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Environmental monitoring during survey by submarine U-864 outside Fedje in 2014

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– an institute in the Environmental Research Alliance of Norway

REPORT

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Abstract

NIVA has done environmental monitoring during a survey by the wreck of submarine U-864 outside Fedje. The survey was done in January 2014 on the vessel Geosund from DOF Subsea Norway. The main task for NIVA was to monitor if the work by the submarine caused any spreading of contaminated sediment. This was done by monitoring of turbidity around the wreck and analysis of mercury in water samples. A water current profiler was deployed in the mid area between the two main wreck sections. NIVA also did measurements for mercury in air on the vessel.

The digging and dredging in the contaminated area caused some spreading of particles contaminated with mercury, but the concentrations in the water samples were low (class II (good) or less). One sediment trap (10 m above the seabed) recovered from a position ca 200m northwest of the operation center contained 4.2 mg Hg/kg dry weight. This is classified as class V (very bad). The high concentration of mercury in the sediment trap shows that the digging and dredging has caused spreading of contamination. Model calculations based on the measurements available from the survey, showed that particle spreading will occur mainly towards northwest. Sediment fractions with size of more than 100 µm will settle within the 50 m model grid surrounding the operation. Particles with size 63 µm will not have travelled far beyond 200 m northwest of the operation center, but fine clay fractions (20 µm) may be transported up to 1 km away. It can be assumed that smaller sized particles will not constitute any significant fraction of the bulk sediment.

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3. Kvikksølv	3. Mercury
4. Turbiditet	4. Turbidity

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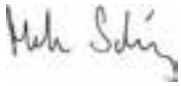

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Environmental monitoring during survey by submarine U-864 outside Fedje in 2014

Preface

NIVA has done environmental monitoring during a survey by the wreck of submarine U-864 outside Fedje. The survery was done in January 2014 on the vessel Geosund from DOF Subsea Norway. The vessel Libas from Liegruppen was also used for retrieving of turbidity rigs. Monitoring of turbidity and water current were done by Pierre Franqois Jaccard and Odd Arne Skogan. Measurements of mercury were done by Ivar Martin Dahl and Sigurd Øxnevad. Modelling of sedimentation was done by André Staalstrøm. Sigurd Øxnevad has been project manager at NIVA.
Håvard K. Berge from DOF Subsea Norway was our contact person during the project.

Oslo, 6.5.2014

Sigurd Øxnevad

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Summary

In January 2014 NIVA participated in a survey by the wreck of submarine U-864 outside Fedje. NIVAs role was to do environmental monitoring during the survey. For safety reasons, equipment that had been used on the seabed or near the seabed was checked for mercury pollution when it was placed on deck. No high concentrations of mercury were found in air in the ROV hangar. The Deep C excavator and dredger got very polluted with mercury. Liquid mercury was found on the excavator and high concentrations of mercury vapour were detected on several places on the machine.

Water samples were taken during the operations, and a total of 74 water samples were analysed. Mercury was detected in only small concentrations in the water samples. The concentrations of mercury in the water samples were in class I (background) and class II (good). The digging and dredging in the contaminated area caused some spreading of particles contaminated with mercury, but the concentrations in the water samples were low.

One sediment trap (10 m above the seabed) from rig OV8 was recovered. The sediment in this trap contained 4.20 mg Hg/kg dry weight. This is classified as class V ("very bad"). The high concentration of mercury in the sediment trap shows that the digging and dredging has caused spreading of mercury.

Due to loss of turbidity rigs there is not sufficient data to assess spreading of contamination with particles. Data for turbidity showed that there were several peaks of turbidity and some longer time periods with high turbidity measured on rig C a little north of the aft section.

Model calculations based on

- current and turbidity measurements on rig C,
- water samples collected from ROV and
- sediment material trapped at station OV-8,

showed that particles larger than 63 μm will sediment less than 100 m from the operation center; most actually within the 50 m model grid surrounding the working area. Typically, 50 to 80% of the sediment on the site is larger than 63 μm. The model showed that silt and clay fractions will be spread further away from the operation site. Particles of 63 μm will sediment mostly within 200 m, whereas the smaller size fractions of 20 μm may be transported up to 1 km through the water mass before settling on the sediment. Due to the prevailing current directions the particles will spread primarily towards northwest. It is assumed that particles smaller than 20 μm constitute a small fraction of the bulk sediment. Thus, we conclude that spreading of contaminated particles will be small beyond 1 km from the operation center.

