The Faroese Fisheries Laboratory

Fiskirannsóknarstovan

Light in Faroese Waters

by

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Table of contents

Table of contents 2
1 Introduction 3
2 Irradiance above the sea surface 4
2.1 Observations made by the Office of Public Works 4
2.2 Irradiance observations from Iceland 6
2.3 Irradiance from Satellite observations 7
2.4 FRS irradiance 8
2.5 Irradiance in air from R/V Magnus Heinason 9
2.6 Concluding remarks on irradiance in air 11
3 Irradiance in water 12
3.1 Underwater irradiance observations from R/V Magnus Heinason 12
3.2 Attenuation coefficient 14
3.3 Comparison of air and under-water irradiance 15
3.4 Concluding remarks on irradiance in water. 15
4 Conclusion 16
5 References 17

• Introduction

In recent years it has become clear that there are large interannual variations of the primary production in Faroese waters (Gaard *et al.* 1998) and that these have profound impacts on the fish production (Gaard *et al.,* 2002). This has stimulated an effort by the Faroese Fisheries Laboratory (FRS) towards better understanding of the processes controlling the primary production, including both observational and modelling activities. The possibility to model the marine primary production was greatly facilitated by a grant from the *"Faroes Partnership"* and the work reported here has to a large extent been funded from this grant.

Primary production in the sea, as on land, depends upon a number of factors, but light is perhaps the most fundamental of these, since the plants, phytoplankton in this case, take their energy from light. A description of underwater irradiance in Faroese waters is therefore a prerequisite for modelling the primary production and it is the aim of this report to provide this description.

To a large extent, the report is based on general information from other areas, but these cannot be applied uncritically, since site-specific factors, such as cloud cover and light attenuation, affect the irradiance. Unfortunately, knowledge of irradiance available in Faroese waters is very limited. In order to measure the irradiance in Faroese waters the Research Vessel Magnus Heinason (MH) has carried out regular irradiance observations in water since 2001 and in 2003 The Faroese Fisheries Laboratory (FRS) started parallel monitoring of the irradiance on land and sea.

The report is structured into two main chapters. First, the available information on above-surface irradiance in the Faroes is summarized and then, sub-surface irradiance is discussed.

Since the primary aim of the report is to provide input to biological modelling, the focus is on those aspects of irradiance which are important in that respect and this also affects the choice of units. The irradiance used in photosynthesis is photons with wavelength 400-700nm (Photosynthetically Available Radiation – PAR). Usually the irradiance in PAR is given in

$$No.photons \frac{1}{m^2 s} = \frac{No.photons}{N_A} \frac{Einstein}{m^2 s} \ ;$$

i.e. the number of photons reaching a horizontal square meter pr second. *1 Einstein* (*E*) is *1 mol photons*.

• Irradiance above the sea surface

• Observations made by the Office of Public Works

The Office of Public Works, Landsverkfrøðingurin (LV) has carried out irradiance observations during 10 years (1987-1996) on 8 different locations on the Faroe Islands (Heinesen, 1997). The irradiance is measured in energy [W/m^2] in the spectral interval 300*nm* – 2500*nm*. Two operations have to be done in order to convert this to PAR. First, the spectral interval has to be reduced to the PAR interval. Approximately 43% of the irradiance energy is in the PAR interval (Jerlov, 1976):

$$E(400nm-700nm)=0.43\cdot E(350nm-3000nm) \qquad [\mathrm{W/m^2}] \qquad (2\text{-}1)$$

This formula is valid in the interval 350nm – 3000nm. By looking at the complete spectrum of the downward irradiance, it is seen that only about 1% of the irradiance is received in the interval 300*nm* – 350*nm* and less in the interval 2500*nm* – 3000*nm*. Therefore this formula is used to convert the observations from LV [W/ m^2] in the interval 300*nm* – 2500*nm* to [W/ m^2] in PAR.

The second step is to convert the energy to quanta and this conversion factor is given as (Jerlov, 1976):

$$PAR\left[\frac{quanta}{m^2 s}\right]=2.75\cdot 10^{18}\cdot PAR\left[\frac{W}{m^2}\right]$$

$$PAR\left[\frac{E}{m^2 s}\right]=4.566\cdot 10^{-6}\cdot PAR\left[\frac{W}{m^2}\right] \qquad (3\text{-}2)$$

Another conversion factor is given in the Chelsea calibration certificate, and this conversion factor is a few percent different (3-3):

$$PAR\left[\frac{E}{m^2 s}\right]=4.234\cdot 10^{-6}\cdot PAR\left[\frac{W}{m^2}\right] \qquad (3\text{-}3)$$

Equation (3-2) has been used to convert the LV irradiance from energy to photons, while equation (3-3) has been used to convert irradiance observed with the Chelsea PAR sensor to photons.

The observations contain an average value for each month. The observations are performed on land, which generally is expected to be cloudier than on open sea.

