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# Report for akvARENA

## 3DOD

3-dimensional Oxygen distribution in a cage

### Author

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# Report

## 3-dimensional Oxygen Distribution

3-dimensional Oxygen Distribution in a Cage

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### ABSTRACT

An extensive 3D-mesh of O<sub>2</sub>-probes was deployed in a cage and allows an overview of the O<sub>2</sub>-content in the whole cage volume. This O<sub>2</sub> distribution is statistically analyzed and its gradients discussed in time and location. In addition, current meters and a current profiler allow to discuss the oxygen data in the right context.

Due to technical complications and environmental conditions the conclusion for a most representative O<sub>2</sub>-measurement point is difficult and less universal. Indeed it appears after analysis of the actual dataset, especially the flow data, that is even more complex to give a general statement regarding such a location as expected. Nevertheless knowledge of the processes within the cage has been gained and a wide knowledge base for further experiments of this kind has been generated.

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## 1 Background

The production process in salmon farming is currently mainly based on experience and not knowledge-based. To approach a future growth of economical efficiency, sustainability and animal welfare, more knowledge about the processes within the cage has to be obtained. This experiment aimed to provide knowledge about these processes and related attempts of standardizing the method of oxygen measurement, as well as obtain data for model evaluation, verification or developing.

The experiment was done in a combined effort of a Postdoc scholarship (SINTEF Fisheries and Aquaculture), the "Salmon Dynamics" project funded by the Norwegian Research Council and an AKVArena project (SINTEF F&H, ACE, SALMAR and Aanderaa/ITT), and in addition supported by Simrad.

## 2 Experimental goals

An extensive 3D-mesh of O<sub>2</sub>-probes was deployed in a cage to allow discussing the O<sub>2</sub>-content in the whole cage volume. The obtained O<sub>2</sub>-information discussed in addition with data from current meters and a current profiler are analyzed towards a statement about a most representative measurement setup for Oxygen and provide elements for a better understanding of the processes within the cage.

## 3 Experimental setup

The experiment was performed at ACEs full scale production site Tristein (Fig.1). The results and conclusions of the experiment have of course to be discussed with respect to the properties of the site, like the bottom topography and the cage-setup of the farm.

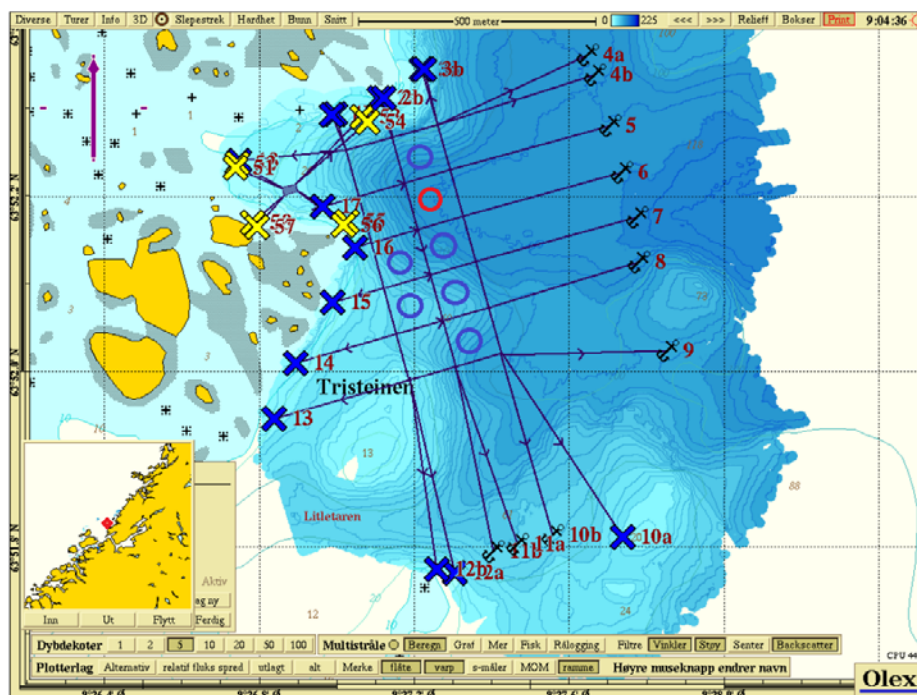






Figure 1: Mooring system at the Tristein site (LV509); red circle indicate the position of the cage where the experiment took place, blue circles indicate other cages in use at the trail period; the red dot on the map in the lower left corner indicates the position of the site on the Norwegian coast north-west of the Trondheim fjord.

The experimental data of approximately one month were obtained in March 2011.

### 3.1.1 Setup on site

For the experiment, 21 O<sub>2</sub>-probes, 5 current meters and a current profiler were used. In general a geometric setup was chosen to allow a rather simple deployment method but also provide a wide range of information for the parameters to be observed. Furthermore the usual but stringent simplification of a main current direction was assumed. The basis of decision for this direction was provided by a report of Havbruksstjenesten AS (HAV09) and the fish framers' daily experience. A schematic of all relevant features within the setup is given in Fig. 2.

icon	item
	O <sub>2</sub> probes (5m, 9m, 13m)
	velocity meter
	current profiler
	mooring buoys

The indications are to be understood as:

- H - at the high site of the current
- L - at the low site of the current
- C - Center position
- N - in the northern part
- S - in the southern part
- SI - in sector 1 of the cage
- SII - in sector 2 of the cage
- SIV - in sector 4 of the cage
- REF - cage close reference (up current)
- Pro - Current Profiler
- Vout - Velocity meter outside

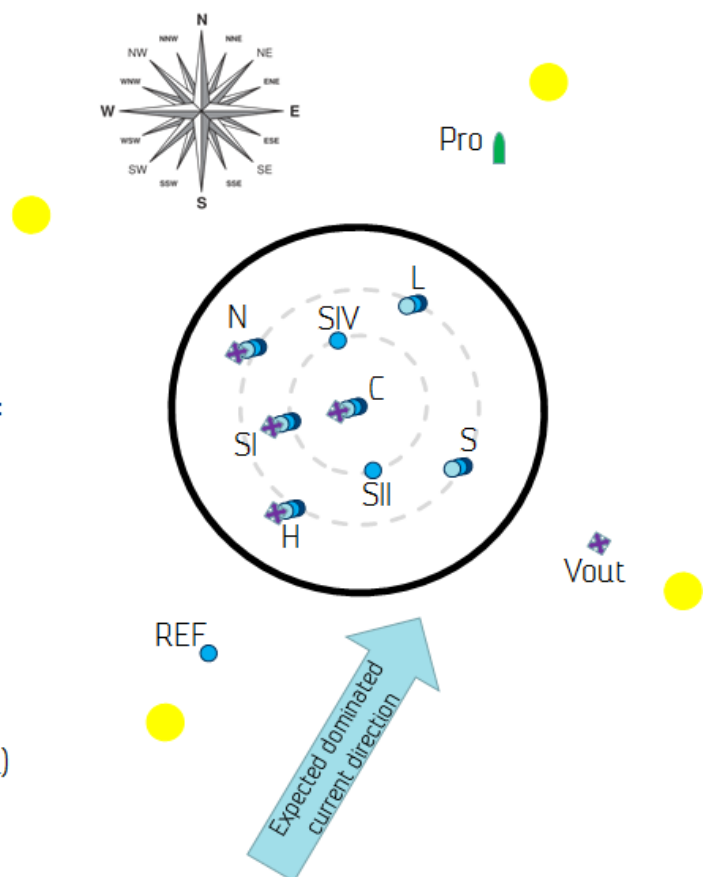


Figure 2: Schematic of the experimental setup with indications of geographical orientation, main current, mooring system and deployed measurement equipment, as well as the abbreviations for the different positions.

