR, CCSM3, for the method used by Tebaldi et al. 2011.

2.3 Summary of Usability Studies

Since the early 1990s, several researchers have conducted usability tests on selected spatio-temporal uncertainty visualisation methods. Over the years these usability tests were carried out in numerous styles giving importance to one or more components of usability, achieving interesting and influential results. In the following, summaries of some distinctive usability tests on uncertainty visualisation methods are presented.

Evans (1997) executed a usability test on the two uncertainty visualisation methods, Static Colour Bivariate Maps, where data and uncertainty were both depicted in one representation, and Flickering Animation method where the speed of flickering was directly proportional to the amount of uncertainty involved. The third method that was assessed was the Toggling method where data and uncertainty are represented on two layers and these layers are toggled between each other to analyse data and uncertainty one after the other. Data and uncertainty for all these methods were in raster format. The test comprised of questionnaires and user tests on 66 participants. The visualisation methods were assessed on the basis of novice and expert users and on gender wise performances. The responses between novice users and expert users were not significantly different. Overall, the use of composite Static method and Flickering Animation method were both found to be comprehensible and useful by users. However, it was apparent that the interactive Toggling method was not as efficient as the other two methods, thus least preferred by the users.

MacEachren et al. (1998) carried out a usability test on 84 participants, in the form of a questionnaire to acquire the background information of the participants and to pose questions to the related tasks. All the participants were from a geography background. These participants were categorised into several groups to ensure the use of different order of methods. The assessed uncertainty visualisation methods were the Adjacent Maps method and two composite methods where data and uncertainty were presented intrinsically. The first composite method was a *Coincident Visually Separable* rendering where data was represented through a colour fill and the uncertainty was represented by an overlay of texture. The second was a *Coincident Visually Integral* depiction where data and uncertainty both were represented through different colour characteristics. The outcome from this study was that participants preferred the Coincident Visually Separable method over the rest, and the reasons being the flexibility and easiness to analyse data and uncertainty separately by disregarding the textual overlay when needed, thus was said to be most useful for exploratory causes. The visually integral composite method was found rather useful for presentation uses.

Cliburn et al. (2002) assessed the usability of three uncertainty visualisation methods, which are the use of Colour Model Transparency as a focus metaphor and the use of Glyphs. This usability test comprised of informal interviews and the participants were categorised as domain experts, usability experts and decision makers. Users with scientific backgrounds preferred the use of Glyphs as it supposedly accounts to depict more information whereas the users with less experience in sciences preferred the Colour Models using an RGB (RedGreenBlue) scheme as it gave them a better impression at a first look without much complexities. In future climate prediction, the visibility scheme (Transparency) was preferred by decision makers as it was said to have given them a quick impression of the depiction without having to spend more time on reading the more informative Glyphs, which was in contrary to the users with scientific background who chose the Glyphs.

Aerts et al. (2003) conducted a web-based survey in the form of a questionnaire to qualitatively assess the Adjacent Maps method and the Animated Toggling method. 66 participants took part in the survey with equal number of expert users and novice users. The survey was divided into two separate websites in which each carried out the assessment for one particular uncertainty visualisation method. Each method was presented in a single colour scheme and a bi-colour scheme. The participants were divided into two groups, each consisting of expert and novice participants. The study was based on the two visualisations and 8 questions pertaining to these visualisations. According to the results of this assessment, 60% of the expert users preferred the static Adjacent Maps method while 40% preferred the Toggling method. 83% of the novice users preferred the static Adjacent Maps method and 17% preferred the Toggling method. Overall, the static Adjacent Maps method was favoured slightly over the Toggling method. Most users commented the Toggling method to be annoying due to its periodical change of data layers. As of the comparison between the two different colour schemes, a little more than 60% of the static Adjacent Maps group preferred the single-colour scheme and participants who evaluated the Toggling method equally preferred single-colour and bi-colour schemes. The responses were analysed using a Chi-square test.

Kardos et al. (2006) assessed 9 uncertainty visualisation methods on a web-based survey. 34 participants took part in this survey and all of these participants had some sort of understanding in GIS. The methods that were selected for this assessment were Adjacent Maps (Chapter 2.2.1), Texture Overlay, Image Sharpness, Fog Overlay, Pixel Mixture (a Colour Model), Colour Saturation, Sound, Blinking Areas and Animated Flickering. All these methods were thus assessed on the basis of visual appeal, speed of comprehension and overall effectiveness. The results from the survey enlightened that users performed better in the Blinking Regions method compared to Pixel Mixture, Image Sharpness, and Animation methods, in terms of speed of comprehension and overall effectiveness. However, these methods were quite undesired by the users when it came to visual appeal. For example, some users were irritated by the flickering display.