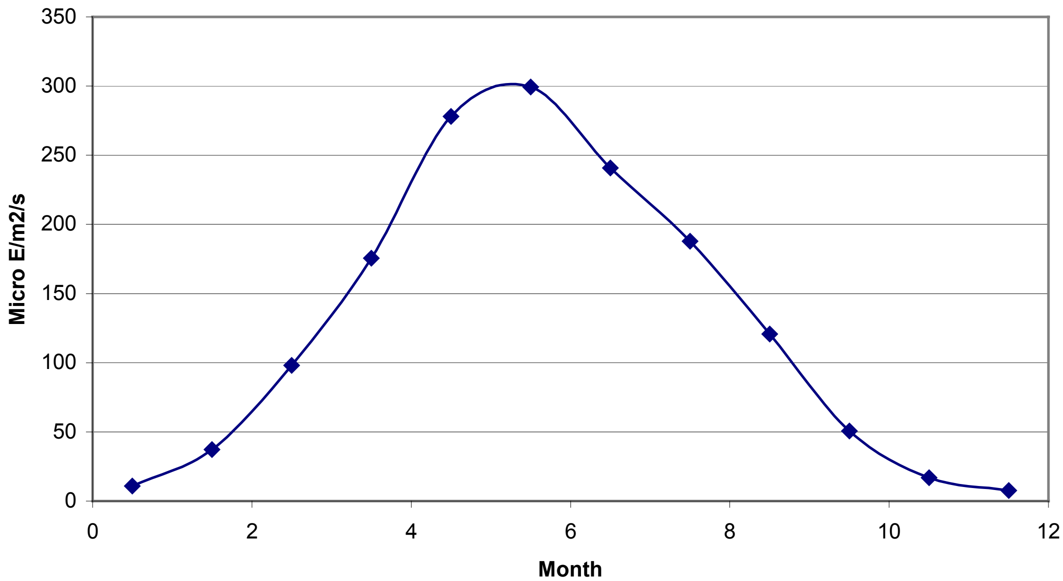

Figure 0-1.Average LV irradiance observations during 10 years. The dots are the average values from all stations.

In order to simulate the real irradiance during a month, the average irradiance is interpolated by a general Lagrange interpolation polynomial. In this way it is possible to calculate the average irradiance every day (Figure 0-1).

The average daily irradiance value is used to simulate a daily irradiance variation. The procedure is as follows:

If there was no atmosphere, the irradiance at ground level would be proportional to the sine of the solar elevation angle α. The effect of the atmosphere varies depending on cloud cover etc, but comparison to observations, indicates that the irradiance can be fairly well approximated by the equation:

$$I = I(\sin\alpha) = \begin{cases} I_0 * \dfrac{\cos(\sin(\alpha)+\pi)+1}{2}; & \alpha \geq 0 \\ 0; & \alpha < 0 \end{cases} \qquad (3\text{-}4)$$

where $\sin\alpha = \sin\varphi \sin\delta - \cos\varphi \cos\delta \cos\tau$;

φ is the latitude

$$\delta = 23.45 \sin(\tfrac{JD-91}{365} \cdot 360) \qquad (3\text{-}5)$$

JD is Julian day number and τ is the decimal time of the day, $0 \leq \tau < 1$ (Sakshaug *et.al.*, 1992).

From these equations, the intensity I_0 can be related to the average daily irradiance:

$$\langle I \rangle = \frac{1}{T}\int_0^T I(\sin\alpha(t))dt = \frac{1}{T}\int_{t=sunrise}^{t=sunset} I_0 \frac{\cos(\sin(\alpha(t))+\pi)+1}{2}dt$$
$$= \frac{I_0}{T}\int_{t=sunrise}^{t=sunset} \frac{\cos(\sin(\alpha(t))+\pi)+1}{2}dt \cong \frac{I_0}{T}\sum_{t=sunrise}^{t=sunset} \frac{\cos(\sin(\alpha(t))+\pi)+1}{2}\Delta t$$

(3-6)

and from this I_0 can be found by numerical integration:

$$I_0 = \frac{\langle I \rangle T}{\sum_{t=sunrise}^{t=sunset} \frac{\cos(\sin(\alpha(t))+\pi)+1}{2}\Delta t}, \tag{3-7}$$

and $I(t)$ computed (Figure 0-2).

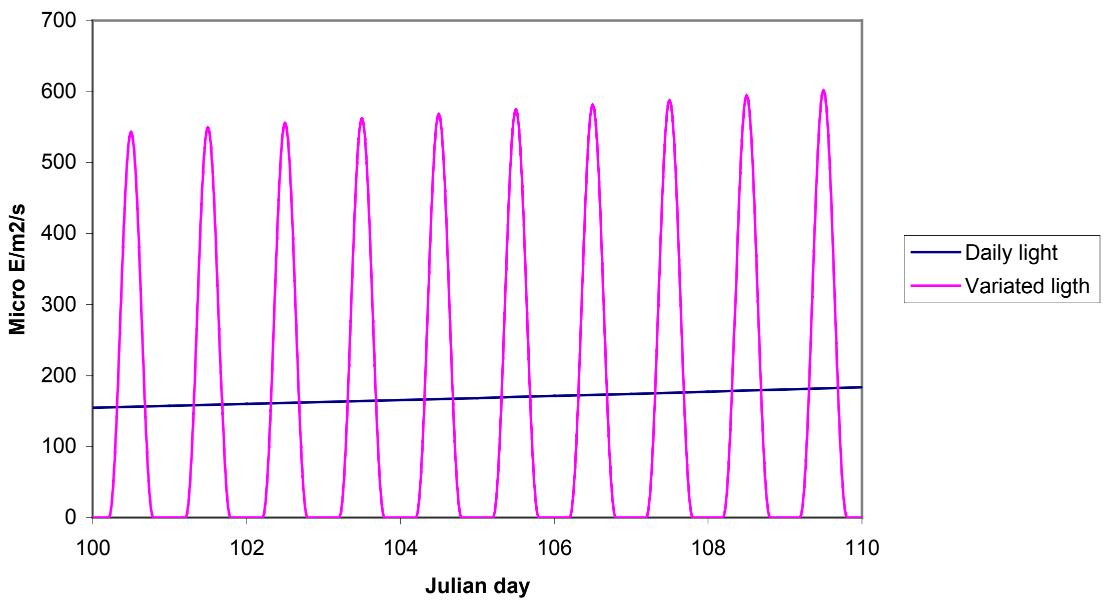

Figure 0-2.The daily variation in irradiance computed from average daily irradiance and sun angle

This method, of course, gives a very regular irradiance series, increasing the first half of the year and decreasing the second half. It takes into account variations of cloud cover on monthly time scales, but not more rapid variations. This series will be used in the comparisons below.