### 3.2 Dissolved Oxygen

The dissolved Oxygen was measured with Optodes from Aanderaa (AAD11). These probes were additionally calibrated to best compensate variation in offset as the membranes used for these sensors show ageing effects. Nevertheless some smaller offsets may appear due to a certain inaccuracy of this calibration as well; furthermore the probes are used in different operation modes. Data have been collected via a) direct communication utilizing the available Telcage Ethernet system, b) Aanderaa Datalogger and c) computers running the Aanderaa OxyView Program. This results in different signal appearances (see also 4.1.2) and the fact that for some probes the temperature could be measured in addition to the O<sub>2</sub>-concentration.

The probes were deployed at three depths (3m, 9m and 13m) at six locations named with H, L, S, N, C and SI, as indicated in Fig.2. Additional probes were placed at three other locations (REF, SII, SIV) in only 9m depth. This arrangement of probes allows to obtain information with a rather high resolution in a horizontal slice at 9m depth, the "first" sector/segment of the cage and on the long axis (in the estimated ambient current direction and orthogonal to it).

### 3.3 Flow

To determine the given flow conditions, three different instruments were used. Outside the cage, a current profiler (Nortek, Aquadopp) was placed at 20m depth attached in a distance of ca. 12m (keeping the cage out of the measuring volume) to the North-Eastern bridle at the location indicated as Pro (Fig.2). A second instrument, a Nortek Aquadopp current meter, was deployed beside the cage at a bridle (south-east) at 9m depth. Within the cage, Nortek Vector velocity meters were used to get local velocities at 9m depth at the 4 positions indicated with N, H, SI and C in Fig.2.

## 4 Results

### 4.1 Oxygen and Temperature

#### 4.1.1 Temperature

The temperature variation in Tristeins environment within the experimental time was comparatively low. Data from an environmental monitoring buoy (Fugro OCEANOR AS, SEAWATCH Midi 185) approx. 500m away show that variations less than 1K were present within the water column down to 45m depth. This rather homogeneous temperature was also observed with the instruments deployed for this experiment. Fig.3 show how insignificant, with respect to the accuracy of the used equipment and size of the investigated system, the temperature changes and variation for the experimental period is. In fact for most interpretation and argumentation the temperature can be assumed as constant at 4.5°C.

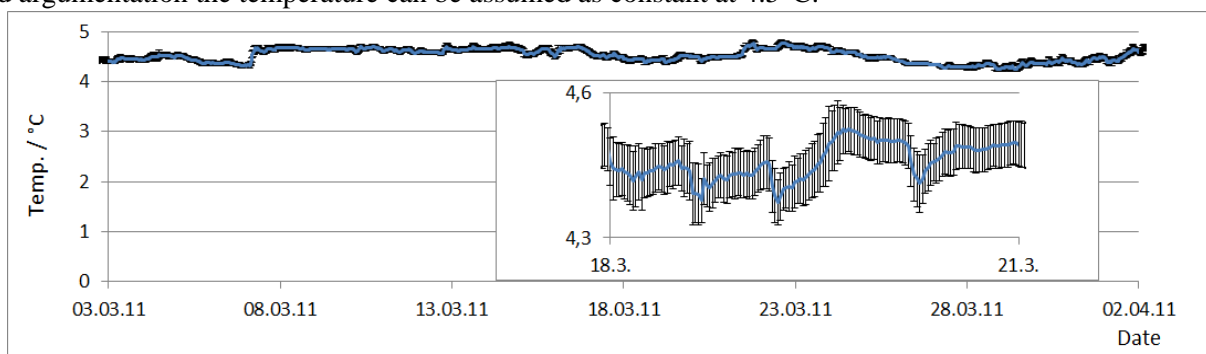


Figure 3: Mean temperature during the experimental time period with standard deviation (Temperatures from SI9, N9, H9, C9, C5, C13).

#### 4.1.2 Impact of applied measurement technologies

As already indicated the 21 Oxygen probes were used in different operational modes. Consequently differences in the sensor signals were expected, e.g. slightly other resolutions in time and value. Unfortunately the use of different operational modes had unexpected bigger impact on the signals as this. Whether the signals obtained via the Telcage system and the Oxyview program are comparable, are the data obtained with the data loggers significantly different, i.e. show a different baseline. Fig. 3 demonstrates this, visualizing an extraction of the time series for the measured mean value for the data obtained via Telcage readout and by one of the data loggers, respectively. Obviously the variance within one sampling method is very small and the differences between the two methods are significantly higher. It has to be said that the three baselines from datalogger1, datalogger2, and the RS232 readouts (Telcage and Oxyview) are very well reflected in all corresponding signals independent of where the probe was located.

A consequence of this impact of the probes operational modes is that signal comparison (e.g. O<sub>2</sub>-level differences) is limited to signals obtained with the same communication mode and data logger, respectively. This limits the possibility of data analysis strongly. Beside possible hardware related reasons, like temperature dependencies of device this strong impact might be only so obviously as the general differences in the oxygen levels are very small. Nevertheless a general statistical interpretation of all signals ignoring the

here described dependency has been done and some individual oxygen signals are compared as well (4.14, 4.3), naturally under the prerequisite mentioned above.

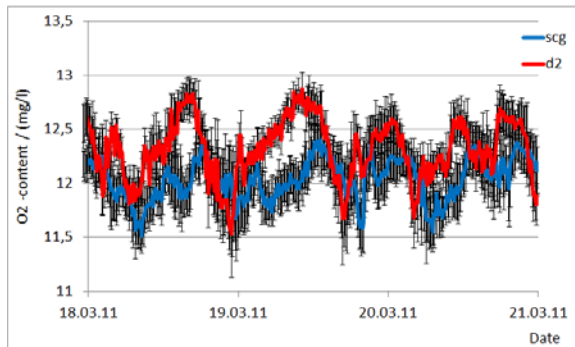


Figure 3: Mean Oxygen content with standard deviation, determined for two different methods: scg - Telcage data readout of probes (n=5) via RS232 interface; d2 - (the "second") Aanderaa data logger reading out the probes (n=5)

### 4.1.3 Statistics

The different oxygen levels within the experimental period varied little. Fig.4 shows the mean value and the standard deviation of all O<sub>2</sub>-probes. This O<sub>2</sub>-mean-level within the farm is strongly similar to the "minimum baseline" of the oxygen signal (Fig.5) measured from the buoy (Fugro OCEANOR AS, SEAWATCH Midi 185) at approx. 500m distance of the farm. Even the very clear expression of this baseline in the buoy's O<sub>2</sub>-signal needs more interpretation, the general increase of the peaks reflecting photosynthesis and respiration effects are well correlated with measurements monitoring the increase of Phytoplankton during this period.