Gerharz & Pebesma (2009) assessed the usability of Adjacent Maps, Whitening and Aguila (a tool that introduces a statistical dimension to GIS). The usability assessment took place as a small pilot study with 10 participants at different user levels. The users were personally interviewed and asked to perform certain tasks on these methods. The concluding results showed that the method Whitening was hard to interpret quantitatively, Adjacent Maps method was preferred by all users and Aguila method (see also Figure 15) was commented to be more suitable as an expert too.

A more recent usability assessment was performed by Senaratne et al. (2012), on the visualisation methods, Adjacent Maps, Contouring, Glyphs (symbols), Aguila, and Error bars & Intervals. The aim of this study was to clarify which methods were the most suitable to be used by each of the user domains; GIS, map visualisation, statistics, decision support and urban planning. Through a measurement of correspondence between performance and preference the concluding results showed that most suitable visualisation methods were Contouring and Adjacent maps within all domains and Adjacent Maps for user who did not belong to any of these domains.

3. Visualisation Methods in GeoViQua

3.1 Iconic Visualisation: The GEO Label

Development of a GEO Label is part of the GeoViQua Task 5.1. The task's goal is to design, prototype and evaluate an iconic "label" which can assist users in assessing and comparing the quality of geospatial datasets in terms of their fitness for use for a given purpose. GeoViQua's GEO label will aim to convey both quantitative and qualitative (or objective and subjective) information about a given dataset; this information will be drawn directly from the data within the set, its metadata, and from community-based feedback The development of the proposed GEO label is drawing heavily from accepted methods of trust and assurance communication in the realm of e-Commerce.

The GEO label is actively being developed within the GeoViQua project at the time of writing this report. The staged research and development process for the GEO label involves extensive user studies; to date, in-depth user interviews to elicit user opinion and requirements as well as a comprehensive survey of user attitudes towards related concepts from e-Commerce and the proposed function of a GEO label have been completed. On the basis of these data collection activities, prototype GEO labels have been developed and user opinion will again be elicited to determine preference and suitability of the various prototypes for future development. GeoViQua's goal is to deliver a practical, working GEO label which will be of immediate benefit and use to the GEO community. The final concept will be presented in deliverable 6.2 and is out of scope of this work.

In essence, the GEO label proposed by GeoViQua will serve as a high-level decision support tool; it will support active comparison of datasets to allow dataset users to make informed dataset selections relative to specific contexts of use. An iconic quality representation which aggregates, simplifies, and allows interrogation of dataset quality information at a level which is easily comprehended by the increasing spectrum of GEO dataset users is an excellent supplement to the methods described in this report.

3.2 Visualisation Methods for the GeoViQua Scenarios – a First Matching

The GeoViQua project started with a set of pilot case studies (PCs) which were intended to apply the methods developed in work packages two, three and six to data and application scenarios from the GEOSS user community. However, after further refinement of the available resources and a re-focus of the applications which are to be validated in the PCs, a new set of scenarios was agreed upon to replace the pilot case studies. Since these scenarios are the new road of development, we will shortly present potential visualisation methods for each of the scenarios in the following sections.

3.2.1 GeoViQua Scenarios

The *Mobile Air Quality* scenario will focus on the provision of air quality information to mobile users. It will provide users of location-aware mobile platforms with a location-based service to explore time series of in-situ data (one-dimensional) which are enhanced with a visualisation of the data quality, as well as two-dimensional data coming from interpolation of values from a monitoring network. Quantified model quality information will be communicated, and visualised, on the mobile platform and bring the GCI and GEOSS into the hands of regular citizens.

The Expert Data Intercomparison Scenario will focus on scientific intercomparison of satellite data and how quality information at granularity of measurement can be integrated into GeoViQua and GEOSS. This utilizes the GECA (Generic Cal/Val Analysis Environment) toolset[6] and explores how to integrate it in a web-based service chaing.