- ## Irradiance observations from Iceland

In order to estimate whether the LV irradiance, converted from energy in 350-3000*nm* to photons in 400-700*nm* interval is correct, we have compared it to irradiance observations from Vestmannaeyjar in Iceland. This is approximately on 63.5º latitude, i.e. 1.5º further north than the Faroe Islands. From (Sakshaug *et.al.*, 1992), fig 5.2, we expect the irradiance in Iceland to be less than the Faroese in the winter, but approximately the same in the summer. The Icelandic irradiance observations are from the years 1989-1991 and are measured in quanta in PAR.

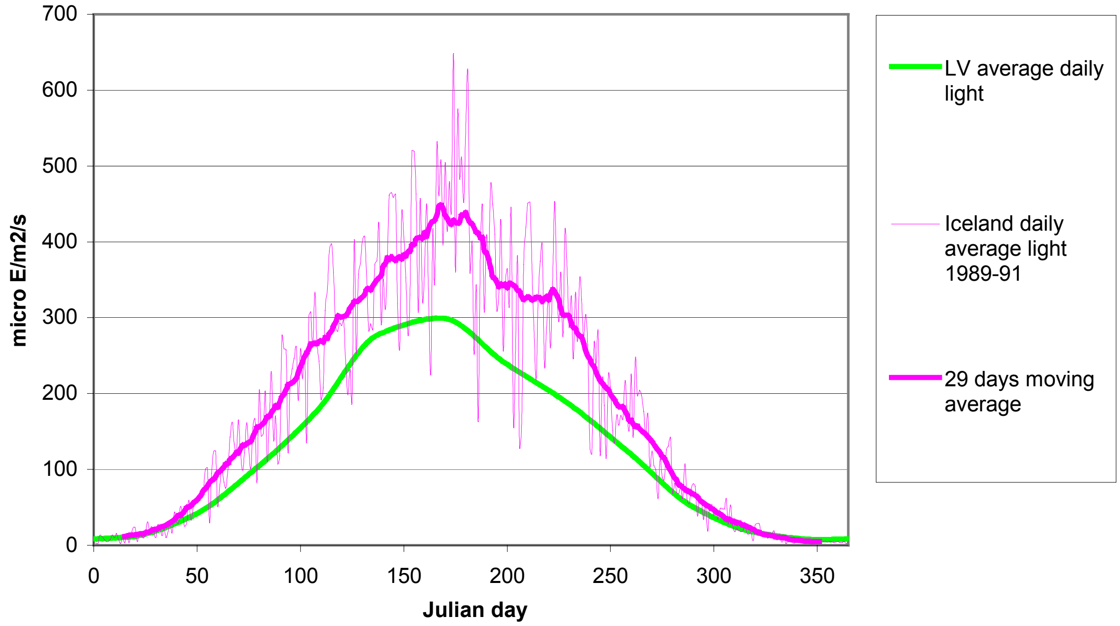

Figure 0-3. PAR irradiance from Vestmannaeyjar, Iceland, 1.5º north of Faroe Islands from 1989-1991. Plotted together with the LV PAR irradiance.

Figure 0-3 shows irradiance observations from Iceland compared with LV observations. In the winter the Icelandic irradiance is approximately the same as the Faroese, while it is higher in the summer. The discrepancy can either be ascribed to annual variations, to different observations methods or to bias in one of the observations.

- # Irradiance from Satellite observations

From an internet site: http://satel-light.com, it is possible to download irradiance from Torshavn, Faroe Islands. This irradiance is deduced from satellite irradiance observations during 1996 – 1997 and has naturally more variations than the LV irradiance since the sampling is every half hour.

The Satel irradiance is measured in quanta in PAR. Comparing the Satel irradiance with LV (Figure 0-4) shows that the Satel irradiance in average is 20-25% higher than the LV 10 years average.

