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Ocean colour changes in the North Pacific since 1930

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In this paper we present an analysis of historical ocean colour data from the North Pacific Ocean. This colour is described by the Forel-Ule colour index, a sea colour comparator scale that is composed of 21 tube colours that is routinely measured since the year 1890. The main objective of this research is to characterise colour changes of the North Pacific Ocean at a timescale of lustums. Next to the seasonal colour changes, due to the yearly cycle of biological activity, this time series between 1930 and 1999 might contain information on global changes in climate conditions. From seasonal independent analyses of the long-term variations it was found that the greenest values, with mean Forel-Ule scale, $\overline{FU}$, of 4.1 were reached during the period of 1950–1954, with a second high ($\overline{FU} = 3$) in the period 1980–1984. The bluest ocean was encountered during the years 1990–1994. The data indicate that after 1955 a remarkable long bluing took place till 1980. [DOI: 10.2971/jeos.2010.10015s]

Keywords: ocean colour, North Pacific, Forel-Ule scale, global change

1 INTRODUCTION

In 1992, the physical oceanographer Bruce Parker investigated the retrieval of historical oceanographic data and emphasized the importance of the so-called oceanographic "data archaeology" [1]. He stated that "a critical requirement for climate and global change research is the availability of global oceanographic data covering long time periods". The colour of the ocean surface waters is one of parameters that is described for more than 3 centuries [2] and one that is measured quantitatively since the year 1890 [3]. Only records on water temperature [4]–[7], salinity [8] and visibility [9, 10] are collected over a longer time period.

Changes in water colour are caused by a change in the composition of the optically active water-quality parameters, like suspended particulate matter, pigments (mainly chlorophyll-a) in algae and dissolved organic matter. Therefore, ocean colour measurements do contribute to understanding the ecology and biochemistry of the ocean [11]. Because large water masses play a critical role in the Earth's climate, the colour of seawater is listed by WMO as an Essential Climate Variable [12]. For instance Fu *et al.* [13] found that abnormal weather, in this case snowstorms and low temperatures, influenced the ocean colour environment. Venrick *et al.* [14] found a significant increase in total chlorophyll-a, during the summer, over a 20 year time span in the central North Pacific Ocean and concluded in Nature (1987) that long-period fluctuations in atmospheric characteristics (decrease in sea surface temperature, increase in wind forcing in winter) changed the carrying capacity of the central Pacific Pelagic ecosystem.

Since the 1980s, ocean colour data is collected on a massive scale, be means of sophisticated optical sensors, from ships, aircraft and satellites. However, the collection period of the newly gained data is limited and covers only the latest decennia (see, for example Antoine *et al.* [15]). In this paper, by means of the result of oceanographic data archaeology, this period is extended backwards by approximately 50 years. The retrieved historical data were collected with the first ocean colour remote sensing device; the Forel-Ule scale [3].

Limited literature is available on the classification of seas by the analysis of Forel-Ule observations. A few geographical maps, based on interpolation of a limited set of Forel-Ule data, exist from before nineteen-hundred [16]–[19]. Furthermore, the U.S. Navy Hydrographic Office published three atlases on marine geography, including Forel-Ule contours of the Sea of Japan, Korea and Indochina [20]–[22]. In her 1970 Masters thesis, Margaret Ann Frederick presented the first extended atlas on Forel-Ule scale numbers for some of the world seas [23]. To create this atlas on the colours of the sea, Frederick had around 24000 Forel-Ule observations, collected globally, to her disposal. Frederick analysed her data per Marsden square, but did not look for trends.

In this paper, we present a trend analysis of 17171 Forel-Ule observations made in the North Pacific Ocean between the years 1930 and 1999. These observations, extracted from the U.S. National Oceanographic Data Centre (NODC), belong to the oldest instrumental datasets that quantifies the Pacific Ocean. The analysis was focused on data from the open North Pacific at a distance at least 500 km off the coast, in order to avoid direct effects of anthropogenic pressure in the coastal

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zones like enhanced loading of nutrients (euthrophication) or higher sediment loading by changes in land use.