This scenario is not to be confused with the Mobile Air Quality scenario just because it also utilizes air quality information. It’s focus is specialist users conducting intercomparison and its integration into GEOSS (deriving quality information), while the other targets non-expert users making data from GEOSS available on mobile devices (displaying quality information). Thus also the users’ situations are completely different (desktop versus outside).

The *Agriculture* scenario builds on the following use case: The international RAMSAR convention paper results in the habitat conservation legislation at European level. EU subventions supporting this legislation define requirements including flooding practices. Farmers fill in a form in which they would state which surface percentage of their fields will be flooded in a given period.
The local administration should then evaluate this farmer’s declaration. In order to guarantee the farmer has kept his word, they need a control system as objective as possible. Therefore they entrust this task to a research center that will develop the corresponding expert system. This system is utilizes a multi-temporal dataset comprised of remote sensing data and aerial images and include (pre-) processing steps to create a categorical map together with a classification accuracy quantification. This categorical layer is combined with cadaster data so that in the end, the user obtains a classification for each parcel with uncertainty information. This data can be evaluated with compliance to the subvention criteria and acted upon by the users very adequately, because they are aware of the data quality, and are a good support for the potential legal process following their findings.
The scenario covers issues related to quality both of processes and the general system in GEOSS: traceability and quality indicators, peer-review and even trustability, for instance.

[6] http://www.stcorp.nl/space_science/projects/geca/

The *Carbon Cycle* scenario addresses the visualisation of global land and ocean CO2 fluxes. It will demonstrate how to support the monitoring, reporting, and verification information required by regulatory frameworks for the inclusion of natural CO2 fluxes in political climate agreements, which will provide a template for a consistent and reliable global carbon flux visualisation system consisting of (1) new tools that ensure user-friendly access by the science community and operational users and (2) quality diagnostics associated with the estimations of carbon fluxes and stocks. Integration into the GEOSS architecture will ensure support for future development of quality-enabled carbon observation visualisations and carbon tracking simulation models.

3.2.2 Potential Visualisation Methods

Table 1 gives a summary of the scenario characteristics and lists potential quality visualisation methods. These are merely a first iteration of finding suitable methods are shall guide the implementation leading parties in defining their visualisation. Nevertheless it should be noted that the available data sets and property data types span across the whole range of possible values and hence can lead to a variety of methods.

A detailed requirements analysis for each scenario shall be conducted in the future to eventually determine which precise quality components must be visualised with which quality visualisation method.

Table 1. First requirements analysis and method matching within the GeoViQua scenarios.

Scenario Name	**Dataset**	**Observed Properties**	**Respon sible**	**Quality Parameters**	**Target of Quality Information**	**Data Type**	**Data format**	**Preferred Approach**	**Suitable Quality Visualisation Methods**
Mobile Air Quality	“Air base” in-situ air quality for (a region of) Europe	SO2, NO2, NO, NOx, O3, CO, PM, wind speed	52N	attribute accuracy	data	continuous	vector	AR, glyphs, maps	Exceedance Probability Mapping, RGB and Whitening colour model, Contouring, Hierarchical spatial data structures, Adjacent maps, Opacity, Glyphs, Statistical dimension in a GIS, Intervals & Error bars
Agriculture	Crop maps of northern Catalonia	Crop type	UAB	positional and attribute accuracy	data	categorical (crop type)	raster, vector		*Attribute/categorical/raster:* Whitening, Adjacent maps, Symol focus, Opacity, Animation, Blinking pixels, Blinking regions *Attribute/categorical/vector:* Whitening, Adjacent maps, Symol focus, Opacity, Glyphs, Hierrarchical spatial data structures, Animation, Blinking regions *Positional/categorical/raster:* Animation, Blinking pixels *Positional/categorical/vector:* Animation
	Vegetation indices from northern Catalonia	Crop stage and wetness		positional accuracy	metadata	categorical	raster		Animation, Blinking pixels
	3. Monitoring environmental measures using remote sensing	Flood stage		positional accuracy		categorical	raster		Animation, Blinking pixels