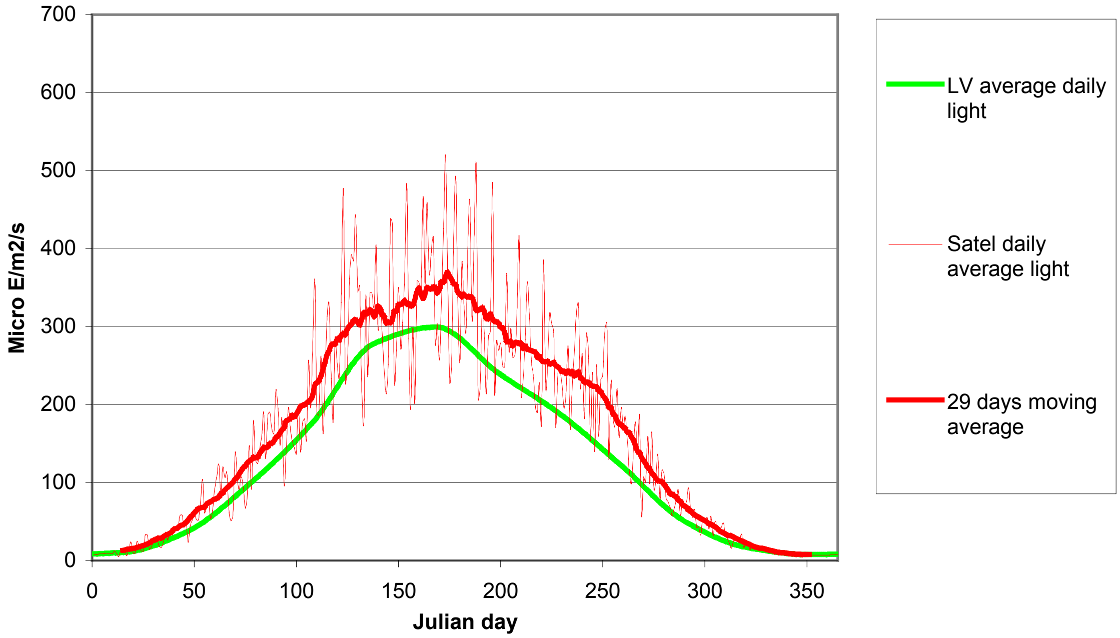

Figure 0-4. PAR irradiance obtained from satellite observations during 1996-97. Plotted together with the LV PAR irradiance.

- ## FRS irradiance

Because of the sparse information on irradiance in the Faroe Islands, an irradiance observation program was initiated in 2003. Irradiance sensors are mounted on R/V Magnus Heinason (MH) and on the office building of the Faroese Fisheries laboratory (FRS). These sensors started to measure at the end of March, and still there are very few data. The first observations from land are processed and compared with the other datasets from the Faroes. (Figure 0-5).

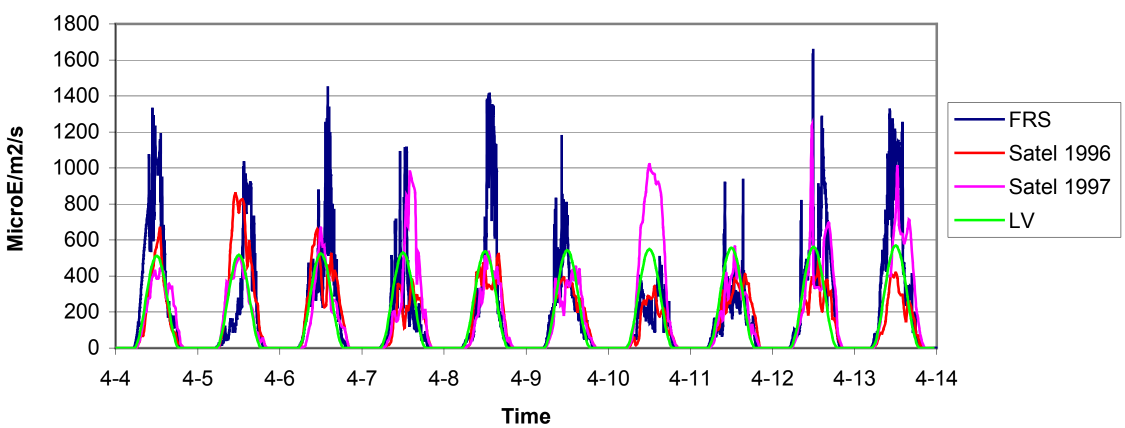

Figure 0-5. PAR irradiance observations at FRS from April 2003 plotted together with Satel and LV PAR irradiance.

The irradiance observations from FRS show higher irradiance values this first month than LV which is expected since the LV series generally is lower than the others. The irradiance from FRS has also been compared with the Satel irradiance from 1996-97, which seems to be comparable with the irradiance observed on FRS most of the days. The high values in the FRS series can be due to very fine weather this April.

- ## Irradiance in air from R/V Magnus Heinason

With the new irradiance monitoring program started in 2003, irradiance is observed both on land and sea in order to estimate the difference that can be expected from differences in cloud cover etc. In Figure 0-6 and Figure 0-7 the irradiance sensors have been compared during a period when the ship was alongside a pier close to the office building (about 1 km) in order to check their relative calibration. It seems as if the ship sensor shows slightly lower values than the land sensor when observing high values, while close to dawn it is the opposite. The difference between the sensors is not constant, being app. 5% or less at 10 o'clock in the morning (Figure 0-7).