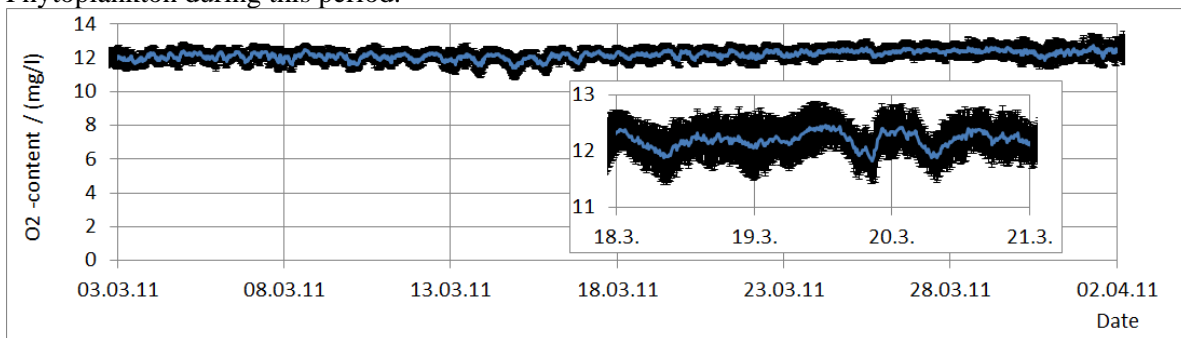


Figure 4: Mean Oxygen content with standard deviation for all 21 probes

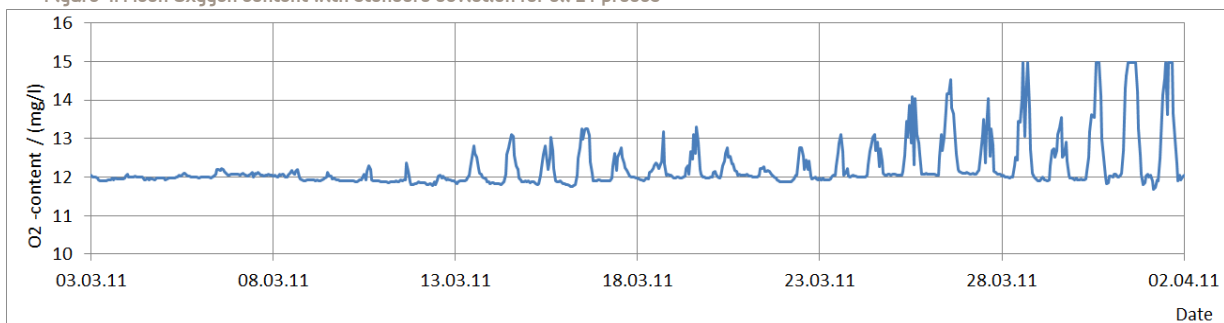


Figure 5: Oxygen content in the surface volume (0.1m) measured by the O<sub>2</sub>-sensor of the OCEANOR buoy approximately 500m from the farm.

The very obvious absence of these peaks within the O<sub>2</sub>-signals measured at the farm might be based on different facts. In general it is assumed, that the O<sub>2</sub>-producing layer in March at the latitude the experiment took place is, due to the striking angle of the light and corresponding penetration depth of photosynthesis-relevant light, limited to depths less than 5m. That means that all probes placed within the farm may not be close to any O<sub>2</sub>-producing environment. On the other hand a stronger mixing of water in the farm compared to the free water where the buoy is placed is expected. The statement of enhanced mixing is based on

expected topographical impacts on the ocean currents by the islands close to the farm, turbulences introduced from the farm structures, currents introduced by the swimming fish and combinations of these, respectively.

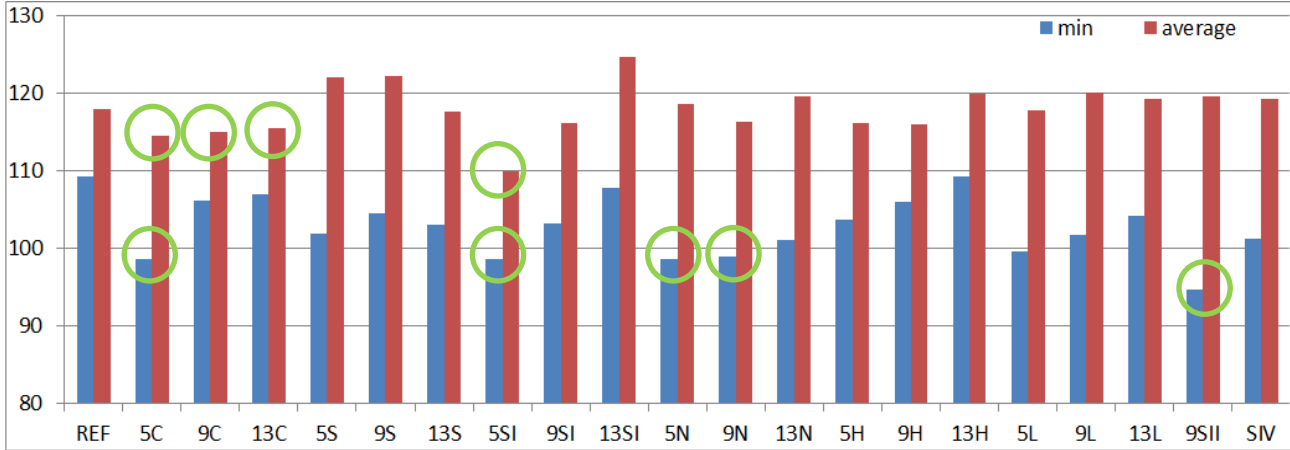


Figure 5: Dissolved Oxygen minimum and average values for the 21 locations in the trial period, with some low values highlighted.

From the oxygen signals of the probes, individual minimum and average values have been determined. Fig.5 gives these values as dissolved oxygen (DO%). Obviously no critical values for the fish welfare have been reached over the measurement period, as lowest DO values were found between 90-100% whether the mean values were all above 110%. The five lowest values were found at 5m and 9m and are not dominated by an operation modus of the probes (compare 4.1.2). Seeking for the best measurement point for oxygen, i.e. the place to monitor the worst conditions means lowest O<sub>2</sub>-contents; the lowest minimum values are compared to the overall average values. Two locations are showing comparable low average and minimum values both located at 5m depth, in the cage centre and at SI. Concluding from these data and for the given setup these locations would be pointed out as measurement location to monitor the worst O<sub>2</sub>-conditions. But one has to keep in mind, that the small differences in the O<sub>2</sub>-content and the strong impact of the used measurement technologies (see 4.1.2) relativize these results.

#### 4.1.4 Oxygen time series

The oxygen-time-function appears as a complex one, composed of and dependent on several possible factors. Main dependencies on transport phenomena like tidal and non-tidal currents or locally introduced flow dynamics are expected. Also local and general oxygen-consumption and production processes, which depend on e.g. light conditions and feeding effects, are relevant. It appears to be difficult to separate individual influences of single process within the complexity of the open cage system. Fig.6 shows for example the time of feeding for several dates and no well-defined system (whole cage) response is obvious in the oxygen data.

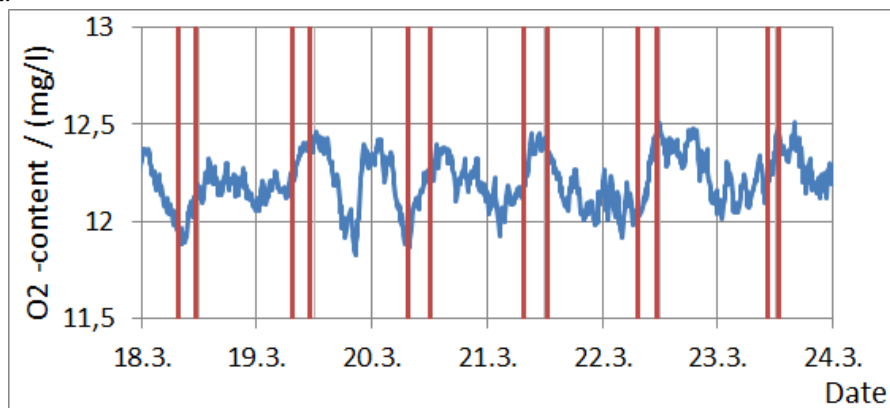


Figure 6: Mean oxygen value of all probes with bars indicating periods of feeding.