First the Forel-Ule scale is briefly introduced and a summary is given of the data-selection procedure. Subsequently the statistical analysis is presented, providing insight in the ocean colour changes in the last century.

2 THE FOREL-ULE SCALE

The Forel-Ule (FU) scale, recently described by Wernand and van der Woerd [3], consists of 21 discrete colours (sealed glass tubes each containing a specific chemical solution) in the range indigo blue to cola brown. This scale was introduced in the late 90s of the 19th century and covers adequately the colours of natural waters, ranging from the purest (oligothrophic) waters, via waters with higher biological activity (mesothrophic) to waters with high sediment load, high algae concentration or high dissolved organic matter loading. In Figure 1, a colour bar is shown representing the FU colours.

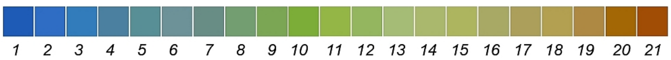

FIG. 1 The colour bar represents the colours of the FU scale with belonging scale number.

In the field, the tube colour of the scale is matched with the actual colour of the sea. The observer holds the scale above the sea surface with the sun at the back and compares the tube colours to the colour of the water column over a submersed Secchi disc located at half the Secchi depth [24, 25]. In a previous study [3], it was shown that the FU scale is a robust and rather objective method for classification of natural waters.

3 DATA SELECTION

FU observations were retrieved from oceanographic and meteorological databases archived by the United States National Oceanographic Data Centre (NOAA-NODC). The NODC global oceanographic dataset, retrieved in 2007, contained 221137 FU observations. First the comma separated values were converted into Excel format and data with NODC codes higher than 21 were removed. The codes 31 to 37 are colours outside the FU comparator range (see Table 1 for an explanation). Two new columns were added to flag the season and 5-years time interval. The seasons were selected according to a meteorological division, i.e., winter covers the months 12, 1 and 2, spring covers months 3, 4 and 5, summer covers months 6, 7 and 8 and autumn covers months 9, 10 and 11. The winter period starts with month 12 of the previous year. Because the size of the data collection was not uniform over the years, multiple years were binned to increase the statistical significance. In this analysis, data are binned in 5-years intervals, starting with the years 1930–1934.

Data collected with a sea area flag of NP or PHS (Philippine Sea), based on the latitude and longitude conventions of the U.S. Geological Survey (USGS), were merged and are referred to as the North Pacific dataset. To avoid the influence of terrestrial run-offs on open ocean water, a so-called mask was created to extract data, at a distance greater than 500 km off the coast, for statistical analysis. The mask was created using the GIS (Geographic Information System) software package from ESRI, ArcMap 9.3.

NODC code	Observed colour
1 to 21	Forel-Ule
31	Green
32	Blue
33	Grey
34	Red
35	Chalky
36	Brown
37	Luminescent

TABLE 1 The NODC FU-codes explained.

4 METHODS

The analysis is based on a univariate representation of quantitative data samples (in this case the FU numbers) in a "box and whisker" diagram [26]. This is a simple and quite complete representation of the statistical properties of the dataset that is graphically displayed. The plot displays the position of the 1st quartile ($Q1$), median ($Q2$), arithmetic mean and 3rd quartile ($Q3$). In addition, limits are displayed in black (lower and upper limits are the ends of the "whiskers") beyond which values are considered anomalous. Consider a sample made up of n FU observations denoted by $(FU_1, FU_2, ..., FU_n)$. The arithmetic mean of this dataset, $\overline{FU}$, is defined as [27]

$$\overline{FU} = \frac{1}{n}\sum_{i=1}^{n} FU_i. \quad (1)$$

Outliers are defined as values that are more than 1.5 times outside the interquartile range. In Figure 2, an example of a box plot is shown. The arithmetic mean, $\overline{FU}$, is displayed by a red plus sign ($+$), and a black lines corresponds to the quartiles ($Q_{1,2,3}$). The blue rhombuses ($\diamondsuit$) correspond to the minimum and maximum values. Outliers, more than 1.5 times the interquartile range, i.e., values that are in the $[Q_1 - 1.5 \times (Q_3 - Q_1); Q_1 - 1.5 \times (Q_3 - Q_1)]$ or the $[Q_3 + 1.5 \times (Q_3 - Q_1); Q_3 + 3 \times (Q_3 - Q_1)]$ intervals, are represented by a hollow circle ($\circ$). Extreme outliers, more than 3 times the interquartile range are displayed by an asterisk ($*$).

