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A Centuries-long History of Participatory Science in Optical Oceanography: from observation to interpretation of natural water colouring

M. Wernand, S. Novoa, H. v.d. Woerd and W. Gieskes

Participatory science is not, as perhaps is believed, something of the 21st century. In this manuscript we show that over a century ago it were not only scientists who collected oceanographic data but also merchant sailors. A good example of such globally collected data are Forel-Ule observations, from which the first date back to 1889. This hardly explored (NOAA) dataset, containing around 228,000 of so-called ocean colour observations, was recently analysed on trends. Some of the material here presented refers to a recent publication 'Trends in Ocean Colour and Chlorophyll Concentration from 1889 to 2000, Worldwide' (Wernand *et al.,* 2013).
Since the launch of satellite-mounted sensors globe-wide monitoring of chlorophyll, a phytoplankton biomass proxy, became feasible. Just as satellites, the Forel-Ule (FU) scale record (a hardly explored database of ocean colour) has covered all seas and oceans - but already since 1889. We provided evidence of the usefulness of the Forel-Ule scale observation record dating back to 1889 from which changes of ocean surface chlorophyll can be reconstructed with confidence from this record. Our analysis has not revealed a globe-wide trend of increase or decrease in chlorophyll concentration during the past century; ocean regions have apparently responded differentially to changes in meteorological, hydrological and biological conditions at the surface related to global warming. Since 1889 chlorophyll concentrations have decreased in the Indian Ocean and in the Pacific; and increased in the Atlantic Ocean, the Mediterranean, the Chinese Sea, and in the seas west and north-west of Japan. Clearly, explanations of chlorophyll changes over long periods should focus on hydrographical and biological characteristics typical of single ocean regions, not on those of 'the' ocean.
To facilitate climate change research we recommend the reintroduction and use of the Forel-Ule scale to expand the historic database. Accordingly, through participatory science, with the help of the public, we like to establish this goal. We suggest the manufacturing and distribution of a new type, easy to make, Forel-Ule scale, recently developed within the EU-project „Citizens' Observatory for Coast and Ocean Optical Monitoring" (Citclops). Additionally, within the same project a smartphone App is being developed to facilitate public involvement in worldwide collection of Forel-Ule data.

Eine jahrhundertelange Geschichte der wissenschaftlichen Beteiligung in der optischen Meereskunde: Von der Beobachtung zur Interpretation natürlicher Meeresfärbung. Schon vor über 100 Jahren sammelten nicht nur Wissenschaftler, sondern auch seefahrende Kaufleute ozeanographische Daten. Ein gutes Beispiel für solche auf allen Weltmeeren gesammelten Daten sind Beobachtungen der Meeresfarbe, die sogenannten Forel-Ule(FU)-Beobachtungen. Die älteste, heute bekannte Forel-Ule Beobachtung stammt aus 1889 und ist Teil eines bis heute kaum erforschten Datensatz der 'National Oceanographic and Atmospheric Administration' (NOAA). Er umfasst ca. 280.000 Beobachtungen und wurde vor kurzem auf Trends analysiert (Wernand et al., 2013).
Mit dem Einsatz von auf Satelliten montierten Sensoren wurde die weltweite Überwachung von Chlorophyll a möglich. Chlorophyll a ist das am häufigsten vorkommende Pigment von Phytoplankton und kann darum als Proxy für Phytoplankton Biomasse benutzt werden. Ein Vergleich beider Datensätze ergibt, dass die Forel-Ule Skala gut dafür geeignet ist, um Veränderungen in der Konzentration von Chlorophyll an der Meeresoberfläche zu rekonstruieren.
Wir konnten keinen weltweiten Trend in der Zunahme oder Abnahme der Chlorophyll Konzentration während des letzten Jahrhunderts feststellen. Verschiedene ozeanische Regionen haben also

offenbar unterschiedlich auf Veränderungen von biologischen, meteorologischen und hydrologischen Bedingungen verursacht durch die globale Erwärmung reagiert. Während die Chlorophyll-Konzentrationen im Pazifik und im Indischen Ozean seit 1889 gesunken sind, ist für den Atlantik, das Mittelmeer, das Chinesische Meer und in der See westlich und nordwestlich von Japan ein Anstieg zu verzeichnen.
Aussagen über Veränderungen von Chlorophyll Konzentrationen über lange Zeiträume sollten daher immer auf spezifische ozeanische Regionen (charakterisiert durch typische hydrographische und biologische Verhältnisse) bezogen werden und nicht auf 'den' Ozean als Ganzes.
Um Prognosen mit Hinsicht auf den Klimawandel zu erleichtern, empfehlen wir um die historische Datenbank zu erweitern durch eine Wiedereinführung und Nutzung der Forel-Ule-Skala. Dieses Ziel wollen wir durch partizipative Wissenschaft, also mit Hilfe der Öffentlichkeit, erreichen. Dementsprechend schlagen wir die Herstellung und den Vertrieb einer einfachen Forel-Ule-Skala vor, die vor kurzem im Rahmen des EU- Projektes 'Bürger Informationsstelle für Küste und Ozean optische Überwachung' (Citclops) entwickelt worden ist. Darüber hinaus wurde innerhalb desselben Projekts eine App für Smartphones entwickelt, die die Einbeziehung der Öffentlichkeit für die weltweite Sammlung von Forel-Ule Daten erleichtert.

1. Introduction

The foureteenth, in the morning, was calme with fogge. At nine, the wind at east, a small gale with thicke fogge ; wee steered south-east and by east, and running this course we found our greene sea againe, which by proofe we found to be freest from ice, and our azure blue sea to be our ice sea. At this time we had more birds then we usually found.

H. Hudson, First voyage, 1607

For thence it may be gather'd, that the Sea-Water reflects back the violet and blue- Making Rays most easily, and lets the red-making Rays pass, most freely and copiously to great Depths. For thereby the Sun's direct Light at all great Depths, by reason of the predominating red-making Rays, must appear red; and the greater the Depth is, the fuller and in-tenser must that red be. And at such Depths as the violet-making Rays scarce penetrate unto, the blue-making, green-making, and yellow making Rays being reflected from below more copiously than the red- making ones, must compound a green.

I. Newton, 1704

Alles, was sich auf die Farbe des Wassers bezieht, ist ausnehmend problematisch.

A. Von Humboldt, 1815

The colour of the Greenland Sea varies from ultramarine blue to olive green, and from the most pure transparency to striking opacity. These appearances are not transitory, but permanent; not depending on the state of the weather, but on the quality of the water. Hudson, when he *visited this quarter in the year 1607, noticed the changes in the colour of the sea, and made-the observations, that the sea was blue where there was ice, and green where it was most open.*

W. Scoresby, 1820

Mit dem Spectroskop untersucht, zeigte sich in dem aus dem Wasser kommenden Licht das Roth ganz verschwunden, das Gelb sehr erheblich verblaßt, so daß die D- Linie kaum zu erkennen war, dagegen erschienen Grün, Blau und Indigo hell und die beiden Linien E und b flossen zu einem deutlichen dicken Absorptionsstreifen zusammen. Meine Absicht, auch das Licht der 'grünen' Grotte zu untersuchen, konnte ich leider wegen plötzlicher Erkrankung nicht ansführen; jedenfalls dürfte sich aber solches der Mühe verlohnen und möchte ich durch diese Notiz Veranlassung geben, das Spectroskop bei Untersuchung der noch in vielen Stücken räthselhaften Wasserfärbung mehr als bisher zu benuntzen.

H. W. Vogel, 1875

La question est depuis longtemps posee : ä quoi tiennent ces differences de couleur? Pour etudier systematiquement la couleur des lacs, j'ai employe deux methodes d'observation : La premiere consiste ä prendre la note de la nuance ou du ton avec des craies de pastel frottees sur un carton grisatre. Aussi ai-je cherche une autre methode. Je me suis fait une gamme de couleurs transparentes en adoptant la disposition suivante: Je fais deux solutions aqueuses, l'une bleue, de sulfate de cuivre ammoniacal, l'autre de chromate neutre de potassium, l'une et l'autre au 1 : 200e.

F. A. Forel, 1895

Wer nur Ost- und Nordsee befahren hat, vermag sich keine Vorstellung von dem satten, tiefen und doch auch hellen Blau zu machen, das dem Wasser gewisser zentraler Teile des Atlantischen Ozeans eigen ist. Schnars-Alquist hat uns in herrlichen, künstlerisch und man darf sagen auch wissenschaftlich vollendeten Gemälden das Blau des Ozeans gezeigt (Fig. 1), *das manchem Beschauer unnatürlich erscheint.*

G. Schott, 1911

A sufficient deep layer of pure water exhibits by molecular scattering a deep blue colour more saturated than sky-light and of comparable intensity. The colour is primarily due to diffraction, the absorption only making it of a fuller hue. The theories hitherto advanced that the dark blue of the deep sea is reflected sky-light or that it is due to suspended matter are discussed and shown to be erroneous.