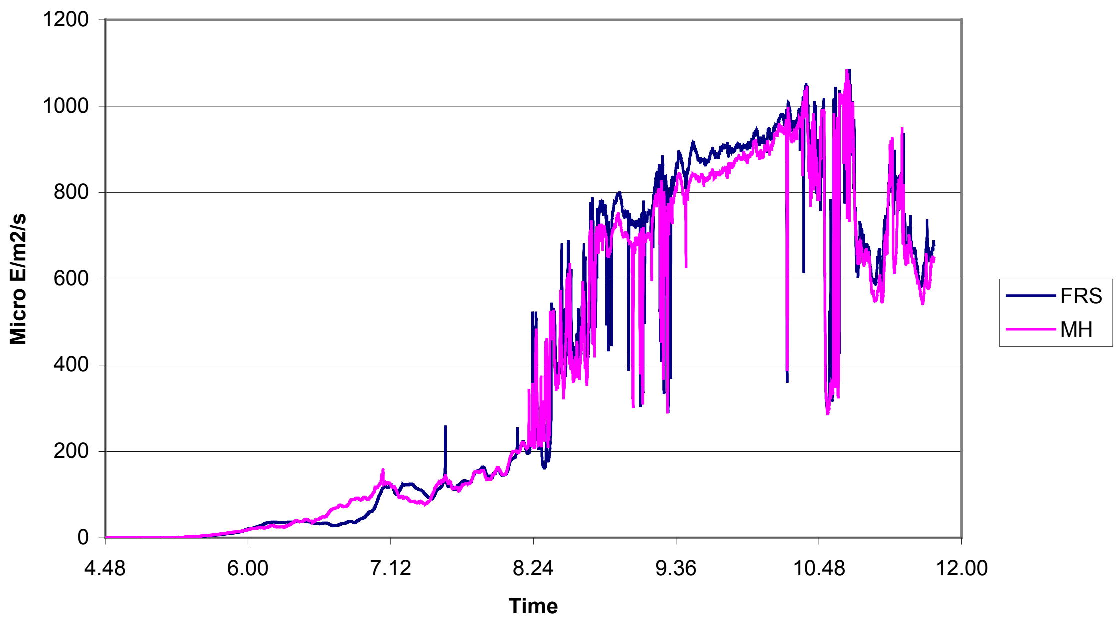

Figure 0-6.Comparison of irradiance sensors 01.04.2003. The research vessel is in harbour, app. 1 km away from the office.

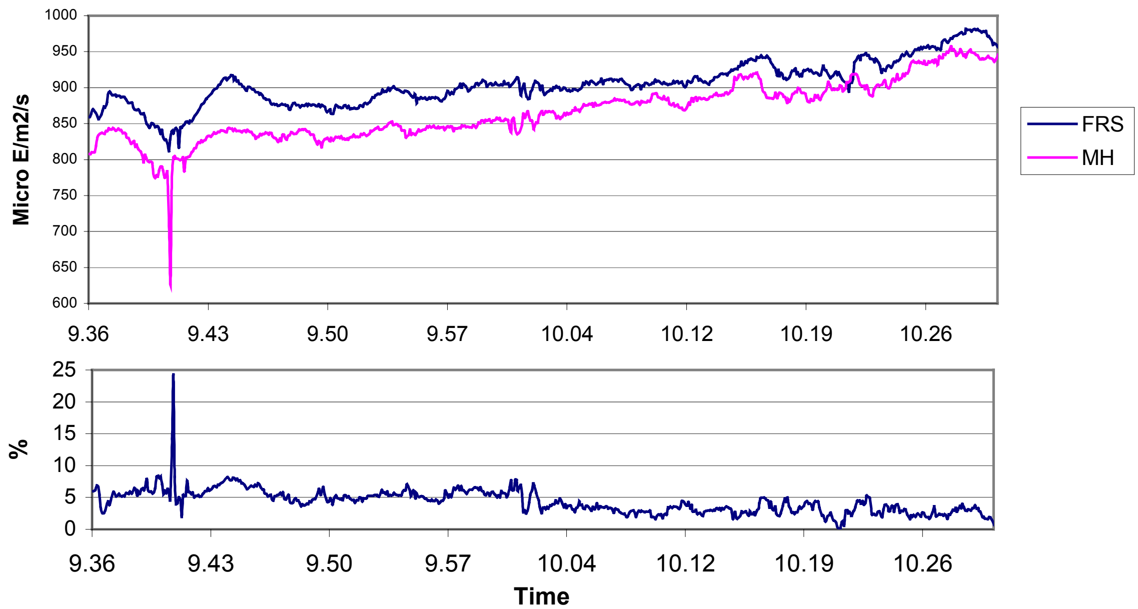

Figure 0-7. Part of the irradiance series in Figure 0-6 showed for comparison. Upper panel is the observations, lower panel shows the difference in percents

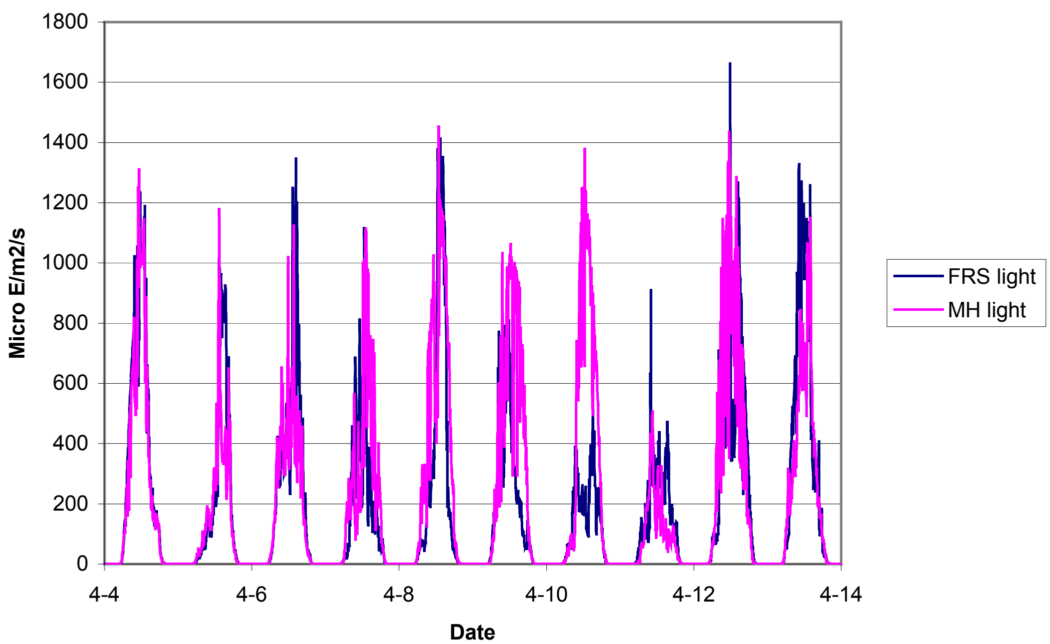

Figure 0-8. Irradiance observations from land and sea.