Accordingly, from the North Pacific FU data a graph is presented with the mean, upper and lower bound per season and per five-year interval to detect possible trends. Let $S(n-1)$ be the standard deviation from the set of n FU observations. From the standard error of the mean

$$SE_{\overline{FU}} = \sqrt{\frac{S(n-1)^2}{n}}, \quad (2)$$

the lower bound on mean, corresponding to the lower bound of the 95% confidence interval of the mean, is defined by

$$L_{\overline{FU}} = \overline{FU} - SE_{\overline{FU}} \times z \quad (3)$$

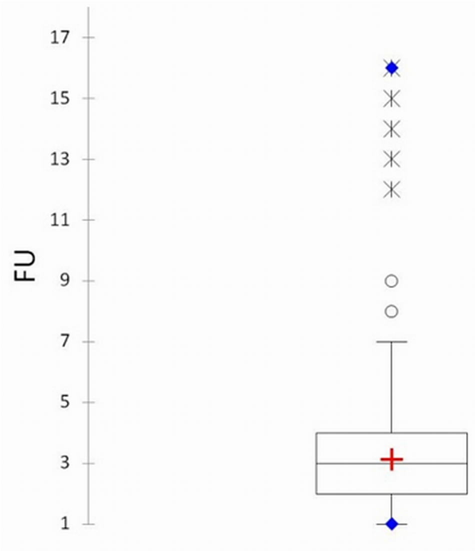

FIG. 2 An example of a box or univariate plot.

where $z = 1.96$ for a confidence interval of 95% [28]. The upper bound on the mean, is calculated accordingly (sign changes to +).

5 RESULTS

A total number of 17171 FU observations were selected over the period winter 1930 to autumn 1999. In Table 2, the number of observations for each season with belonging percentage of the total is given. This table demonstrates that the observations are well spread over the seasons.

Figure 3 shows the FU data distribution over the North Pacific. The shape of the applied data extraction mask, greater than 500 km off coast, can be clearly seen East of Japan. The North Pacific is very well covered; with the exception of the Eastern part (135°E to 145°E) and the North-Eastern part (above 30°N and East of 170°E). In Table 3, the $\overline{FU}$ for the North Pacific for each season is given, together with the lower (L) and upper (U) bound on mean with a 95% confidence.

From Table 3, we conclude that the North Pacific can be called a "blue ocean" with a mean $\overline{FU}$ colour scale of 2. During the winter and autumn, the ocean turns slightly bluer towards a $\overline{FU} = 1.8$ (bluing of the ocean) and in summer the ocean's

Total	17171
Winter	3481
W-%	20.3
Spring	3923
SP-%	22.8
Summer	5371
S-%	31.3
Autumn	4396
A- %	25.6

TABLE 2 The total number of FU observations collected at a distance greater than 500 km off coast during 1930 to 1999 in the North Pacific and the number of observations with a percentage of the total per season.

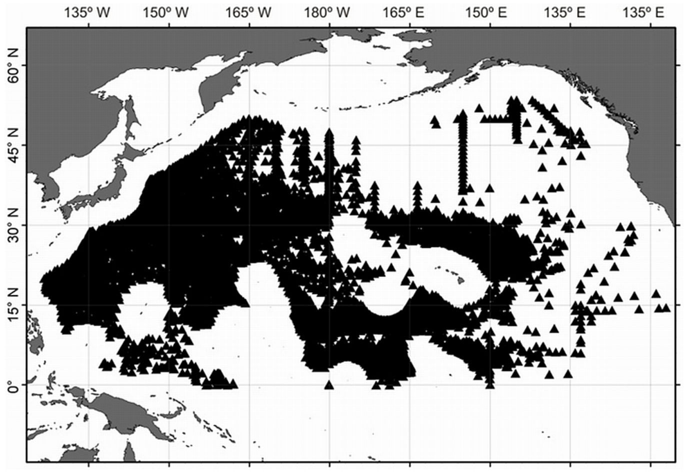

FIG. 3 All North Pacific FU observations collected between 1930 and 1999 at a distance of over 500 km off coast.