C. Raman, 1922

Figure 1: „Auf Blauen Tiefen des Atlantischen Ozeans“ was painted by Prof. Schnars-Alquist) in 1911. From Schott's Geography of the Atlantic Ocean (Geographie des Atlantischen Ozeans, 1912). Copyright Ludwich Möller, Lübeck, 1911.

These quotes indicate that the colour of the sea has been an intriguing phenomenon since the days of Hudson, and probably much earlier. Through time the ever-changing colours of lakes and seas amazed travellers, and inspired painters and writers. At a later stage scientists interested in an explanation of the phenomenon became aware of the fact that the sea colour and its transparency could be related to "what's in the water", i.e. organic and inorganic material, which apparently determined its colour. Already William Hudson, explorer of the sea and navigator of the early 17th century, was aware of the fact that changing sea colours meant change in bottom topography; therewith the observation of 'colour' was useful for navigation purposes. Goethe described the colour of the sea during his crossing from Messina to Naples in 1739 in his book 'Voyage to Italy' (Goethe, 1786). For him, like many others, it was merely a joy to look at the variable colours of the sea. In figurative art that is inspired the sea we usually see beautiful, but most of all colourful seascapes. A painting of a realistically depicted sea by Prof. Hugo Schnars-Alquist (1855-1939), marine painter, titled Marine (1906, Figure 2), is a good example.

During the attempts to explain the colour and transparency of the sea, scientists designed devices to measure and classify these water properties. The observations were considered useful in particular for navigation: the sea's colour indicates, it was realised, the presence of icebergs, shallow water, river discharge location, suspended matter, etc.

Figure 2: Prof. Hugo Schnars-Alquist's oil on canvas, Marine (1906), is a good example of a realistically painted sea.

All explorers, writers, painters and scientists of the old days had one thing in common: their great ability of observing 'the undistinguished'; they wrote about or painted the blue in the ocean, the brown in the rivers, the black in the puddles and the transparency of raindrops. An example of the diversity in colour of natural waters is given in Figure 3.

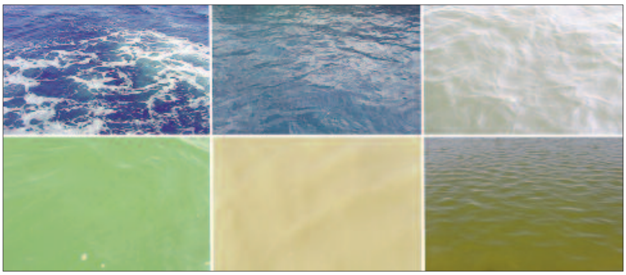


Figure 3: An example of six differently coloured sea areas with from left to right top: Central Atlantic, Central North Sea, Coastal North Sea, left to right bottom; Coastal North Sea during algal bloom, Wadden Sea with lots of re-suspension of sediment and a coastal outlet dominated by coloured dissolved organic matter (photos: Courtesy of B. Aggenbach, A. Hommersom and by the author himself).

During the first quarter of the 19th century more and more theories on the colouring of natural waters were tested and explained. In the following a modern view on the colours of the sea is sketched to clarify what was unknown a century ago. This colour, as we know now, is caused by a combination of scattering of the blue- and absorption of red to green sun rays by water molecules and by what's in the water; besides, the colour can be influenced by the colours of surroundings like rocks, sky, trees and bottom. For this reason we refer to this phenomenon as the apparent colour of water and more generally as 'ocean colour' in the case of marine waters.

Next to seawater temperature, salinity and transparency, 'ocean colour' observations (Wernand and Gieskes, 2011) belong to the oldest time series of climate-related data. Ocean colour is one of the Essential Climate Variables (ECV) for which sustained quality measurements are needed to track and analyse climate change (WMO, 2003). This is nowadays considered an important aspect of the science of ocean optics; changes of climate, ocean circulation and mixing may well have effects on 'ocean colour' and vice versa, if only because the colour is influenced by phytoplankton presence and abundance, two biomass aspects that are closely related to temperature change and hydrographical variations (in currents; in stratification, etc.) that go with such change; 'global change' and 'global warming' are phenomena widely discussed, even in the popular press and in politics because of the economic implications if humanity wishes to curb deleterious effects and consequences.

One of the simplest but most effective ways to capture the colour of natural waters is a colour comparator scale. The complete scale, the Forel-Ule scale, was designed in two steps between 1890 and 1892. The Swiss researcher Frangois Alphonse Forel used eleven colour tones covering the blue to green waters to study the colour of Lake Geneva. Two years later the German Willi Ule extended the scale by covering green to brown waters by adding ten extra colour tones. The scale has been fully described by Wernand and van der Woerd in 2010 and by Novoa et al. in 2013. Forel-Ule observations took place all over the world. Although the Forel- Ule scale more or less fell into disuse after the introduction of hyperspectral optical sensors we must realise the value of the data collected through the use of the scale. Historical observations of the colour of the sea are the only available data that can tell us something, although indirectly, about the amount of chlorophyll, an estimate of phytoplankton abundance, in the sea over the longer term. This of course in context of the relative short period over which satellite ocean colour has been collected.

In this work a brief history on scientists and their work over the years is sketched, followed by the highlights of an already published work (Wernand et al., 2013) on a statistically analysed long-term series (1889 to 2000) of Forel-Ule data. Results of this specific analysis can contribute to climate studies in which long-term changes in the ocean are of interest.

This chapter is followed by a description of new and nowadays ways of data collection, via crowdsourcing, to extend the valuable long-term observations of the colour of the sea. With the upcoming of new observational sources, crowdsourcing, it is important to define simple methods for the collection of scientific data by the public to extend historic data series. A trigger to re-establish the Forel-Ule and Secchi method is the start of the international EU project Citizens' Observatory for Coast and Ocean Optical Monitoring (Citclops). The goal of the project is to empower end-users to perform community-based environmental monitoring to accomplish goals that are otherwise impossible or difficult to achieve, or are subject to the availability of expensive governmental infrastructure. Specifically, Citclops is concerned with water-quality monitoring and will develop improved low-cost sensors and systems for monitoring water colour, transparency and fluorescence, in a location-aware manner allowing for the analysis of spatial patterns.

2. Ocean colour science through the ages

Already far ahead of our time the ever-changing colour of lakes and seas surprised travellers and intrigued scientists.

In 1631 Sir Francis Bacon wrote a small chapter on observations relating to the colour of the sea and other kinds of water in his Sylva Sylvarum or a Naturall History. He literally writes:

> *The water of the sea and also other waters become blackish during movement and much whiter when at rest. Originated by different causes, easy to understand. When sunrays are penetrating this water surface they no longer will follow straight lines but by this constant moving surface progress along a much more obscure way. The opposite takes place when the water is in rest. Here transparency is always accompanied by a sort of whiteness.*

Bacon at this point compares the flat and the rough water surface with respectively a mirror made of glass with a tinfoil or mercury inlay (whiter) and with a simple mirror made of tin (darker). Two small chapters in in the works of John Martyn (1669) contain findings on the colour of some seas and rivers. He writes in one of the chapters:

> *About the colour of the sea, I have to add, That as we went, and passed from a Green Sea to an Azure, in the way when it was dark colour'd (which we formerly have spoken of), the top of each wave, as it was cast up before the Sun, shew'd it self to be Azure, the rest of the wave being dark-colour'd, approaching to black.*
> *And the like I observed coming home; for, though the Sea in its dark-colour resembled exactly what we saw before, as we went out; yet did the tops of the wave break and appear to be green, long before the great Waves or body of the Sea became green. I observ'd, that the Sea, which was Azure, and transparent in Sun-shinny dayes, was black and darkcolour'd, and much less transparent, when the Sun did not shine. But in the Green Sea there happens not the like Difference.*

Thirty years after Captain Wood (Narborough, 1694) established his visibility record Louis Ferdinand Comte de Marsilli (Luigi Ferdinando Marsigli in Italian) started to investigate, amongst other physical parameters, the natural colour of wa-