Taking a closer look at the individual signals, concrete trends appear, e.g. at the centre string of the setup. The tendency that O<sub>2</sub>-values are lower at night time and higher at day time at 5m depth compared to those at 9m and 13m is given. One explanation for these periodical developments might be from the tendency of the fish to crowd at night in the near-surface layer as discussed e.g. in JOH06 and the related increased oxygen consumption. Another explanation might be given by additional water exchanges based on currents introduced by fish swimming in pattern, i.e. schooling at day time day, as suggested in GAN11 and of course a combination of both, respectively.

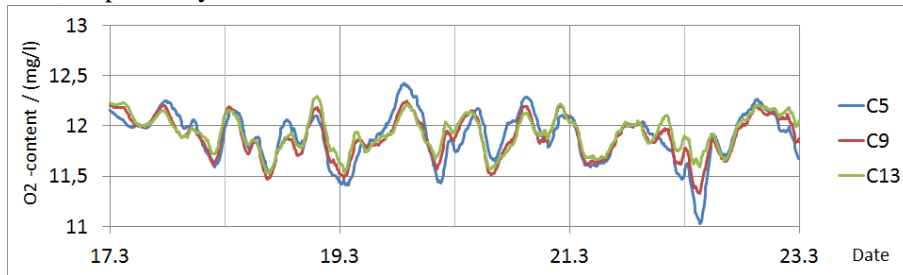


Figure 7: Time series extraction for the 3 central O<sub>2</sub>-probes.

(Further analyses of the data set are planned to be performed in the same manner and will be presented elsewhere.)

## 4.2 Horizontal Velocity

### 4.2.1 Statistics

As already indicated, a main current direction was expected from HAV09. The overall statistics from the current meters in the cage show only small deviations between the different positions, so that the assumed ambient current direction (Fig.2) is confirmed.

Of most interest here might be the direct comparison between the H and C positions. As the position at the "upstream side" of the current (H) shows a strong asymmetry towards a much higher statistical distribution (*appearance*) north-north-east-wards, the central position which lays in the NNE of the H position is more likely symmetrical along the dominant current direction. With respect to this data it might be already concluded that there is no uniform horizontal flow field through the cage and vertical flows may play a significant roll when trying to describe the transport phenomena of water in the cage and the farm.

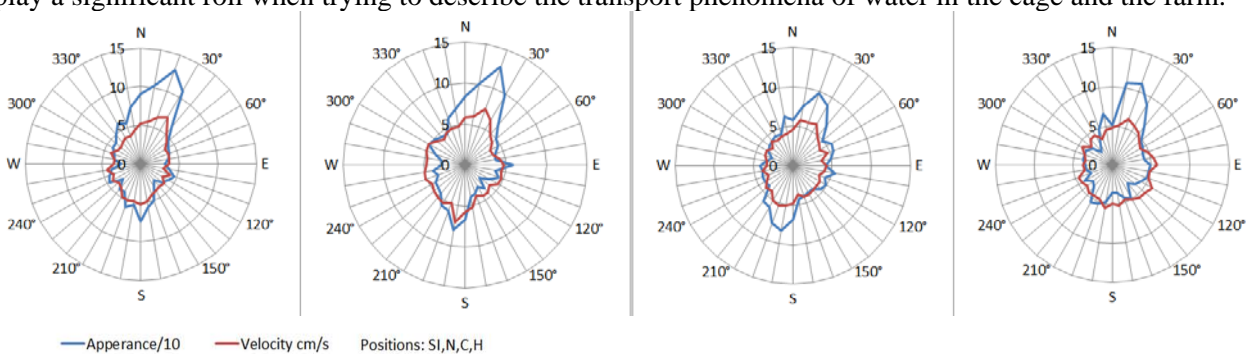


Figure 8: Current roses for the 4 vector velocity meters inside the cage, giving the statistical distribution (*appearance*) of the current direction and the mean velocity for the directions with in the measuring period.

The same conclusion will be obtained taking into consideration the current statistics of the current profiler "behind" and the current meter "at the side" of the cage (Fig.9), considering the dominant ambient current direction as orientation. The statistics from the profiler indicate a positive flow into the cage, i.e. in the opposite direction of the flow stream beside the cage.

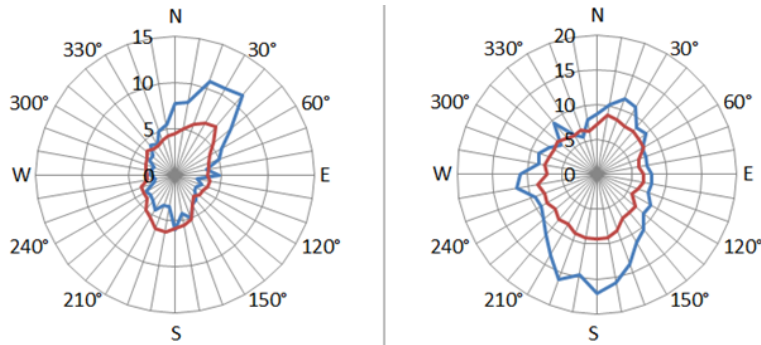


Figure 9: Current roses of the current profiler (right) at 9m depth and of the velocity meter (left) placed beside the cage. Blue: Appearance (which depends on the different sampling rate of the devices, and is factorized for the graphs); Red: mean velocity in m/s.

Discussing these current roses one has to take in mind that these data are representing the whole measuring period at one location and give no hints about time-related effects or how currents appear simultaneously at the different locations. Hence current data are further analysed as time dependent functions. With a moving average for 1h to discuss possible tidal aspects and with moving averages of 25h to filter out most tidal influences and get a picture of the non-tidal residual currents.

*Chapter Appendix:*

For completeness but not discussed, Fig.10 shows the statistics for all 20 depths monitored with the profiler.

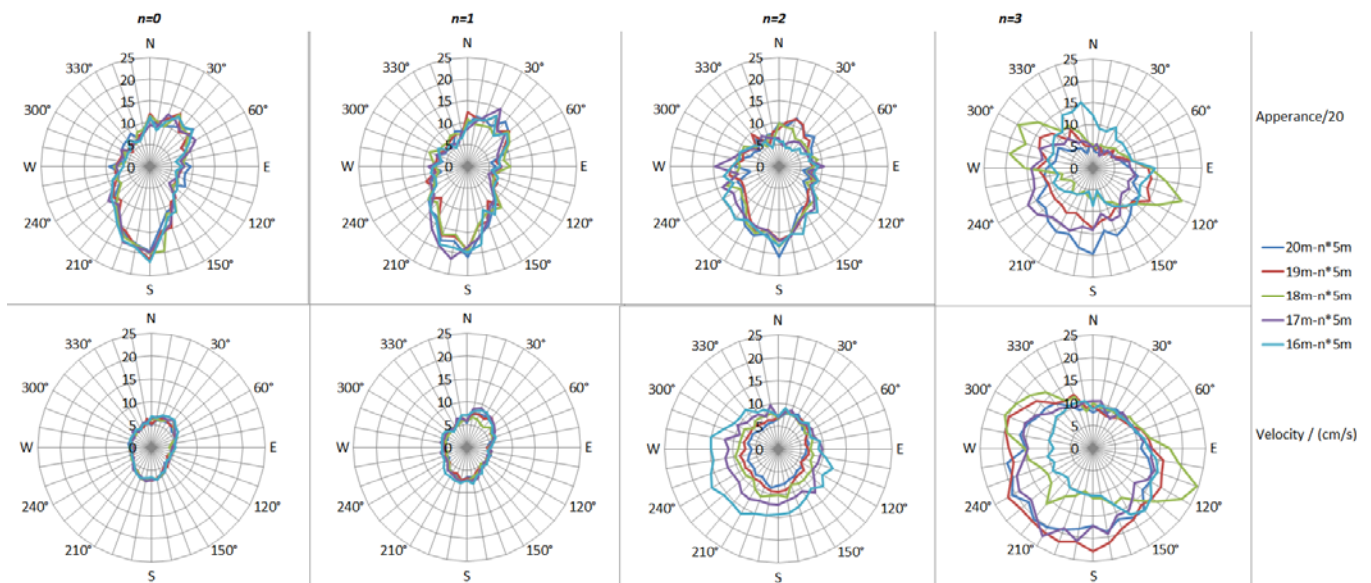


Figure 10: Current roses (again mean velocity and statistical appearance for a certain direction) for the different depth of the current profiler, divided in diagrams representing each 5m of the 20m water column.