	4. Crop water monitoring using remote sensing	Crop evapotranspiration, crop water stress		positional accuracy	metadata	continuous	raster		Contouring, Animation, Animated isolines, Blinking pixels
	5.Maps of flooded rice fields in Ebre Delta	winter flooding		positional and attribute accuracy	metadata	categorical (flood stage)	raster		*Positional/categorical/raster:* Animation, Blinking pixels *Attribute/categorical/raster:* Whitening, Adjacent maps, Symbol focus, Opacity, Animation, Blinking pixels, Blinking regions
Carbon Cycle	Estimates of global carbon fluxes from models data fusion	CO_2 fluxes	CEA	attribute accuracy	data	continuous	raster	Colours and stippling.	Contouring, RGB and Whitening colour models, Adjacent maps, focus/Opacity, Statistical dimension in a GIS, 3D.
Expert Dataset Intercomparison	ENVISAT Satellite based measurements of trace-gases	NO_2, O_3	S&T	positional and attribute accuracy, completeness-omission	data	continuous	vector	3D maps of matching dataset records, Colour legend maps to highlight differences. Multiple maps to show altitude dependencies (profiles).	*Completeness (omission):* Glyphs *Attribute/continuous/vector:* Exceedance probability mapping, RGB and Whitening colour model, Contouring, Hierarchical spatial data structures, Adjacent maps, Opacity, Glyphs, Statistical dimension in a GIS, Intervals & Errorbars *Positional/continuous/vector:* Contouring, Glyphs, Animation, Animated isolines,

4. Conclusion

The challenges of quality visualisation are grounded in the inherent challenges of data quality itself. It is clearly subjective and bound to a certain task. That is why we think that interactive methods promise a high potential. Accessing the modelled data quality information on different systems and platforms is cumbersome already, including a visualisation, at best an appropriate one, increases the difficulty. This is even more the case for high-dimensional and multi-dimensional data where the quality information adds another variable to include. Although this could require the development of more complex methods, we also see a very important task, if not the most important one, in the goal of simplifying the visualisation and thereby focussing on information rather than data. The development of adapted, or complex, or simplified methods can, and should, be based on the existing and partly vetted methods presented in this report – we are sure this report will help designers and developers with their work, The GEO Label as an iconic visualisation method is only mentioned shortly in this work but stands for a promising extreme end of that undertaking to simplify the visualisation for better communication of the information.

Future work includes investigation of information visualisation methods for application in the visualisation of meta-quality (e.g. lineage, user feedback). The presented methods are all applicable for quantified quality information, but especially the user feedback elicitation will create a lot of textual statements, i.e. qualified information. An important challenge is a coherent visualisation of both quantified and qualified quality metadata. The integration of qualified information that is spatio-temporally grounded and focussed, i.e. a user's comment on a specific subset of a dataset, is an example of such a challenge.

This review builds a good foundation for the design of new quality visualisation methods or application of established ones within the GeoViQua scenarios. However, as science does not stand still for the remainder of the project, new publications or software releases might present even different approaches to which an open mind shall be kept. A continued exploration of quality visualisation possibilities is therefore subject to future work and will utilize the GeoViQua Wiki.

The notion of creating a holistic understanding of the quality, with respect to a specific purpose, in the mind of the user is an ultimate goal and particularly interesting when combining different visualisation methods and quality information sources to new approaches we expect to be developed based on this overview report.

5. References

USGS. 1997. Spatial Data Transfer Standard (SDTS): Logical specifications. U.S. Geological Survey, Virginia.

Bertin, J. (1983). Semiology of Graphics: Diagrams, Networks, Maps. (Translation by William J. Berg). The University of Wisconsin Press, Madison, WI, USA.

M. Kate Beard, Barbara P. Buttenfield, and Sarah B. Clapham. NCGIA research initiative 7: Visualization of spatial data quality. Technical Paper 91-26, National Center for Geographic Information and Analysis, October 1991. Available through ftp: ncgia.ucsb.edu. 59pp

Buttenfield, B. P., and R. Weibel. 1988. Visualizing the quality of cartographic data. Presented at Third International Geographic Information Systems Symposium (GIS/LIS 88), San Antonio, Texas.

Brodlie KW (1992) visualization techniques. In: Brodlie KW, Carpenter L, Earnshaw RA, Gallop JR, Hubbold RJ, Mumford AM, Osland CD, Quarendon P (ed) Scientific visualization: techniques and applications. Springer, Berlin Heidelberg New York, pp 37±85

Chrisman N R (1983) The role of quality information in the long-term functioning of a GIS. *Proceedings of AUTOCART06, Vol.* 2. ASPRS, Falls Church, pp. 303-21

Carswell CM (1992) Choosing specifiers: an evaluation of the basic tasks model of graphical perception. Human Factors 34:535±554

Cleveland WS (1985) The elements of graphing data. Wadsworth, Monterey, California

Cleveland WS, McGill R (1986) An experiment in graphical perception. Int J Man-Machine Studies 25:491±500

Fisher, P., 1994, Randomization and sound for the visualization of uncertain spatial information, *in* Unwin, D., and Hearnshaw, H., eds., Visualization in Geographical Information Systems: John Wiley & Sons, London, p. 181-185.