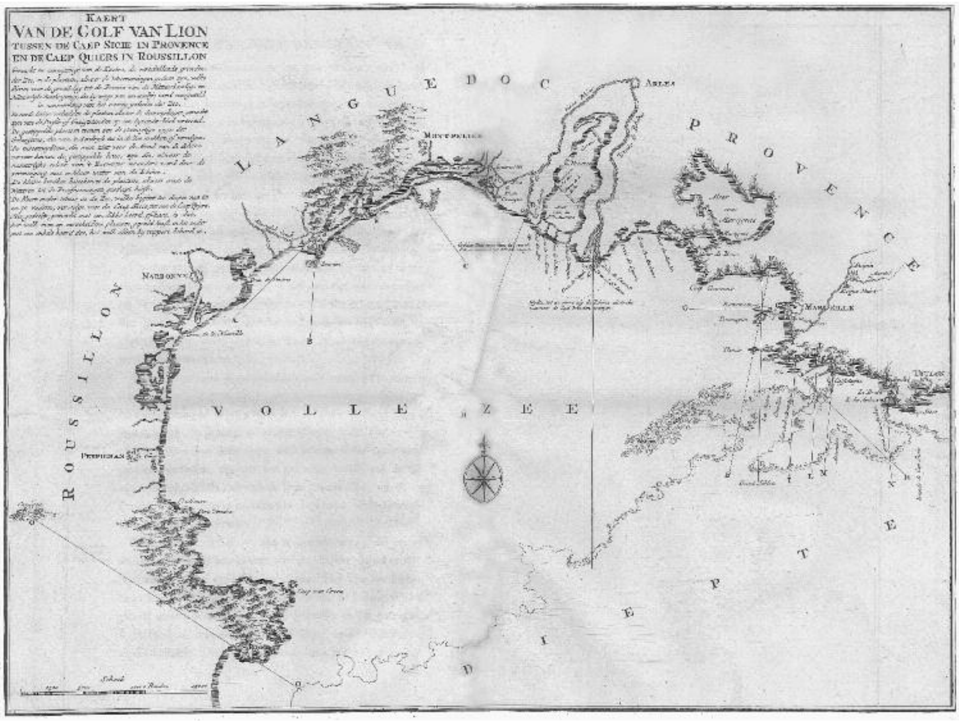


Fig. 4: The Gulf of Lyon where Marsilli startet his Investigations in 1706 his thesis 'The natural history of the sea' (Dutch translated version of 1786).

ter of the Gulf of Lyon (Figure 4). Comte De Marsilli mentions in the chapter "Of its water" of his 1711 Italian dissertation on 'the natural history of the sea' (that transparency and colour are indissolubly aligned. He literally stated:

> The colours are essential, permanent, occasionally and apparent by various reflections. To see its transparency, it must be put in a glass vase without receiving any reflection for it is that which causes all its supposed colours.

The latter is a brilliant remark for its time and was only much later fully understand. Marsilli has written one of the first great scientific works focussed on the physical aspects of the sea with one of them being the colour. Here it is where we for the first time can find a table containing the colour of (sea) water. The table contains tree columns with respectively 'the apparent colour of the surface water', 'the colour of the essential water put into a vase ' and the essential colour of the water taken from a certain depth and put into a vase' (Figure 5). However colours in his table are still defined as "greenish", "bluish", "ash-grey". Sailing in Mediterranean waters (Figure 4), he mentions that he could distinguish a red fish at a depth of 18m. These kinds of remarks can be found in numerous historic papers. At that time research could be called 'descriptive research' instead of the 'quantitative research' nowadays. Also Goethe was intrigued by the colours of the sea. During his trip to Italy Goethe visited Sicily and on Tuesday April the 3rd 1787 looking towards the sea he notes:

> *The northerly location of Palermo makes that the city and coast take an odd position regarding the large celestial bodies (sun and moon), from whom one will never see its reflection on the waves. Therefore also today, a day again full of sun, encountering a dark blue sea, sombre and turbulent, instead of at Naples, from noon on shimmering more cheerful, more ethereal and more blurry.*

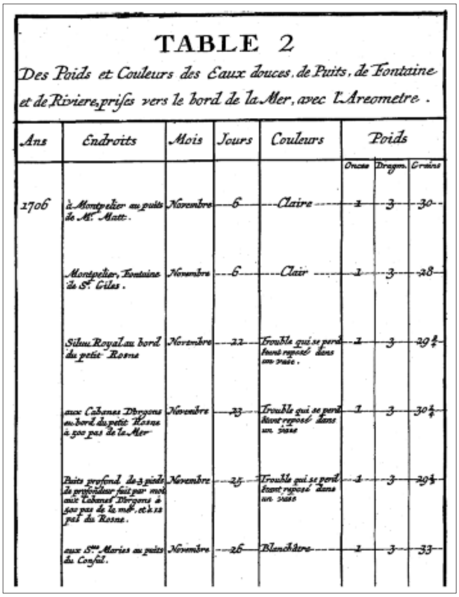


TABLE 2

Des Poids et Couleurs des Eaux douces, de Puits, de Fontaine et de Riviere, prises vers le bord de la Mer, avec l'Areometre.

Ans	Endroits	Mois	Jours	Couleurs	Poids: Onces	Poids: Dragm.	Poids: Grains
1706	à Montpelier au puits de Mr. Matt.	Novembre	6	Claire	1	3	30
	Montpelier, Fontaine de St. Giles.	Novembre	6	Clair	1	3	28
	Silieu Royal au bord du petit Rosne	Novembre	22	Trouble qui se perd étant reposé dans un vase.	1	3	29 3/4
	aux Cabanes D'orgons au bord du petit Rosne à 500 pas de la Mer	Novembre	23	Trouble qui se perd étant reposé dans un vase	1	3	30 1/4
	Puits profond de 3 pieds de profondeur fait par moi aux Cabanes D'orgons à 500 pas de la mer, et à 12 pas du Rosne.	Novembre	25	Trouble qui se perd étant reposé dans un vase	1	3	29 1/3
	aux Stes. Maries au puits du Consul.	Novembre	26	Blanchâtre	1	3	33

Figure 5: Table with Marsilli's observations on the colours (couleurs) of the Gulf of Lions as it was presented at the end of his thesis 'The Natural history of the sea'.

On the trip back from Messina to Naples on May the 12th just leaving the port he writes that the whole sky was covered in a white haze, through which the sun, without seeing its silhouette, illuminated the sea, adopting the most beautiful heavenly colour which one could ever imagine. Monday the 14th nearby the island of Capri he continues his diary by writing:

> *Under an immaculate clear sky the almost flat glossy sea, through the absence of wind, lay before us as a transparent pond.*

But the absence of the wind together with the strong currents around Capri had them almost been shipwrecked.

Neither standardised colour scales nor other instrumentation, to record the colour of lakes, seas or oceans exist before 1800. Or it should have been the cyanometer,[1] which was used around 1799 by Baron Alexander Von Humboldt

[1] The cyanometer was used to study the blueness of the sky.

(Von Humbold and Bonpland, 1815) who investigated the blueness of the equinoctial surface waters. However most of the investigated water, having a greenish tint, could not be matched to the cyanometer colours.

During his travels towards the new continent von Humboldt compared the deep blueness of the sea with the skies above the Venezuelan steppe during a drought. At another occasion he employed the cyanometer by pointing it to the extensiveness of the ocean's water and by looking through a pin-hole. At that particular moment he experienced the most beautiful ultramarine colour as he wrote down in his memoirs. A remarkable saying of von Humboldt is:

> *All that is accounted to the colouring of natural water is problematic in the highest grade.*[2]

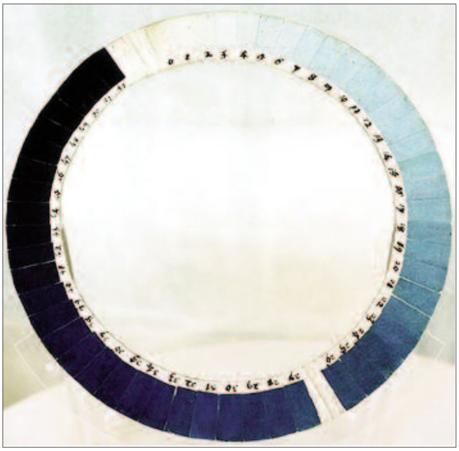


Figure 6: The cyanometer from Horace-Benedict de Saussure with 53 nuances of blue (Musee d'histoire des sciences, Geneva), proposed in 1791. The circular paper scale to establish the sky's colour was also used to establish the ocean's colour.

The cyanometer used was described by its inventor Horace-Benedict de Saussure (1791, 1803, 1842). The scale consisted out of a paperboard circle comprising 53 radial sectors with nuances of blue between white and ink-black numbered from 0 to 52. The paper-scale was first used on top of the Mont-Blanc, near Chamonix, in 1787 and is shown in Figure 6. This scale is not to be confused with Frangois Arago's, in 1845, converted polarimeter instrument with the same name. This instrument is fully described by Arago himself and by Bernard in 1865.