The parallel acquisition of land-based and ship-borne irradiance measurements has run for too short a period to allow any comparison as this report is being written but Figure 0-8 shows a ten days period with observations of irradiance in air from land and sea as illustration.

- ## Concluding remarks on irradiance in air

There are five different irradiance series from Faroe Islands and Iceland, that have been compared in the PAR spectrum. The LV series is always lowest when compared to the other four, indicating that this series might be slightly too low (20-25%). The Icelandic irradiance is the highest, despite the more northerly location. This can be due to annual variations or different observation methods. The Satel data series, being higher than LV, less than the Icelandic, and comparable with the FRS and MH irradiance series for the short period these two are available, seems reliable together with the FRS and MH observations. Therefore, although the LV series might be too low, the LV and Satel have a good quality, and can be used in the marine ecosystem model, provided that the LV series is used with care. The irradiance observation program, started in 2003, will provide more good quality data, which can be used in the ecosystem modelling in the future.

• Irradiance in water

When light reaches the water surface, one part is reflected at the surface, and the rest is transmitted into water where it is refracted by Snell's law, and changes direction, depending on the refraction index and incoming angle. The ratio of transmitted irradiance to incident irradiance is given as:

$$T = 1 - \frac{1}{2}\left(\frac{\sin^2(i-j)}{\sin^2(i+j)} + \frac{\tan^2(i-j)}{\tan^2(i+j)} \right) \qquad (3\text{-}1)$$

where i is the incoming angle and j the transmission angle. This formula is valid for a plane surface, which the sea, of course, is not. Observations show that the transmission is higher on a rough surface, but this will be neglected here (Sakshaug *et.al.*, 1992).

In the water, the light will be attenuated exponentially as it travels downwards:

$$I(z) = I_0 e^{-kz}, \qquad (3\text{-}2)$$

where I_0 is the initial irradiance transmitted through the sea surface. The attenuation coefficient k depends on the visibility in water and can be determined from irradiance observations down through the water column.

• Underwater irradiance observations from R/V Magnus Heinason

Systematic measurements of underwater irradiance from R/V Magnus Heinason have been carried out at CTD stations since early 2001. In 2001, the observations were carried out with a Chelsea PAR irradiance meter, lowered separately into water. From the beginning of 2002, a Biospherical Instruments photometer has been mounted on the CTD, measuring while the CTD is lowered through the water. For the observations from 2001, the ship was generally oriented to prevent shading, but this has not been the case since then.

As an example, Figure 0-1 shows irradiance measured at one station by the Chelsea Par irradiance meter in 2001. The exponential decrease is clear from the lowest plot. In a similar manner, Figure 0-2 exemplifies the measurements in 2002.

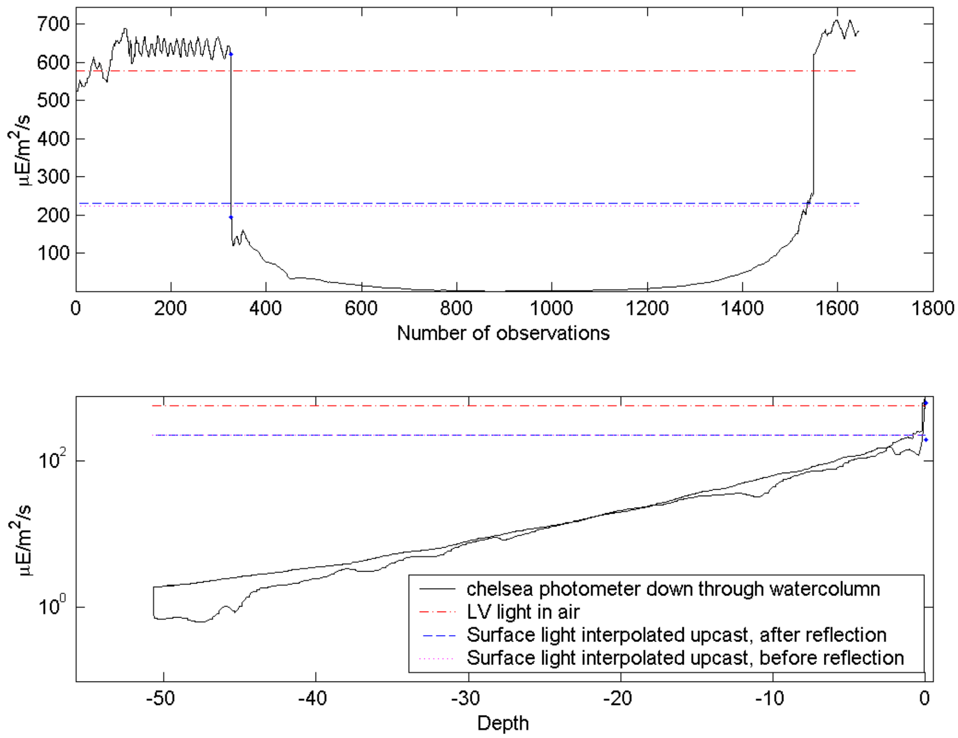

Figure 0-1. Irradiance measured down through the uppermost 50 m on day 189 in 2001, starting at 11:56 GMT. Top panel shows irradiance (in a linear scale) against time. Lower panel shows irradiance (in a logarithmic scale) against depth.