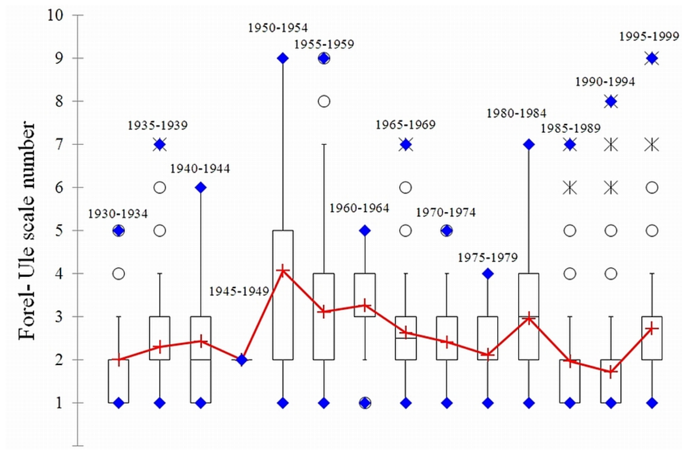

FIG. 4 A box plot of all FU data collected in the North Pacific binned in 5-year intervals. The red line indicates the variation of the mean FU-number over time. The greening of oceanic water reaches a maximum between 1950 and 1954. After this period, the water is bluing again to a $\overline{FU} = 2.1$ in the 1975–1979 period. Hereafter follows an increase to a $\overline{FU} = 3$ and during the 1990–1994 decade the $\overline{FU}$ reaches its overall minimum value $\overline{FU} = 1.7$. The ocean is at its bluest.

$\overline{FU}$ shifts upwards to 2.3 (greening of the ocean) by enhanced biological activity (presence of algae). A prominent influence on the results of the calculation of the overall $\overline{FU}$ is due to the numerous observations collected during 1985–1994.

A box plot of the FU data grouped in 5-years bins is shown in Figure 4 with respectively in red the variation of over time, the Q_1 and Q_3 values, outliers and in blue the minimum and maximum FU values. The figure shows two anomalies; an increase of the colour from 2 to 4 during 1930-34 to 1950-54 and a less pronounced increase of the from 2 to 3 between 1975 and 1985. In both cases the ocean is greening. During 1950–1954 to 1975–1979 and 1980–1984 to 1990–1994, the ocean slowly turns blue again.

The greening of the ocean starts again after 1994. We have to bear in mind that data are not seasonally split at this point. During 1945–1949, only two colour observations were made in total, therefore the period is omitted from the data analysis.

In order to investigate if this temporal behaviour is related to

$\overline{FU}$	2.0	Winter	1.8	Spring	2.0	Summer	2.3	Autumn	1.8
$L_{\overline{FU}}$	2.0	$L_{\overline{FU-w}}$	1.8	$L_{\overline{FU-sp}}$	2.0	$L_{\overline{FU-s}}$	2.2	$L_{\overline{FU-a}}$	1.8
$U_{\overline{FU}}$	2.0	$U_{\overline{FU-w}}$	1.9	$U_{\overline{FU-sp}}$	2.0	$U_{\overline{FU-s}}$	2.3	$L_{\overline{FU-a}}$	1.8

TABLE 3 The $\overline{FU}$ for the North Pacific with, the lower (L) and upper (U) bound on the mean (95% confidence) for all seasons and for each of the four seasons (w = winter, sp = spring, s = summer, a = autumn).

changes in a seasonal cycle,the primary production data was split into seasons. In Figure 5, the black dots represent the $\overline{FU}$ per time bin. The dotted lines indicate the lower and upper bound on the mean, $L_{\overline{FU}}$ and $U_{\overline{FU}}$, respectively.