In several 19th century publications speculations were made assuming that the colouring of water could be due to some impurity in the water. This assumption begged to answer first the question whether water had any colour in itself, and if so what that colour would be, before saying anything about the effect of these impurities on the colour. At the same time the awareness grew that pure water not only had a reflected colour but also a transmitted one. In laboratories the purest bluest water found in nature together with distilled water were thoroughly investigated on the cause of their colouring.After a short stay at Edinburgh university in 1806 William Scoresby junior escorted his father, the well- known whaling

[2] „Dass alles, was sich auf die Farbe des Meeres beziehe, im höchsten Grade problematisch sei", „Tout ce qui a rapport a la couleur de l'eau est extrement problematique".

captain, to the higher latitudes and makes the world aware of the unbelievable transparency of the water in the vicinity of the Spitsbergen Sea (South of) during its crossing). Referring to deep waters Scoresby junior came to the conclusion that all light rays except the blue were absorbed by water before they reached the bottom. At that time a remarkable but true conclusion.

A book published in 1815 by Catteau-Calleville has an inspiring title with respect to the sea; 'Gemälde der Ostsee' or 'Painting of the Baltic' (Scandinavia). The book is a physical, geographical and historical retrospect on the Baltic Sea. However, only a small phrase on the bright-blue colour of the Baltic seawater was found in a chapter concerning 'colour, mirroring and phosphorescence of the water'. According to Catteau-Calleville this colouring could only be seen during the most beautiful season under bright and calm weather. He found it much more interesting to write about other phenomena such as so-called sun-smoke (sea fog) covering the sea surface:

> *The fog, appearing mostly in July, after diluting and letting the sunrays through revealed the most glossy shine and diversity in watercolours.*

Sir Humphry Davy, one of the pioneers trying to explain the arcane colouring of natural waters, wrote in 1829, just before he died, an interesting article on the colour of the water and the tint of the oceans. He was the first to say that a blue colour could be dedicated to pure water (rain- and melting glacier water were of the purest kind at that time), but the processes causing this blue appearance where not clear at all. He ascribed the colour of the greenish ocean to the presence of iodine and bromine. Davy tested his thoughts by an experiment in an icy lake near the Chamonix-Mont-Blanc valley at the France-Swiss border. It was here where he mixed a little iodine with melting water on top of the ice layer. Accordingly he saw colour changes from dark blue towards the green of the sea to the green of grass to yellowish green.

> *Possibly these halogens are also responsible for the decomposition of marine vegetation. Dissolved in small amounts colours the water yellow and together with the blue of pure water produces the green tint of some seas.*

Although he never used this experiment as proof of the existence of green seas he was enlightened by his presumption. Half a century later the German Franz Boas still shared Davy's opinion in his dissertation 'A contribution to the discernment of the colour of water' (Boas, 1881).

The Berliner poet and painter August Kopisch (re-)discovered the 'Grotto Azura' or 'Blue grotto' in 1826 and gave it to the world.

> *It was on August the 27th 1826 when Kopisch, Fries, Pagano and bargeman Ferraro first entered the Grotto.*

The grotto is situated on the island Capri, in front of Naples, Italy. The original story has been written down in 1885 by Ferdinand Gregorovius in his travel book 'Die Insel Capri'. Kayser as well as Gregorovius read the original notes made by Kopisch which over the years were safely kept by the, at that time aged, landlord Pagano. Most of the sunlight enters the grotto through the underwater entrance of the cave; most colours are absorbed by the water molecules except for the blue rays. These blue ray are scattered upwards into the cave, which gives its inside a magnificent lapis lazuli colour.

Around the mid-nineteenth century R. Bunsen published an article (1847) on the inner relation of pseudo- volcanic appearances of Iceland. To determine the composition of lava on Iceland he visited several (hot) springs under which the one at Reykir, Nordurlands Vestra. At this site the beauty of its aquamarine crystal clear water, beyond any description, impressed him very much. He memorises:

> *Nowhere this transparent greenish blue water can be found with such purity as on this spot*

Musing on this phenomenon made him write:

> *That chemical pure water was not colourless as in general was presumed I knew but that it had its own pure blue colour was less known to me.*

A strong supporter of the idea that the ocean's blue was caused by reflection of the blue sky was H. Burmeister. In 1853 this German zoology professor published a book on geological views on the history of the earth and its inhabitants. Observations made by him during sea going expeditions during rain, under dark clouds and sunny or white clouds condition enforced the opinion that the sky coloured the ocean from respectively greyish, greyish blue to dark blue. In case the water was blue of itself. Burmeister continues then the water should stay blue independent of the weather or sky condition. A few of Burmeister's statements:

> *I) During the night the water itself turns up dark grey as the mirrored image of the sky*
> *II) Under rainy conditions the water itself should become completely black due to the colourless being of raindrop.*

Burmeister was convinced of the correctness of his sky theory and was found support in earlier thoughts of von Humboldt as a supporter of the same theory.

Painted disc experiments performed in 1865 by Cialdi and Secchi included spectroscopic investigations of the light reflected by the disc in the Mediterranean waters. The Secchi disc became a standard method in the 20th century to establish the transparency of natural waters and is used to enhance contrast in case a Forel- Ule observation is performed.

Matthias Jacob Schleiden stated in his book 'Das Meer' of 1867 that according to all divers the light in the deep coloured reddish-yellow to dark red until it reaches the utmost depth and becomes blackish like the colourless night (translation from the German, Figure 7), which we know now to be a wrong assumption. Some illustrations in his chapter on the colour of the sea (Figure 8) enlighten his book.

Figure 7 (right): The phrase that M.J. Schleiden wrote in his book 'The sea' (Das Meer) on the red colour of the sea at great depth.

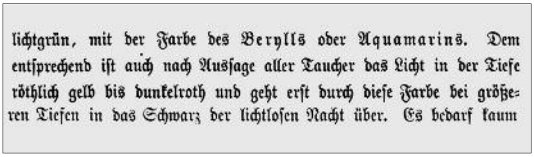

lichtgrün, mit der Farbe des Berylls oder Aquamarins. Dem entsprechend ist auch nach Aussage aller Taucher das Licht in der Tiefe röthlich gelb bis dunkelroth und geht erst durch diese Farbe bei größeren Tiefen in das Schwarz der lichtlosen Nacht über. Es bedarf kaum

Figure 8: A picture from the chapter on the colour of the sea by M.J. Schleiden's 'Das Meer' showing the colour of the calm sea near an almost un-urbanised Gibraltar (after Gudin).

Heinrich Wallmann, in the sixties of the 19th century, extensively describes the colours of alpine lakes in Austria, Hungary, Switzerland, Italy and Germany. Parts of a comprehensive article (117 pages) on alpine lakes, published in the 1868 yearbook of the 'Österreichischen Alpen-Vereines' were written down more from a philosopher's point of view then from a scientific point of view and a delight to read. In the first pages he imagines the utmost fascination of the traveller, crossing the Alps, towards the appearance of alpine lakes:

> *Lots of travellers will remember a delightful feeling, after a day of severe hiking through small gloomy dales surrounded by sky-high rockfaces and along murmuring brooks, reaching an open spot discovering*

a dark-green or blue lake amphitheatre like enclosed by either pine tree woods or hundreds of fathom high rock formations.

Curiously Wallmann further compares the different appearances of alpine lakes with a housewife:

Incline to be soft, tender and quiet; the serene restful lake and the other time she scares us and makes us feel uncomfortable through here eccentric and capricious touchiness; the lake during storm and thunder.

In 1869 the American assayer to State of Massachusetts Aug. A. Hayes (1870) after investigation of Lake Geneva water came to the conclusion that the cause of its azure colour was found in the peculiar hue of the sky, which was transmitted to the eye by the 'colourless water'.

In other countries, there are bodies of'colourless water' which do not exhibit the colouration, commonly seen in Lake Leman. Such localities are not favoured with clear blue skies.

Around 1870 researchers came close to explaining the cause of the blue colouring of lakes and seas. Each in their own way, Tyndall (1870) and Soret (1870, 1884, 1886, 1888 and 1897) based the scattering of light on the presence of small particles, i.e. particles small enough to scatter only the blue light. It was now also known that water absorption was much more affecting the longer wavelengths. The saying 'the darkness of true transparency' really meant at that time that in case a liquid was completely free of particles it was thought to believe the water would not reveal (reflect) its blue colour, which later was proven to be a wrong thought. From this time on tubes of all kinds and lengths were use in the laboratory and in the field to establish the origination of the different colouring of lakes and seas. From the mid-19th century on more laboratory experiments started to investigate the 'purest water'. Colour could only be seen through a water column of a certain height.