**4.2.2 Tidal aspects**

To give a reference for the tidal current conditions Fig.11 shows the observed water levels at the Rørvik tidal station. The expected harmonic tidal currents at Tristein are qualitatively the same with a certain phase shift due to the physical distance between the two locations and whether the tidal wave is standing or progressive.

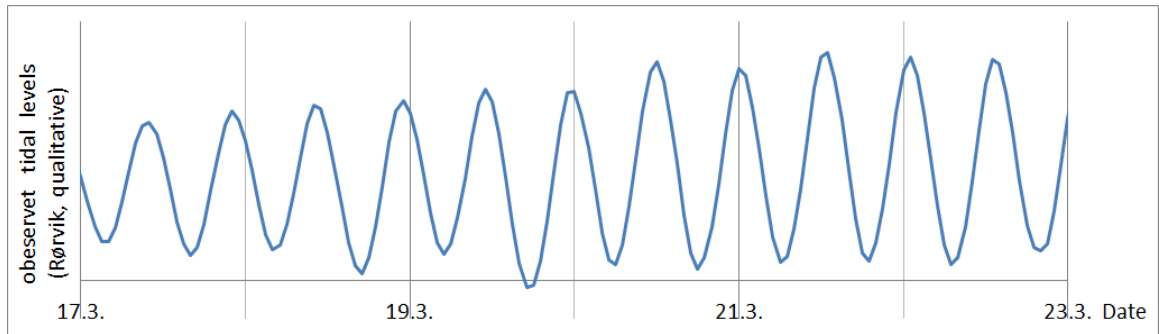


Figure 11: Observed water levels at the Rørvik tidal measuring station, expected high current conditions are expected between the minima and maxima.

Fig.12 shows the 1h-moving average of the velocity for the individual north and east components of the current profiler at 9m (Pro) and the current meter aside the cage (Vout). Beside a high noise level in these signals, at least on some days the tidal variability is well expressed. For the 18<sup>th</sup> for example are 4 extreme values expected from the Rørvik data, which are easy to find in the north component of Vout as a max-min-max-min oscillation during the day. Although noisier, this is also to be seen in the east component and both components of Pro.

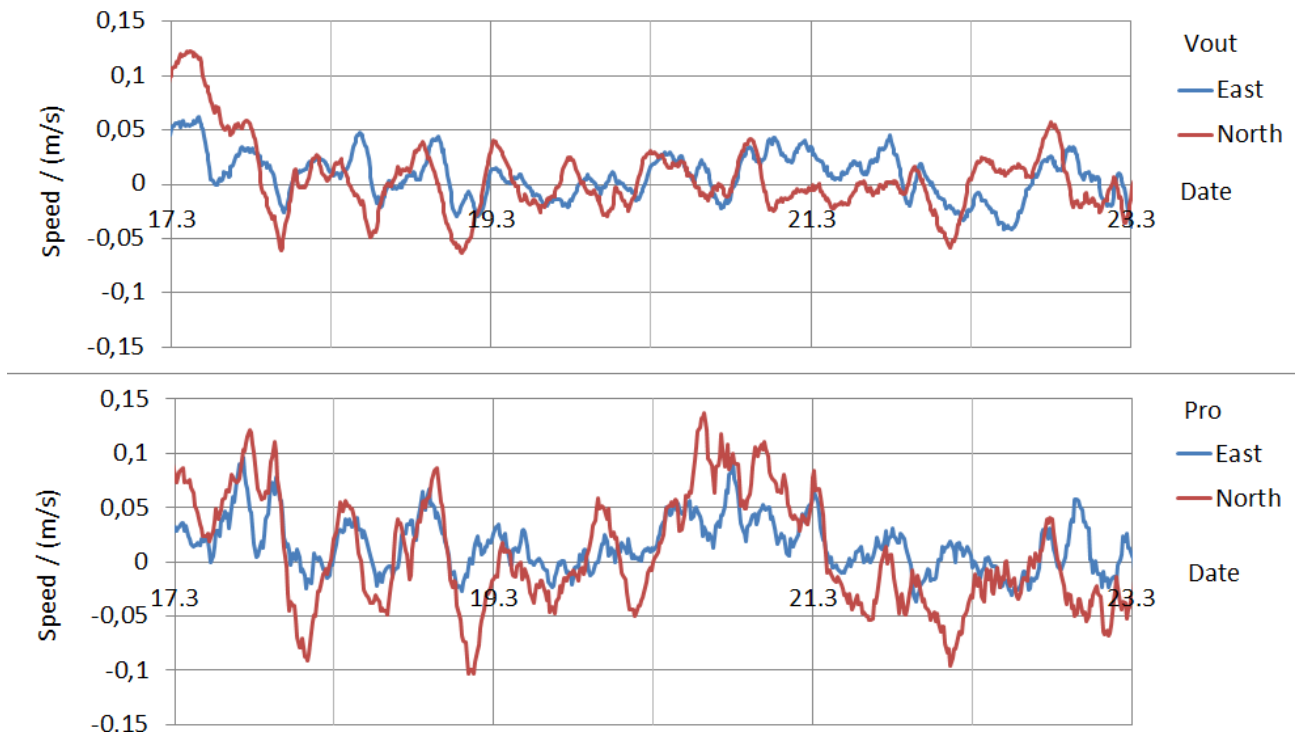


Figure 12: Time series for directional velocity components (north east) determined at the bridles at 9m depth.

The tidal impact at these two positions can be better visualized with plots of the horizontal speed and direction of the flow, as given in Fig.13. Especially the flow direction shows from the midday 17<sup>th</sup> until the 20<sup>th</sup> clear periodical behaviour like the tides measured in Rørvik. These tidal fingerprints in the local current time dependencies are however not quite consistent as e.g. the pattern for the 20<sup>th</sup> and the 21<sup>st</sup> are strongly different. However these currents have to be seen as a superposition of tidal effects, non-tidal residual currents and, as they are 1h moving averages, of lower frequency eddies. Hence they are not expected to be purely tidal constituents.