The top graph shows the $\overline{FU}$ over all seasons. The graphs below show data for each season per 5-years bins. For all seasons between 1930 and 1949, the North Pacific is dark blue with a $\overline{FU}$ of 2.2. During the next years, 1950–1954 the water is greening to a $\overline{FU}$ of 4.1. The next 25 years, the ocean is bluing again slowly until the 1975–1979 period. Hereafter, a period of greening (1984–1989), a period of bluing (1985–1994) and a last period of greening can be recognized (1995–1999). Concerning "the all season" colour of the North Pacific it is the period 1990–1994 that shows the bluest colour with a $\overline{FU}$ of 1.7.

As shown in Figure 5, the period 1950–54 concerning the North Pacific's colour can be marked as a remarkable period as for winter, spring and autumn the highest $\overline{FU}$ values (4 to 5) are encountered. For the summer, this period of highs occurs during 1950–1965 with a maximum $\overline{FU} \approx 4$ during 1955–1959. All seasons more or less show the same features. Looking at the highs in the periods 1950–1954 and 1980–1984 of the seasonal curves shown in Figure 5 we can conclude that within a relative short period of 5 years the ocean can green significantly while the reversed process, the transition greenish blue to blue, takes a longer time.

Venrick *et al.* [14] mentioned, in their 1987 Science publication, that a significant increase of integrated chlorophyll-a in the water column during May-October in the central North Pacific Ocean could be observed during 1968–1985. This is in full agreement with our findings. The summer graph of Figure 5 shows an increase in colour from blue to blue-green in the period 1975–1984. The autumn graph shows that the ocean already starts to green significantly during the lustrum 1970–1974. Ocean colour is strongly related to the chlorophyll, i.e., an increase in chlorophyll means greening. Furthermore, the "all seasons" graph of Figure 5 shows a contiguous bluing and greening during 1985–1994 and 1995–1999 respectively.

Antoine *et al.* [15], in search for long term trends in ocean colour, globally compared Coastal Zone Colour Scanner data (CZCS, 1979–1986) with Sea-viewing Wide Field-of view Sensor (SeaWiFS, 1989–2002) data. One of the outcomes, a ratio of the logarithm of SeaWiFS to CZCS data, was an overall increase of the world ocean average chlorophyll concentration of 22%, although mainly found in inter-tropical areas. In contrast, they found in oligotrophic gyres a declining of the chlorophyll concentration. Their findings mean a greening of the inter-tropical areas and a bluing of the oligotrophic gyres. When we compare their presented annual North Pa-