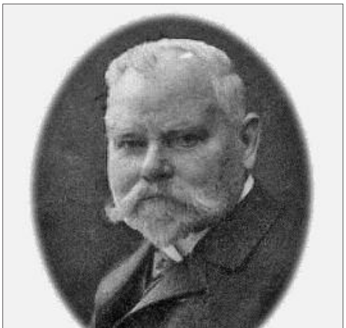
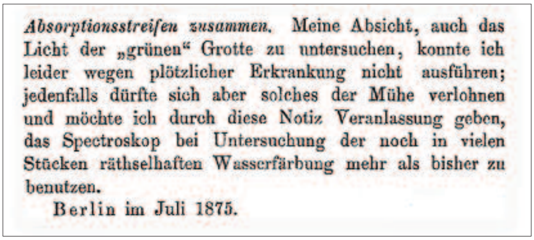


Figure 9: Captain Carl Koldewey led the second German North Pole Expedition as captain on the "Germania" in 1869/70 (Photo from The Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research).

Forster (travelling with Cook, 1778), Darwin (1787), Maury (1855) and Captain Carl Koldewey (1871, 1874, Figure 9) agreed that blue was the general colour for oceans and that green seas were an exception to the rule. For rivers and lakes green was the general colour and here blue was an exception to the rule (cited by Von Jolly (1872) and noted in Boguslawski's handbook (1884).

Like Herman W. Vogel (1875) ten years later, experimenting in the 'Grotta Azzurra' they came to the same conclusion; red was the first to disappear, then followed yellow and green until the blue, indigo and violet remained. This is why the inside of the 'Grotto' appears blue like lapis lazuli; sunlight enters the grotto not via the small air-opening but through the huge underwater opening. All colours are 'filtered out', except the blue. It never came to an investigation of the nearby Green Grotto, as Herman Vogel got seasick (Figure 10)


Absorptionsstreifen zusammen. Meine Absicht, auch das Licht der „grünen" Grotte zu untersuchen, konnte ich leider wegen plötzlicher Erkrankung nicht ausführen; jedenfalls dürfte sich aber solches der Mühe verlohnen und möchte ich durch diese Notiz Veranlassung geben, das Spectroskop bei Untersuchung der noch in vielen Stücken räthselhaften Wasserfärbung mehr als bisher zu benutzen.

Berlin im Juli 1875.

Figure 10: Herman Vogel wrote in his 'Spectroscopische Untersuchung des Lichts der blauen Grotte auf Capri' that he was unable to investigate the Green Grotto as during his work in the Blue Grotto as he got seasick.

In 1882 John Aitken wrote one of the first papers dealing with both absorption and reflection causing the blueness of natural waters. The year before Boas wrote his dissertation on related matter. Both tried to answer the question if it was the selective reflection or the selective absorption causing this blueness.

Wild (1856) and Glan (1870) and Franz Boas were among the first pioneers to determine the absorption properties of water in the laboratory. In his thesis 'Erkenntnisse der Farbe des Wassers' (1881) Boas describes the retrieval of the 'absorption coefficient' of distilled water. During these experiments with distilled water he was intrigued by the colour difference of its green-bluish transmitted light and the bright blue reflected colour of the Mediterranean Sea samples. According to him it was not easy to explain what matter caused this colour shift. A possible explanation could be ascribed to the presence of tiny suspended particles in the Mediterranean water. An article 'On the scattering of light by small particles' by John William Strutt (the later Lord Rayleigh) in 1871 made him believe so. According to an article published in the beginning of 1900 Rayleigh stated that that the proper colour of water cannot be seen unless the sunlight traverses a sufficient depth before it reaches the observer which occurs looking into the ocean; a true statement. But Rayleigh continues by saying that in case the ocean's water is very clear there is nothing in it that can send light back to an observer and therefore, under those conditions its proper colour cannot be seen and the dark-blue colour of the deep see is simply 'the blue of the sky' by reflection. The latter statement is a wrong conclusion and criticized by Raman in his 1922 publication 'On the molecular scattering of light in water and the colour of the sea'.

At the end of the 19th century scientists proposed techniques to establish the colour of natural water by means of comparison against some colour(ed) standard. The first notes mentioning such a standard, if we do not take into account De Saussure's cyanometer, dates back to a session of 'La Societe Vaudoise des Sciences Naturelles, Lausanne' 21st of December 1887 when Frangois Alphonse Forel (1890) proposed a 13 colours scale, covering blue to green, for a quick identification of the colour of the sea, lake or river water. In 1892 the scale was extended towards the brownish colours by Willi Ule (1892).

In an article on limno-physics the Austrian Josef Roman Lorenz Ritter von Liburnau (1898) wrote his opinion on the recording of colour and transparency of natural waters. In this paper von Liburnau firstly criticized the naming of the Secchi-disc which was still in use at the time. He previously had used such a white disc to measure the transparency of the Mediterranean seven years earlier than Secchi, and which he already had named 'the disc system'. Secondly, Lorenz von Liburnau criticized the natural water 'colour scale' proposed by Francois Alphonse Forel due to its limited range of blue to green. He therefore proposed a sea colour scale according to the colours of minerals. However, no field observations were found where this mineral scale was used to establish the colour of the sea. In the same publication by Von Liburnau (1898) the Radde international colour scale was mentioned as reference to determine the colour of natural waters (1898). Again, no field comparisons with this scale were found. Raddes's original paper-scale series is kept in the University of Munich.

The search for an explanation of the mechanisms responsible for the mysterious colouring of water really ended in 1922 with the publication „On the molecular scattering of light in water and the colour of the sea" by C.V. Raman. The colour blue, attributed to the purest water and to the most oligotrophic oceans, is caused by molecular diffraction and scattering.

The Forel-Ule scale, also known as Xantho-meter became the most common and well-known colour scale used to determine the colour of seas and lakes and rivers. In the past hundred-thousands of such measurements (scale comparisons) were performed all over the world (around 280.000). Data has been collected during scientific expedition and by merchant sailors and is archived by the U.S. National Oceanographic Data Centre). So, in the early 19 hundreds we can already speak about participatory science. The Forel-Ule scale is still in use and its use is even promoted to extend the century long data record of the colour of natural water to facilitate climate change studies.

3. An unexplored database

Since 1890 the Forel-Ule scale became the most commonly used and most simple scale to determine, through comparison, the colour of seas, lakes and rivers. Besides Forel and Ule, the inventors of the scale, Krümmel (1893), Von Drygalski (1897), Luksch (1901) and Chun and Schott (1912) were amongst the first to use this colour comparator method at open sea. Krümmel performed observations during the plankton expedition of the Humboldt Society in 1889 (Figure 11).

The mathematician Von Drygalski used the Forel's part of the scale at open sea during the Greenland Expedition of the Geographical Society between 1891-1893 (Die Grönland-Expedition der Gesellschaft für Erdkunde). The map of **Figure 12** shows the ship's track with the observed colour per station written separately on the map.

At that time only the blue to blue-green part of the scale (scale numbers 1 to 11) was used to classify the colour of open water. An example of Krümmel's contoured sea colour map is shown in Figure 13. The data was collected in the Atlantic during the Plankton Expedition of 1889 and the colour of the sea was expressed as a percentage of ayellow potassium chromate solution added to a blue copper-sulphate solution.

Josef Luksch collected observations over eight years during the 'Pola' expedition (1890-1898) in the Mediterranean, Aegean- and Red Sea (Figure 14). The colour of the ocean observed by Chun and Schott during the 1898 to 1899 German deep-sea expedition on 'Valdivia' is shown Figure 15.

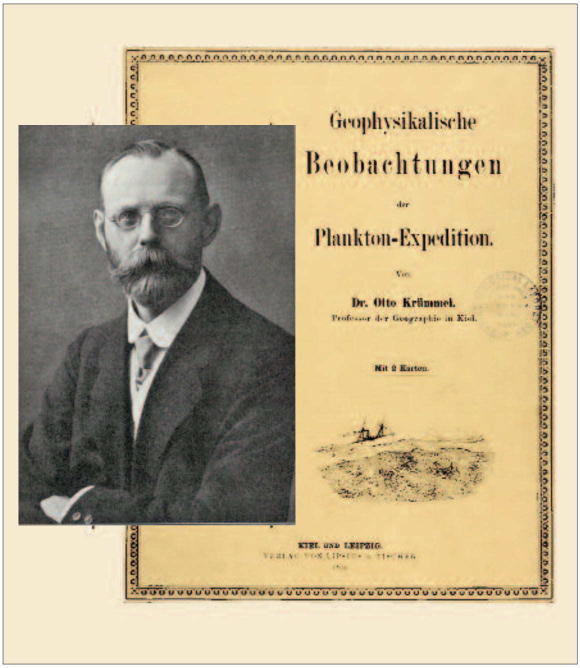


Figure 11: Otto Krümmel (NOAA photo library), German oceanographer (1854-1912), published his observations of the plankton expedition of the Humboldt Society in 1893.