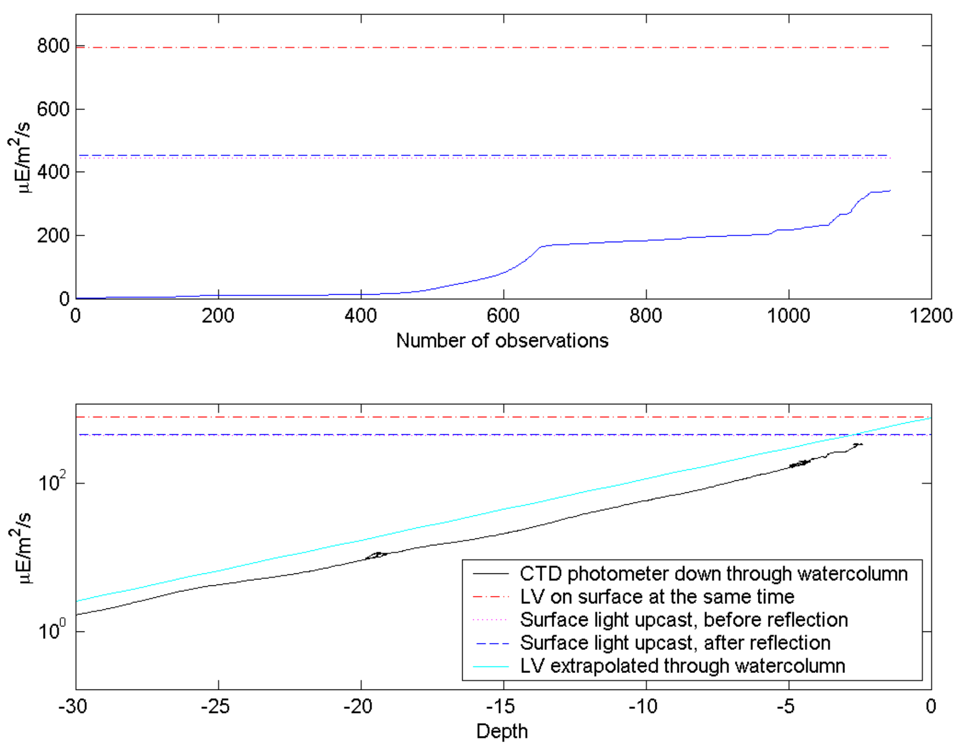

Figure 0-2. Irradiance measured down through the uppermost 30 m on day 180 in 2002, starting at 12:30 GMT. Top panel shows irradiance (in a linear scale) against time, observed upcast. Lower panel shows irradiance (in a logarithmic scale) against depth.

- **Attenuation coefficient**

Based on the observations from R/V Magnus Heinason, the attenuation coefficient *k* was determined for all the stations in 2001 and 2002. This was done by assuming an exponential decrease of the irradiance (3-2) and perform linear regression to the logarithm of the irradiance observations for the topmost 1-30 meters The resulting values for *k* vary between 0.05 and 0.3 m^{-1} (Figure 0-3).

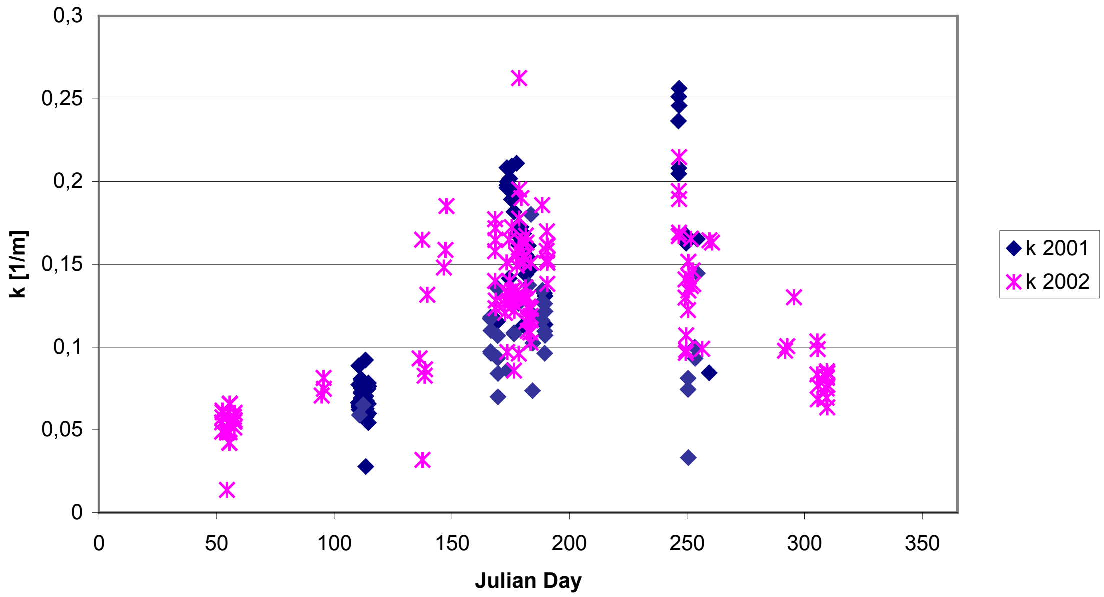

Figure 0-3. Attenuation coefficients plotted versus Julian day number. Each point represents one station.