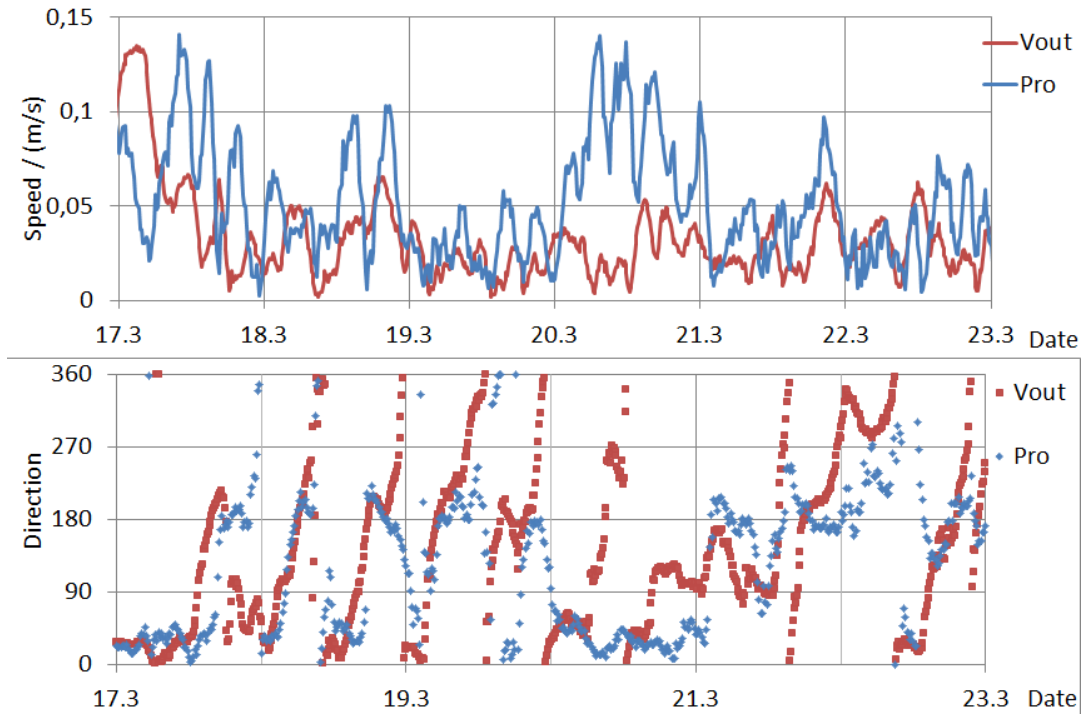


Figure 13: Alternative visualization of the signals in Fig.12 here shown as horizontal speed and direction (0°=>North)

The same can be stated for the 1h moving averages of the horizontal velocities within the cage (Fig. 14). In general the velocities at these 4 positions show a qualitatively similar trend over time. However the correlation of these signals to those obtained beside the cage is not very high, which indicate that additional current-related-phenomena with time constants above 1h take place within the cage.

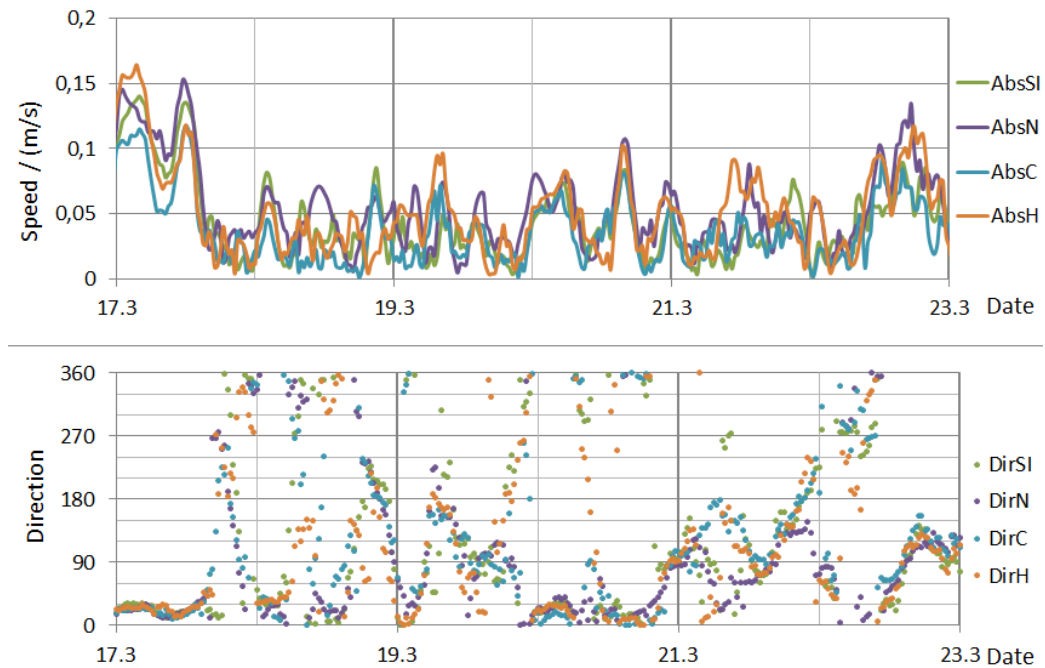


Figure 14: Horizontal speed and direction for the current meters inside the cage.

### 4.2.3 Non tidal residual currents

Fig.15 and Fig.16 visualize the underlying non-tidal residual currents for Fig.13 and Fig.14 for a longer time period. It is clearly to see in these two figures that the non-tidal current condition is hardly to be assumed as steady over time. The horizontal directions and magnitude of the currents underlying the tidal effects are changing continuously and significantly.

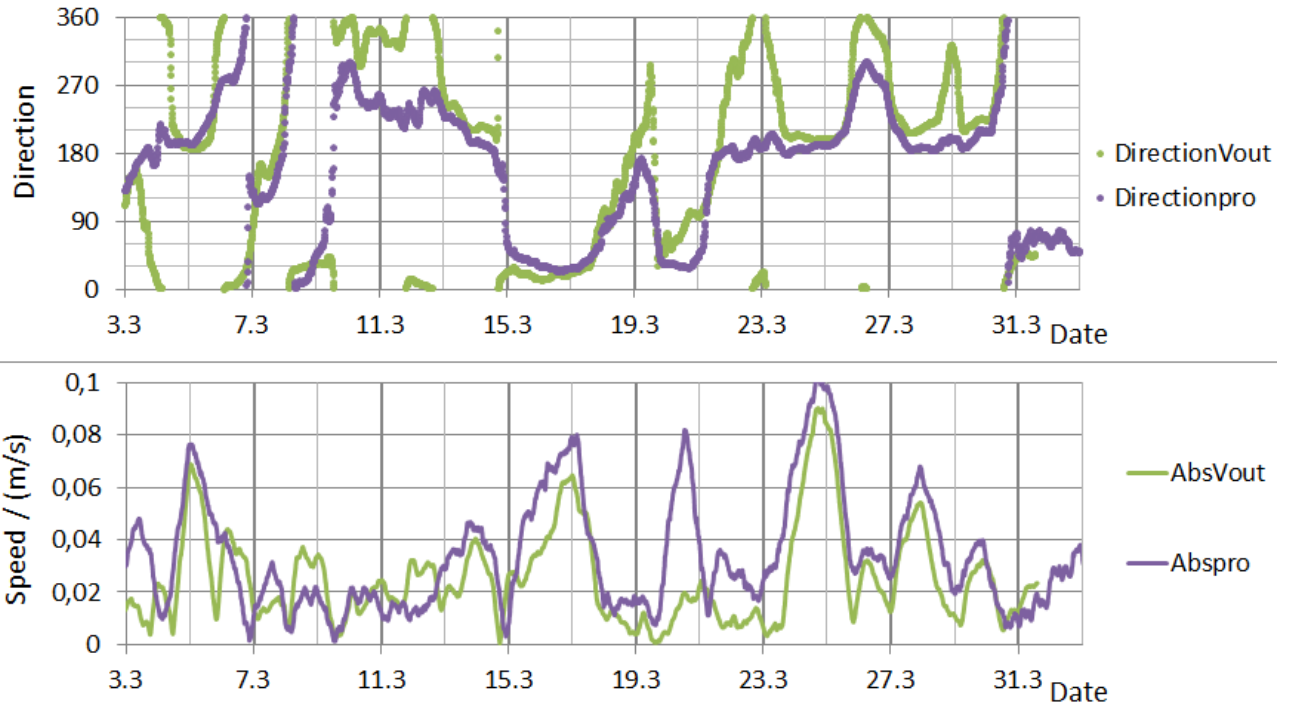


Figure 15: Horizontal speed and flow direction at the location beside the cage as 25h moving average.