M. Green (1998), „Toward a perceptual science of multidimensional data visualization: Bertin and beyond“, *ERGO/GERO Human Factors Science*, S. 1–30.

Hengl T., Walvoort D. J. J., Brown, A. (2002). Pixel (PM) and Colour Mixture (CM): GIS Techniques for Visualisation of Fuzziness and Uncertainty of Natural Resource Inventories. In: Hunter, G. J., Lowell, K. (Eds.), Proceedings of the 5th International Symposium on Spatial Accuracy Assessment in Natural Resources and Environmental Sciences (Accuracy 2002), Melbourne, Australia. 300-309.

Hengl T. 2003, Visualisation of uncertainty using the HSI colour model: computations with colours. 7th International Conference on GeoComputation (CD-ROM), pp. 8.

Hesselink L, Post F, Wijk JJ van (1994) Research issues in vector and tensor field visualization. IEEE Comput Graph Appl 14:76±79

ISO/IEC 9000:2005 *Quality management systems — Fundamentals and vocabulary*. International Organization for Standardization, Geneva, Switzerland.

A. E., Kehrer J., and Hauser H. (2009), „Critical design and realization aspects of glyph-based 3D data visualization“, in *Proceedings of the 2009 Spring Conference on Computer Graphics*, New York, NY, USA, S. 19–26.

MacEachren, A. M. (1995). How Maps Work: Representation, Visualization and Design. Guilford Press. New York, USA.

MacEachren, A. M., Robinson, A., Hopper, S., Gardner, S., Murray, R., Gahegan, M., Hetzler, E. (2005). Visualizing Geospatial Information Uncertainty: What We Know and What We Need to Know. Cartography and Geographic Information Science, 32, 139-160.

Marr, D. (1982). Vision. W.H. Freeman and Company. New York, USA.

K. Koffka. Principles of Gestalt Psychology. Harcourt-Brace, New York, 1935.

Krygier, J., Wood, D. (2005). Making Maps: A Visual Guide to Map Design for GIS. The Guilford Press, 1st edition, 2005, New York, NY.

Colin Ware. Information Visualization: Perception for Design. Morgan Kaufmann Publishers, 2nd edition, 2004.

Pebesma, E. J., K. de Jong and D. J. Briggs (2007). Interactive visualisation of uncertain spatial and spatio-temporal data under different scenarios: an air quality example. International Journal of Geographical Information Science 21(5): 515–527.

Poynton, C., The rehabilitation of gamma, *in* Rogowitz ,B. E.,l and T. N. Pappas (eds.), *Human Vision and Electronic Imaging III*, Proceedings of SPIE 3299, 232-249 (Bellingham, Wash.: SPIE, 1998)

Edward R. Tufte. The Visual Display of Quantitative Information. Graphics Press, Cheshire, CT, 2nd edition, 2001

Rimbert, S., 1993, Social context, *in* Kanakubo, T., ed., The Selected Main Theoretical Issues Facing Cartography: Report of the ICA-Working Group to Define the Main Theoretical Issues on Cartography: International Cartographic Association, Cologne, p. 29-28.

Stone, M. C., 2004 Color in information display principles, perception, and models“, in *ACM SIGGRAPH 2004 Course Notes*, New York, NY, USA, 2004, S. 21–.

Tebaldi, C., J. M. Arblaster, and R. Knutti (2011), Mapping model agreement on future climate projections, Geophys. Res. Lett., 38, L23701, doi:10.1029/2011GL049863.

UncertWeb Deliverable 3.3, 2011, http://www.uncertweb.org/documents/deliverables

van der Wei, F. J. M., Hootsman, M. R., and Ormeling, F., 1994, Visualization of data quality, *in* MacEachren, A. M., and Taylor, D. R. F., eds., Visualization in Modern Cartography: Pergamon, Oxford, p. 313-331.