Gerhard Schott presented in his 'Geographie des Atlantischen Ozeans'

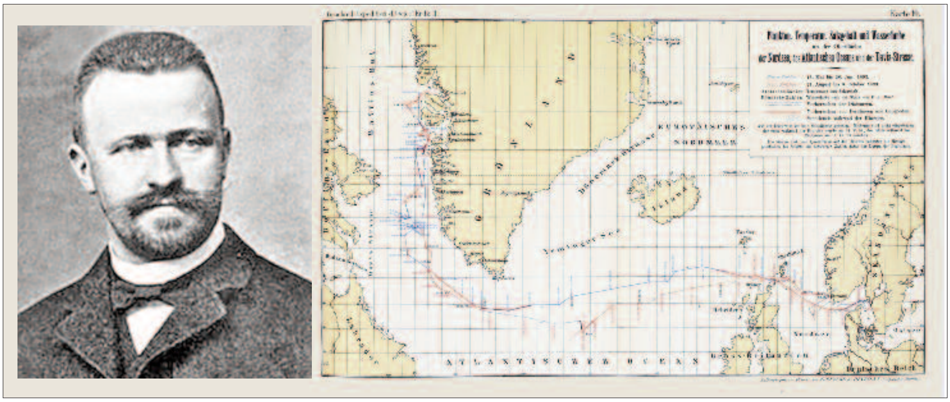


Figure 12: The Grönland-Expedition (1891-1893) was made possible by the 'Gesellschaft Für Erdkunde' in Berlin and was led by Erich Dagobert von Drygalski (1865-1949). The Forel index (Wasserfarbe), as text written along the ship's track, can hardly be identified on the map published in 1897.

Figure 13: Krümmel's contoured North Atlantic Forel-map (1889). The sailing track of the steamship 'National' is shown in black. The colour (Wasserfarbe), the first part of the Forel-Ule scale, was indicated as a percentage of a yellow potassium chromate solution added to a blue copper-sulphate solution. The legend indicates the FU-scale colours 1 to 21.

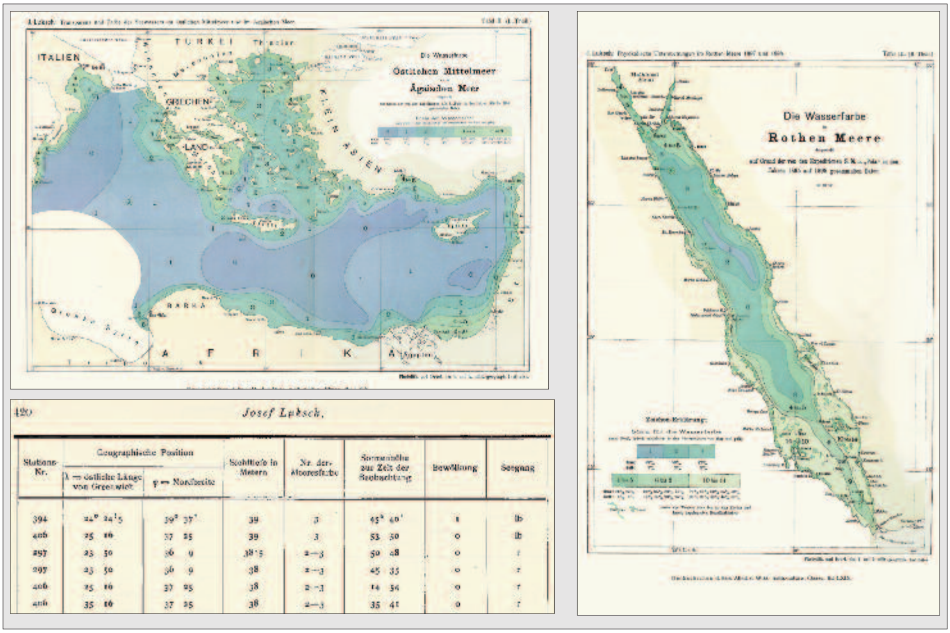


Figure 14: Between 1890 and 1898, Luksch, on-board the steamer 'Pola' crossing the eastern Mediterranean and Red Sea (Luksch, 1901, pp. 400-401), used a small forty-five centimetres disc over which he established the Forel colour.

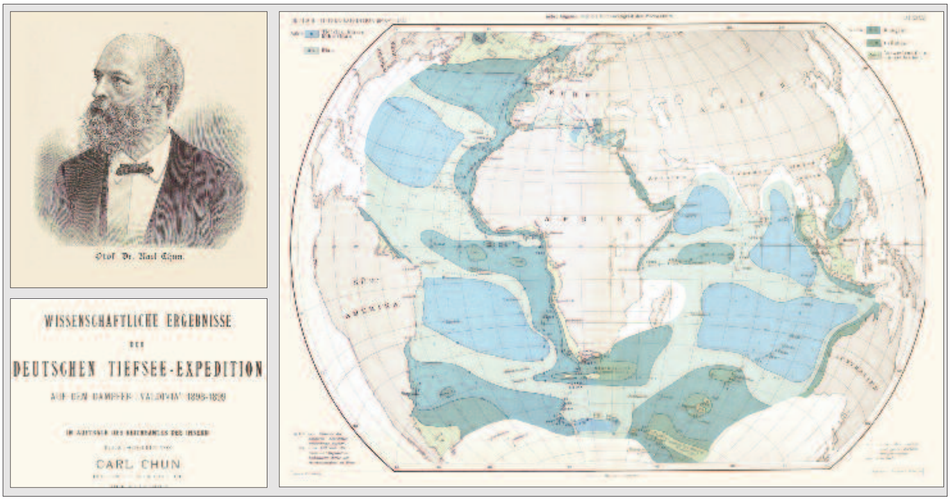


Figure 15: Forel contour map established by Gerhard Schott (1866-1961) from the German deep-sea expedition on the steamer 'Valdivia' between 1898 and 1899. The expedition was led by Carl Chun.

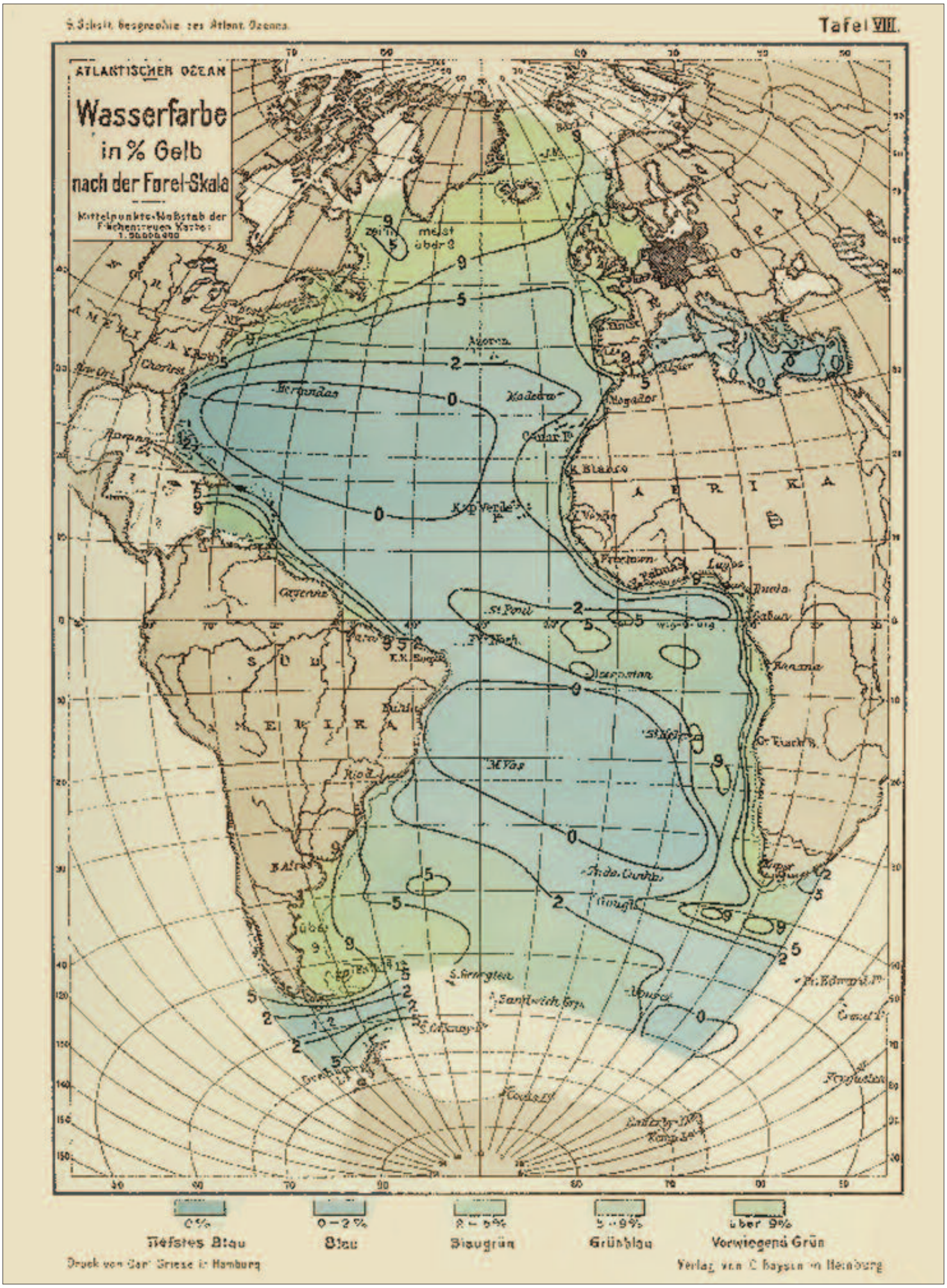


Figure 16: A (re-) contoured Forel map (see Figure 15) used as illustration in 'Geographie des Atlantischen Ozeans' (1912) from Prof. Dr. Gerhard Schott Schott's. The percentage given in the index is the percentage of yellow (solution) used to establish a tube colour. 0%=FU-scale 1, 9%=FU-scale 4.