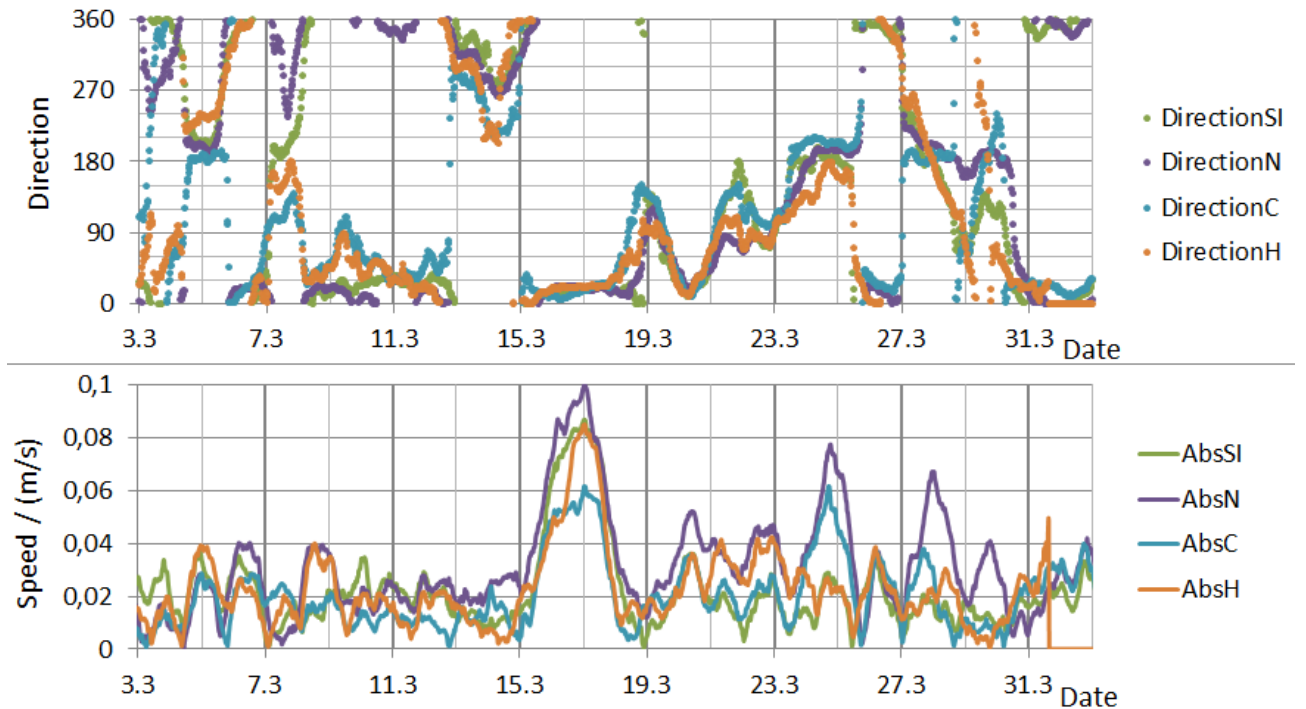


Figure 16: Horizontal speed and flow direction in the cage as 25h moving average.

This information has a clear impact towards the projects aim to conclude a most representative oxygen measuring point. Changing current conditions indicate that the position with the lowest O<sub>2</sub>-content may actually change daily within the cage. That means reducing the amount of oxygen monitoring locations leads to a risk of not-monitoring the worst oxygen conditions. This is a fact independent from other aspects not included in the discussion so far, like fish distribution in the cage and its variation.

For the 25h moving average a better correlation between currents within and beside the cage is given. Especially at high current situations e.g. at the 17<sup>th</sup> of March a rather homogenous flow field can be observed at the whole area. Further analysis and discussions focussing on the current situations will be published elsewhere.

### 4.3 Vertical Velocity component

Up to now the analysis and discussion were based on horizontal flows and the vertical flow components were ignored. Fig.17 shows these components for the locations in the cage and outside, for the tidal dependent 1h average and the 25h moving average for the non-tidal currents. The vertical current components given in these graphs are as strong as the horizontal flows, i.e. significant to describe the system. Tidal effects might be interpreted for some signals but the signal to noise ration is quite low.

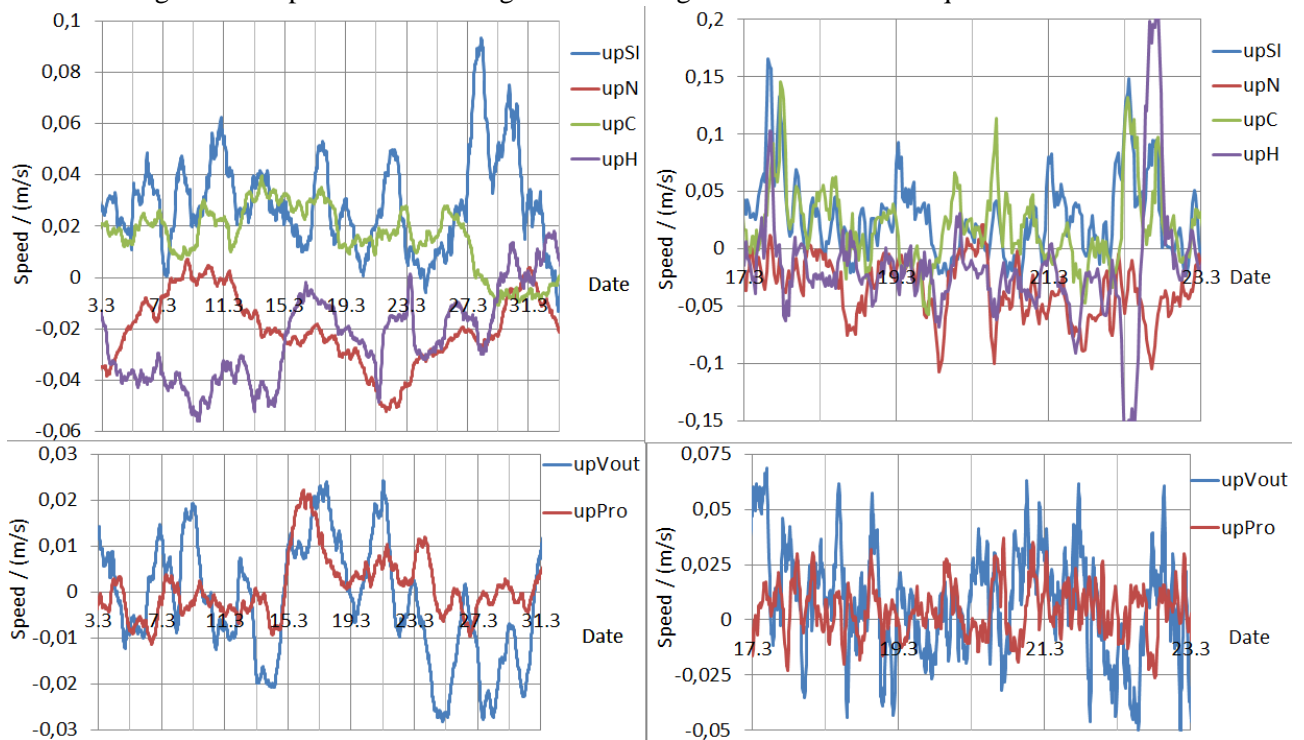


Figure 17: Vertical velocity components at 9 m depth beside (lower panel) and in the cage (upper panel) as 1h averages (right) and 25h moving average (left).