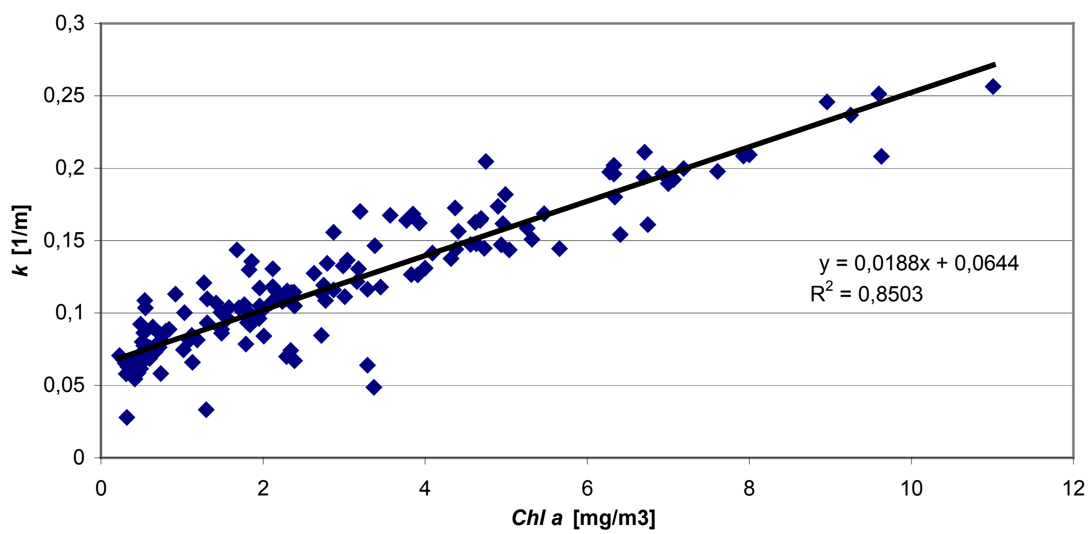

Figure 0-4. Attenuation coefficients observed in 2001, plotted against *chlorophyll a*. The equation for the linear regression is also shown.

The attenuation coefficients from both years are comparable in size. For the observations from 2001, the attenuation coefficients have been compared to the mean *chlorophyll a* concentration at their respective stations as measured by a fluorometer on the CTD. This comparison is shown in Figure 0-4. This shows a linear relationship between the phytoplankton concentration and the attenuation coefficient, having an R-squared value of 0.85.

• Comparison of air and under-water irradiance

Observations of underwater irradiance from R/V Magnus Heinason have been compared to irradiance in air. For the observations in 2001 (Figure 0-1), the sensor started measuring in air. Thus, these data give an impression of the magnitude of the observed transmission of irradiance through the sea surface. The topmost plot in Figure 0-1 shows a very large drop in irradiance as the sensor passes through the surface. This indicates that the transmission is much smaller than predicted from theory (3-1), and this is a general pattern through all the observations from 2001. The reason for this is unknown, but perhaps it has something to do with the instrument construction. While the sensor is in air, the observed irradiance is close to that expected from the LV observations, but the small value for the transmission makes the observed underwater irradiance in 2001 much smaller than the values that can be computed from observed irradiance in air and theory.

Figure 0-2 shows an irradiance observation from 2002. The irradiance sensor is only measuring while in water, and therefore it is only possible to compare the surface irradiance with the irradiance in water by extrapolating the irradiance in water up to the surface and divide by the transmission coefficient or by extrapolating the irradiance in air downwards through the surface and the water column. Both of these are done in Figure 0-2. In this particular example, the observed underwater irradiance is smaller than the values predicted by the air irradiance based on the LV observations. The difference is, however, so small that it could easily be due to the temporal variability of the irradiance in air. The comparison of the surface irradiance from all observations with LV irradiance at the respective times shows that there is consistency and the magnitude of the water irradiance observations is as expected from the LV dataset.

• Concluding remarks on irradiance in water.

The irradiance from the R/V Magnus Heinason measurements in air from 2001 has a good agreement with other data observed in air. The observed transmission of irradiance into the water in 2001 is much less than expected from the theoretical transmission and also less than what is seen in 2002 (Figure 0-1). This low transmission, is probably due to some special properties of the irradiance sensor.

Although the irradiance observations in water from 2001 do not agree with other observations, the attenuation coefficients computed from these observations seem to agree with those computed from the 2002 observations. The attenuation coefficient has a very clear linear relationship with the phytoplankton concentration, which can be used in the modelling.

The observations from 2002 do not contain data from air, but in this dataset the irradiance observed in water has in average the same magnitude as when computing it from air observations with a theoretical transmission coefficient. Therefore it will be assumed that these irradiance observations are representative for irradiance in water, and can be used in the ecosystem model. Also observations in air extrapolated into water by the methods described can be used in the model.

- ## Conclusion

A rewiev of the irradiance data available in the Faroe Islands is presented in this report. The LV and Satel data series have a good quality, and can be used in the marine ecosystem model, provided that the LV series is used with care. The irradiance observation program, started in 2003, will provide more good quality data, which can be used in the ecosystem modelling in the future.

The data obtained in water are reliable from 2002 and onward, and can be used in the model aswell.

- **References**

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