(1912) a (re-) contoured Forel-Ule map of of the one that was drawn shortly after the 'Valdivia' expedition (Figure 16).

4. The Forel-Ule data record (1889-2000)

Over the years only a limited number of geographical maps, based on interpolation of sets of Forel-Ule data, became available. The U.S. Navy Hydrographic Office published in the 1950s three atlases on marine geography, including Forel-Ule contours of the Sea of Japan, Korea and Indochina (U.S. Navy Hydrographic Office, 1951a, b, c). A more comprehensive work in this field was conducted by Margaret Ann Frederick who presented her research in her 1970s master thesis 'An Atlas of Secchi Disc Transparency Measurements and Forel-Ule Color Codes for the Oceans of the World'. In the thesis she presents contoured Forel-Ule maps for a number of seas and oceans (Frederick, 1970). Frederick had around 24,000 globally collected Forel-Ule observations to her disposal to create her contour maps on averaged sea colours, however, without any trend analysis. The majority of Forel-Ule observations used in a recent ocean colour trend analyses were retrieved from oceanographic and meteorological databases archived by NOAA-NODC (WOD, 2005). For the trend analysis observations were extracted for open waters only. Figure 17 shows an IDW interpolation off all available Forel-Ule observations.

In 2013 Wernand et al. tried to improve the understanding of the links be-

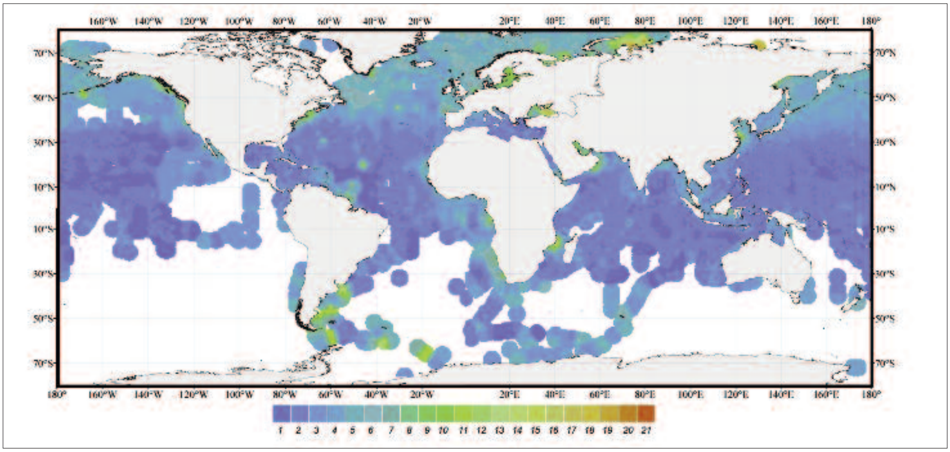


Figure 17: A global inverse distance weighing interpolation of available Forel-Ule observations collected between 1889 and 2000.

tween climate and the marine ecosystems by an analysis of this almost 'forgotten' global-wide collected ocean colour data. An analysis is presented of the temporal variation of ocean colour from 1889 till the year 2000, based on a subset of 221110 globally collected FU observations. In the paper first the data selection and quality control procedures were described followed by a bio-optical model that provides a simple relation for the conversion from Forel-Ule index to chlorophyll concentration as shown in Figure 18.

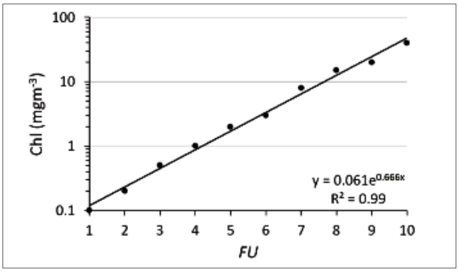


Figure 18: For open sea and oceans the chlorophyll concentration as a function of the Forel-Ule index.

Subsequently the world-wide collected data were grouped in 28 seas and oceans and binned in 10 year intervals. For the oceans only Forel-Ule has been converted to chlorophyll. In the PLos-ONE paper significant decadal variations in ocean colour were described. Some of the most significant trends, on a timescale of a century, of 28 investigated seas and oceans are shown in Figure 19.

Statistical and trend analyses (Mann-Kendall test) of sea and ocean colour changes were related to the long- term biological activity. To read about all results, the authors refer to the original manuscript: Wernand MR, van der Woerd HJ, Gieskes WWC (2013) Trends in Ocean Colour and Chlorophyll Concentration from 1889 to 2000, Worldwide. PLoS ONE 8(6): e63766, doi: 10.1371 / journal.pone.0063766.

The authors conclusions in a nutshell are:

- The Forel-Ule classification of natural water started in the late nineteenth century and can be marked as one of the oldest oceanographic records, next to salinity, temperature and water transparency records. In no way these valuable ocean colour records can be replaced by other data, and it is not acceptable to simply reject historic datasets or methods that are relatively unknown by classifying them as 'subjective'; this has happened in the case of Secchi disc records (Preisendorfer, 1986).
- The results of our analysis presented in PLoS ONE suggest that since the early 20th century chlorophyll concentrations have decreased in the Indian Ocean and have fluctuated in the Pacific; they increased in the Atlantic Ocean, the Mediterranean, the Chinese Sea, and in the seas west and north-west of Japan.
- No global trend of a uniform increase or decrease in chlorophyll concentration, and therefore phytoplankton abundance, has been identified.

5. Extending long-term data series

To facilitate climate change research Wernand and Van der Woerd (2010) recommend the reintroduction of the Forel-Ule scale (Figure 20) and Wernand (2010) recommends a reintroduction of the Secchi disc to expand another historical data-

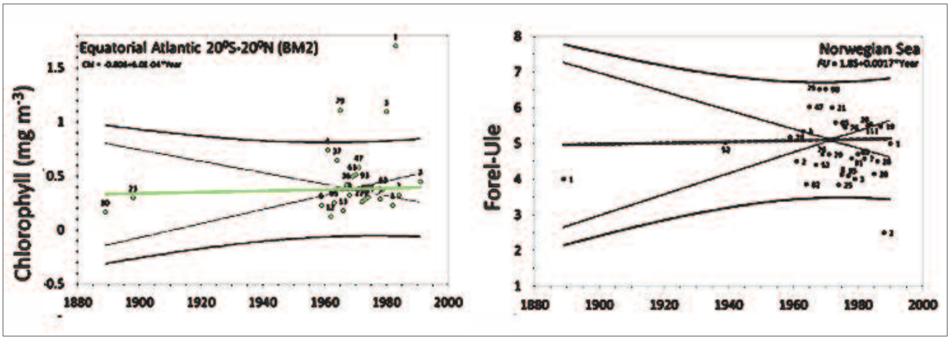


Figure 19: Examples of greening and bluing oceans and seas; arithmetic mean Chlorophyll (Chl, left) and Forel- Ule (FU, right) values. More result to be found in Wernand et al., PloS ONE, 2013.

base, that of the Secchi depth. The classic method to establish colour of natural waters is the comparison of the Forel-Ule scale colours with the colour of the water above a Secchi disc immersed to % Secchi depth (Figure 21). New and easy techniques and methods should be developed to stimulate the collection of these specific data. Collection can be done by sea going oceanographers (40 years ago these were standard observations during scientific cruises), but also by non-citizens, 'the public'. The latter is described, in a modern term, as participatory science. As already mentioned in the introduction a trigger to re-establish the Forel-Ule and Secchi method was made with the start of the international EU project Citizens' Observatory for Coast and Ocean Optical Monitoring (Citclops). The reintroduction of these two historic methodologies will allow the coverage of larger areas of the oceanic and continental waters, and extend this long-term data series, providing two continuous types of measurements, Secchi depth and Forel-Ule index.