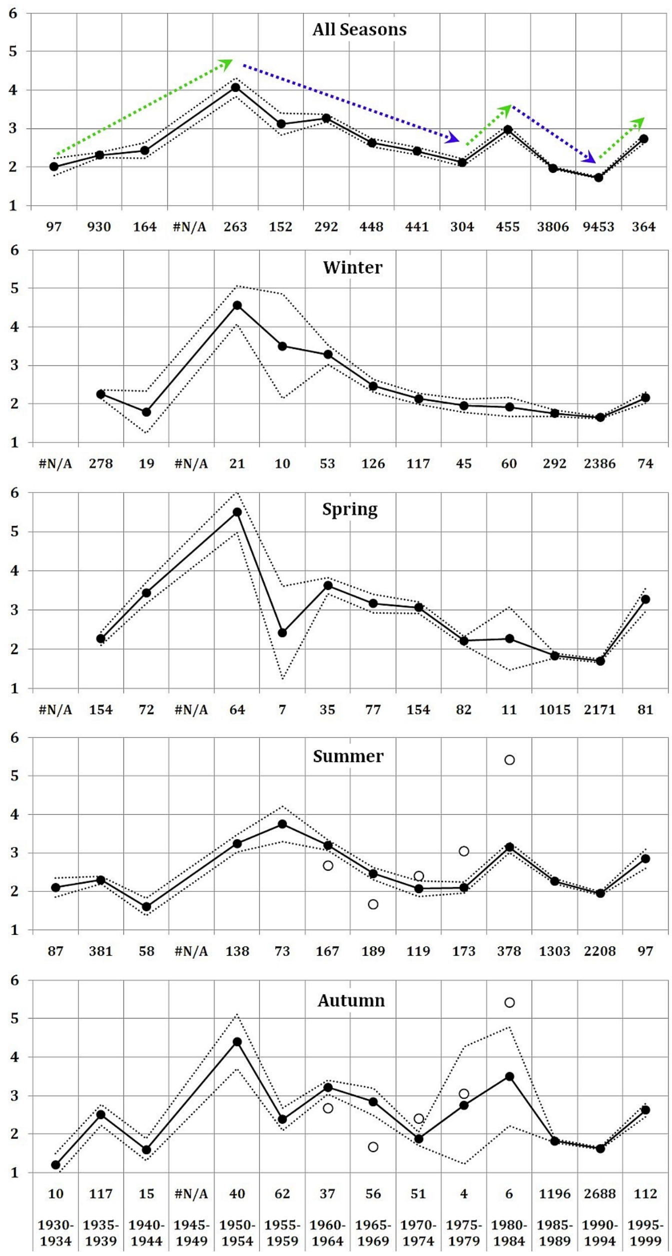

FIG. 5 Seasonal North Pacific means $\overline{FU}$ (black dots with connecting line), per lustrum including the number of observations, collected between 1930 and 1999 (#N/A means no or omitted data). The dotted lines indicate the lower and upper bound on the mean, $L_{\overline{FU}}$ and $U_{\overline{FU}}$. In general, a trend, the greening of the water between 1930 and 1954, can be detected for all seasons. After the 1950s, the colour is slowly bluing, hereafter a greening period with a high in the 1980–1984 period and a low in the 1990–1994 period. Then the greening starts again. Per 5 years averaged total chlorophyll-a (Venrick *et al.* [14]) are shown as open circles in the summer and autumn graph. The integrated chlorophyll-a collected during May-October varies between 12 mg m^2 and 24 mg m^2.

cific chlorophyll ratio average, of the area presented in Figure 3, we indeed see a bluing. Although small, comparing the

1980–1984 and 1995–1999 period (see Figure 5, all seasons) the result presented here is similar to the results described by Antoine *et al.* One must bear in mind that comparing intermediate periods between 1980 and 2000 the bluest North Pacific oligotrophic water is found in the 1990–1994 period, as mentioned before.

In 2001, Karl *et al* [29] presented results on long-term changes in plankton community structure and productivity in the North Pacific subtropical gyre. One of their graphs, showing the standing stock chlorophyll concentration over the period 1965 to 2000 shows a maximum in euphotic zone depth-integrated chlorophyll concentration during 1980–1984 and is confirmed through our findings; a short greening of the North Pacific.

6 CONCLUSIONS AND RECOMMENDATION

We have presented FU observations collected over seventy years in the North Pacific from which the oldest observations date back to 1930. It is one of the very few long-term oceanographic datasets archived by NOAA-NODC. The data was averaged in 5-year intervals (lustrum) between 1930 and 1999. To characterise colour changes and to identify inter-lustrum patterns 17171 observations located over 500 km off-coast were analyzed to establish the mean FU colour for all season and per season. It was found that concerning its colour the North Pacific can vary significantly between blue and greenish-blue covering the FU scale colours 1 to 6. Interestingly, it was found that this variation is only partly due to a yearly repetitive variation in the biological activity over the seasons.

Averaged over all seasons the greenest values with a $\overline{FU} = 4.1$ were found during the years 1950–54, with a second high of $\overline{FU} = 3$ in the period 1980–1984. The bluest ocean was encountered during 1990–1994. Hereafter, the ocean trends to green again. A remarkable long period of bluing took place between 1950–1954 and 1975–1979.

A significant increase in total chlorophyll-a in the water column during summer in the North Pacific between 1968 and 1985 as described by Venrick *et al.* is confirmed by the outcome of our research.

Ocean colour (biological activity), in this case the FU colour, is an essential climate variable. Future work will focus on the link between (climate) forcing factors that control the changes in colour, e.g. by historical FU observation analysis of other world oceans and merging of FU data sets with satellite derived ocean colour data.

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