More conclusive is the 25h moving average. Obviously the vertical current components in 9m depth are most likely higher in the cage than outside. In addition it seems to be that the vertical current components at the locations in the cage have a tendency to be more un-balanced within the monitoring period compared to the once at the Pro and Vout locations. In fact the H and N locations, closer to the cage netting, show a downward flow over the month of March, i.e. water is flowing significantly to deeper areas at these locations (Fig.18) while it flows up at the SI and C location.

Not enough data are available for a definite explanation of this. Information of the flow at the L location would be helpful as well as information where the fish are located over the period as average but also at given times. Further, these results might be interpreted as supportive to the fish-introduced currents,

discussed in GAN11 or as a consequence of the biomass of fish forcing the water to flow "around" (over and under) this flow resistance with a higher velocity.

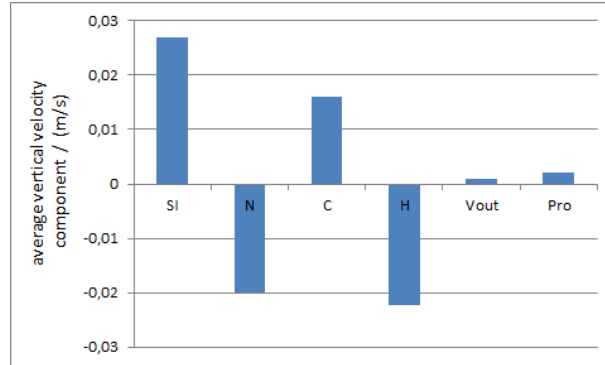


Figure 18: Average of the vertical velocity components in march at the different locations in 9m depth

#### 4.4 Horizontal Velocity and Oxygen

As discussed, the oxygen content is developing over time dependent on several parameters so it is not surprising that no direct correlation of single oxygen signals for example with the currents are given. However changes in variations for different locations can be discussed. So is the 25h moving average of the O<sub>2</sub>-signals in 9m depth at the reference, high and centre location not easy to correlate with the local currents, but their differences between inside the cage (H, C) and the reference (REF) show 3 significant minima (Fig.19). These occur always when the currents at both outer-cage positions are going with a high speed southwards (compare Fig.15). In addition it can be observed, that the oxygen differences between H and C are bigger when low currents occur at the outer positions. This shows the strong relation between oxygen distribution and the cage surrounding current condition.

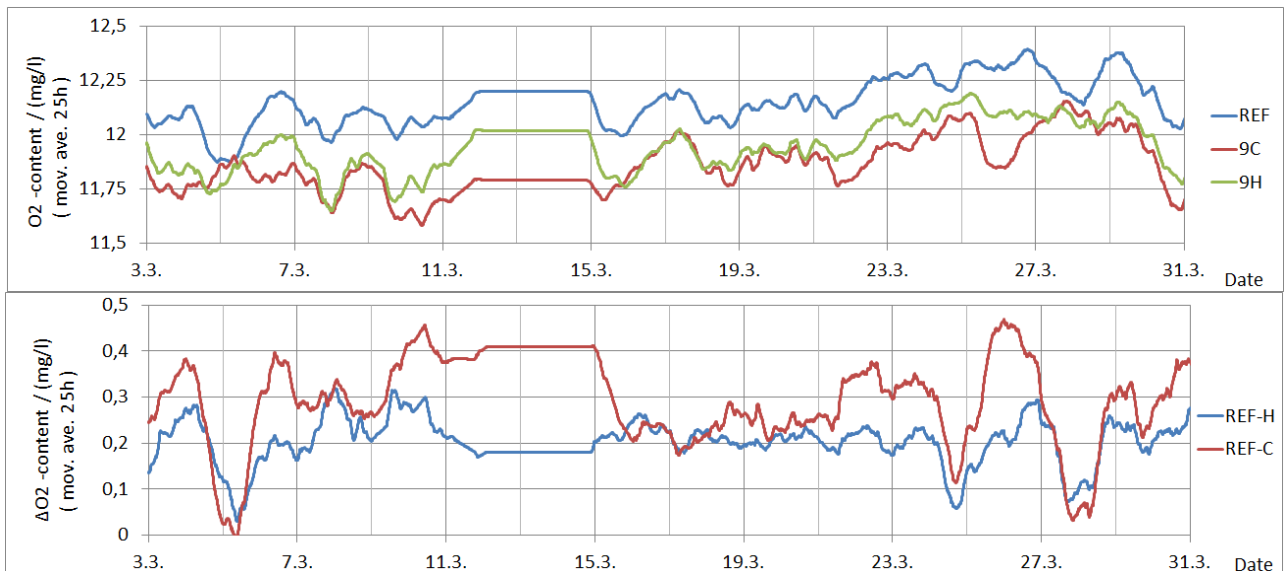


Figure 19: 25h moving average of the O<sub>2</sub>-signals (upper panel) at 9m depth along the "dominating current direction" (Fig.2) and the differences between the outer-cage reference and the locations in the cage (lower panel). (Straight signal lines are a measuring artefact.)

## 5 Conclusion

*Practical implications for further attempts* to determine the best oxygen measuring location are obtained from the given results.

- As very high oxygen values and very low oxygen gradients were found in the experimental period, future trials have to be performed in periods with worst environmental oxygen conditions, e.g. in August.
- Analysing the data was limited, as no well known location of the fish were available. Hence future trials should use several echo sounders to determine where the fish is located. This is essential to understand the changes and differences in Oxygen and flow better, as well as to define how relevant the location with the worst O<sub>2</sub>-level is for the fish, i.e. if they are located there.
- After the analysis of the oxygen data and the variance in the signals based on the operation modus, it is obvious that sensors of the used type can only be applied in one operational mode within the same setup.
- Data analysis indicated that an oxygen depth profile of the environment should be monitored in future experiments as well, as a single value from the reference buoy or nearby the cage does not seem to be sufficient to interpret e.g. effects of O<sub>2</sub>-production of plankton.

*Concluding the best oxygen measuring location* was the main goal, this experiment was planned to contribute to. However the results obtained from the experiment widen the context of discussion further instead of pointing out a simple strategy or solution:

- This appears as a consequence from the limited accuracy of the sensor systems used and also from the environmental conditions in the period of the trial, both resulting in O<sub>2</sub>-levels at the measurement locations which are not production representative.
- Furthermore, it has been shown that, as expected, the current conditions around the cage are strongly correlated to the oxygen distribution and its differences inside the cage. However unexpected, it was documented that these currents are very un-steady. Consequently it is indicated that one location may never be concluded as "the best oxygen measuring location", at least for certain sites.

Site or seasonal specific aspects might be the reason for these un-steady conditions, but it is more likely systematic for a certain type of location. To prove this and develop a strategy to answer the need for a common oxygen reference measurement an even better overall picture is required. That means that measurements at different seasons and different cages as well as farms have to provide more data, to give the opportunity to develop a strategy where and if a good oxygen measuring location can be defined.

*Regarding the processes within the cage* small insights could be gained. Periodical changes with the day time in the Oxygen differences and huge dependencies of the vertical currents from their individual locations show a significant impact of the fish on the current state in the cage. These will, subsequently analysed and combined with other experimental data, lead to a better general description of the fish-flow interactions.



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