Thus, the Citclops project aims to develop an infrastructure that will allow citizens to provide information on the colour of natural waters that can be used, on one hand, by scientists to study ocean colour trends, connecting historic Forel-Ule and Secchi disc observations with future observations provided by the public. On the other hand these data, on the colour and transparency, of coastal and continental waters, can offer information on the water quality in these environments (IOC-

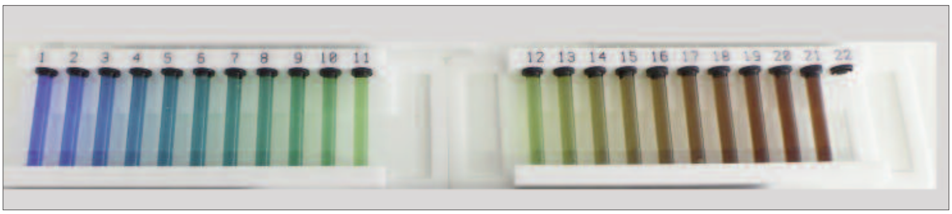


Figure 20: Forel-Ule scale following the original recipes developed by Forel (1890) and Ule (1892). See Novoa et al. (2013) for more details.

CG, Chapter 7, 2008), which is very useful for water quality assessment programs and to policy makers. The colour of water in natural environments is altered by (i) phytoplankton, considered as an indicator of the eutrophication risk, (ii) suspended particulate sediments, and indicators of water pollution as they can negatively impact biological productivity and human health, and (iii) dissolved organic material, also an indicator of water pollution in coastal and continental waters. The colour of the water provides valuable information on the presence of these elements in aquatic environments and therefore be of particular interests to communities affected by a decrease in water quality, thus motivating their participation in the project. It could be argued that new expert methodologies provide a better assessment of water quality and more precise measurements of chlorophyll-a concentrations, however, these methodologies are expensive, time consuming and in general, not able to cover large areas. From a statistical point of view, in order to assess changes in the environment, it is more suitable to have higher numbers of less accurate measurements extended over large areas, than fewer very precise measurements covering more limited regions. Here relies the strength of the project, the capability of obtaining large amounts of consistent data coming from all over the world.

Ideally, the original liquid scale developed by Forel and Ule should be prepared and distributed among citizens. However, its preparation is laborious (see Novoa et al. 2013), and the chemicals used to prepare the solutions can be toxic to humans. For that reason, two low-cost and innocuous products are being developed to determine the colour of natural waters based upon the Forel-Ule index.

The use of smartphones is increasing among citizens, hence the first product developed for the Citclops project is a smartphone application (also known as 'APP') that will be distributed among citizens at no cost. This product is currently under development, but initial tests carried on the field show promising results. Transmission measurements of the Forel-Ule scale prepared according to the inventors' original recipe were used to calculate the colour of the Forel-Ule scale in standard RGB format, a format mainly used in digital devices. The digitised Forel-Ule colours shown on the screen of the smartphone can then be compared by the

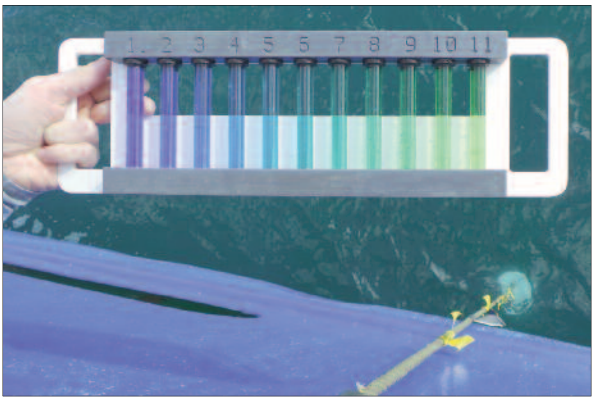


Figure 21: Forel-Ule observation with the original liquid scale using the Secchi disc at half its depth. The colours on the white part of the scale (bottom) are compared to the colour on top of the Secchi disc. In this case the FU colour selected was number 6.

user to the colour observed on the water on top of the Secchi disc, at half its depth. At the moment this can only be completed using a Secchi disc, however, to be able to reach a wider public, work is being conducted towards the development of a colour determination method without a Secchi disc. On the other hand, we consider it still interesting to continue the method that includes the white disc, as it will allow to be able to record its depth and extend the historic water transparency data set.

The second product established within the Citclops project is a Forel-Ule scale (Figure 22, left) developed using plastic filters. The utilized plastics to prepare the scale are low-cost standardised 'LEE' filters (used in theatre lighting). We envisage the use of this scale as a replacement of the liquid scale, a complement to the APP (Figure 22, right), for those who do not own a smartphone or for educational purposes.

These two products still need to be thoroughly validated in the field, by comparing the colour determined with the original Forel-Ule liquid scale and the colour obtained with the APP and the plastic scale (Figure 23). Preliminary results of comparisons carried on in 16 locations across the Netherlands, including rivers, lakes and coastal waters, show promising results. In addition, comprehensive colour measurements will be undertaken in the laboratory in the near future to obtain the most accurate colour matches between the scales. These validations will allow us to trust the measurements acquired by the community and ensure that they can be connected with Forel-Ule and Secchi measurements acquired in the past.

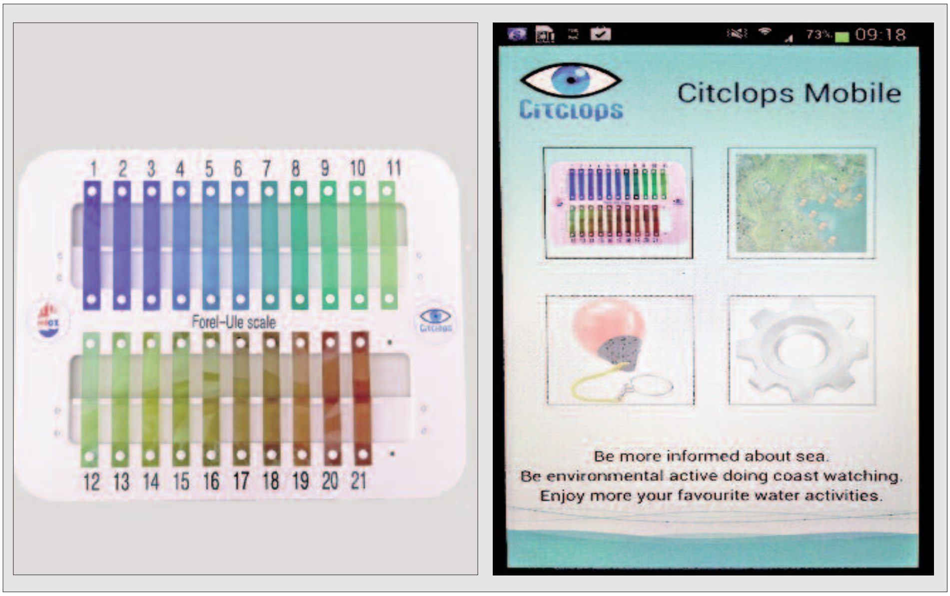


Figure 22, left: Plastic prototype of the Forel-Ule scale developed within the EU Citclops project; right: First prototype of the Forel-Ule Colour measurement APP.

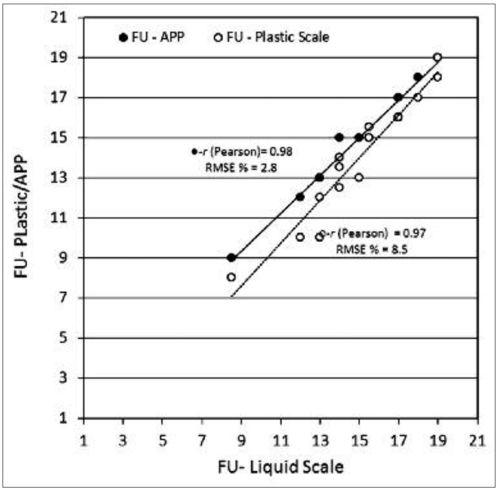


Figure 19: Examples of greening and bluing oceans and seas; arithmetic mean Chlorophyll (Chl, left) and Forel- Ule (FU, right) values. More result to be found in Wernand et al., PloS ONE, 2013.

In summary, the Citclops project aims to introduce tools and develop an infrastructure that will increase the observations concerning the colour and transparency of natural waters by means of participatory science, allowing not only to link the past to the future, but also to monitor the water quality in those environments.

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