Dissolved fractions of mercury have not been investigated in this work. However, previous measurements of water samples with suspended sediments have shown that the concentration of dissolved mercury is very small compared to the particulate fraction.

Sammendrag

I januar 2014 deltok NIVA på et tokt ved ubåt U-864 utenfor Fedje. NIVAs rolle var å utføre miljøovervåking. Av sikkerhetshensyn ble det gjort målinger av kvikksølvdamp på alt utstyr som hadde vært i kontakt med sjøbunnen i nærheten av ubåten. Det ble ikke påvist noen høye konsentrasjoner av kvikksølv i luft i ROV-hangaren, men det ble påvist høye konsentrasjoner av kvikksølv på gravemaskinen og mudringsslangen som hadde blitt brukt til arbeid ved ubåtvraket.

Vannprøver fra fire stasjoner rundt ubåtvraket ble analysert for kvikksølv. Vannprøvene ble tatt gjennom hele perioden, og totalt 74 prøver ble analysert. Det ble bare påvist lave konsentrasjoner av kvikksølv i vannprøvene. Konsentrasjonene av kvikksølv i vannprøvene var i klasse I (bakgrunn) og klasse II (god tilstand). Vannprøver som ble tatt bak mudringsslangen mens det pågikk mudring viste noe høyere konsentrasjoner av kvikksølv, men nivåene var likevel lave. Analysene av vannprøvene viste en sammenheng mellom partikkelinnhold og kvikksølv. Det betyr at det er grunn til å anta at der hvor det observeres høy turbiditet vil det også være økte konsentrasjoner av kvikksølv.

En sedimentfelle (fra 10 m over sjøbunnen) fra rigg OV8 ble tatt opp. Prøven i denne fellen inneholdt 4,20 mg Hg/kg tørrvekt, som klassifiseres som svært dårlig (klasse V). Vi skal være varsomme med å konkludere på grunnlag av en enkelt prøve, men funnet av kvikksølv i denne sedimentfellen indikerer at grave- og mudringsarbeidene ved ubåten har medført spredning av kvikksølv minst 200 m nordvest for operasjonsområdet.

På grunn av tap av turbiditetsrigger har vi ikke nok data til å vurdere partikkelspredning godt nok. Data fra den midtre turbiditetsriggen (C) viser at det var flere topper med høy turbiditet og at det også var lengre perioder med høy turbiditet på stasjonen rett nord for der hvor det foregikk arbeid ved ubåten.

Modellberegninger basert på strøm- og turbiditetsmålinger fra rigg C, vannprøver samlet inn ved hjelp av ROV og sediment fra sedimentfellen fra stasjon OV-8 viser at partikler større enn 63 μm vil ha sedimentert mindre enn 100 m fra det sentrale arbeidsområdet. Anslagsvis 50 – 80 % av sedimentet i dette området er større enn 63 μm. Modellen viser at silt- og leirefraksjonene kan ha blitt spredt lengre vekk fra arbeidsområdet. Partikler på størrelse 63 μm vil i hovedsak ha sedimentert innenfor en radius på 200 m, mens partikkelfraksjoner på 20 μm kan ha blitt transportert opp til 1 km med vannmassene før de har sunket til bunnen. På grunn av de rådende strømforholdene vil partiklene primært ha drevet i nordvestlig retning. Det antas at partikler mindre enn 20 μm utgjør en liten del av sedimentet. Vi konkluderer derfor med at det har vært lite spredning av forurenset materiale lengre enn 1 km fra det sentrale arbeidsområdet.

Løste fraksjoner er ikke undersøkt i dette arbeidet. Erfaringer fra andre operasjoner har vist svært liten utløsing av kvikksølv fra suspenderte, forurensede sedimenter så det er rimelig å anta at spredning av kvikksølv i all hovedsak vil være knyttet til spredning av partikler.

1. Background

In February 1945 the German submarine U-864 was sunk outside Fedje, on the south western coast of Norway. The submarine was torpedoed midship, broke in two and sank, and is located at 150 m depth. U-864 is assumed to have had 67 tons of liquid mercury onboard, stored in 1857 carbon steel cans in compartments inside the keel. When torpedoed, the mid-section of the submarine was blown up, and an unknown number of the steel cans were destroyed and mercury was spread to pollute the surrounding seabed. Mercury cans may also have corroded during the decades that have passed since the torpedition event and started to leak mercury to the seabed.

The authorities have decided to further evaluate two different methods of pollution abatement:

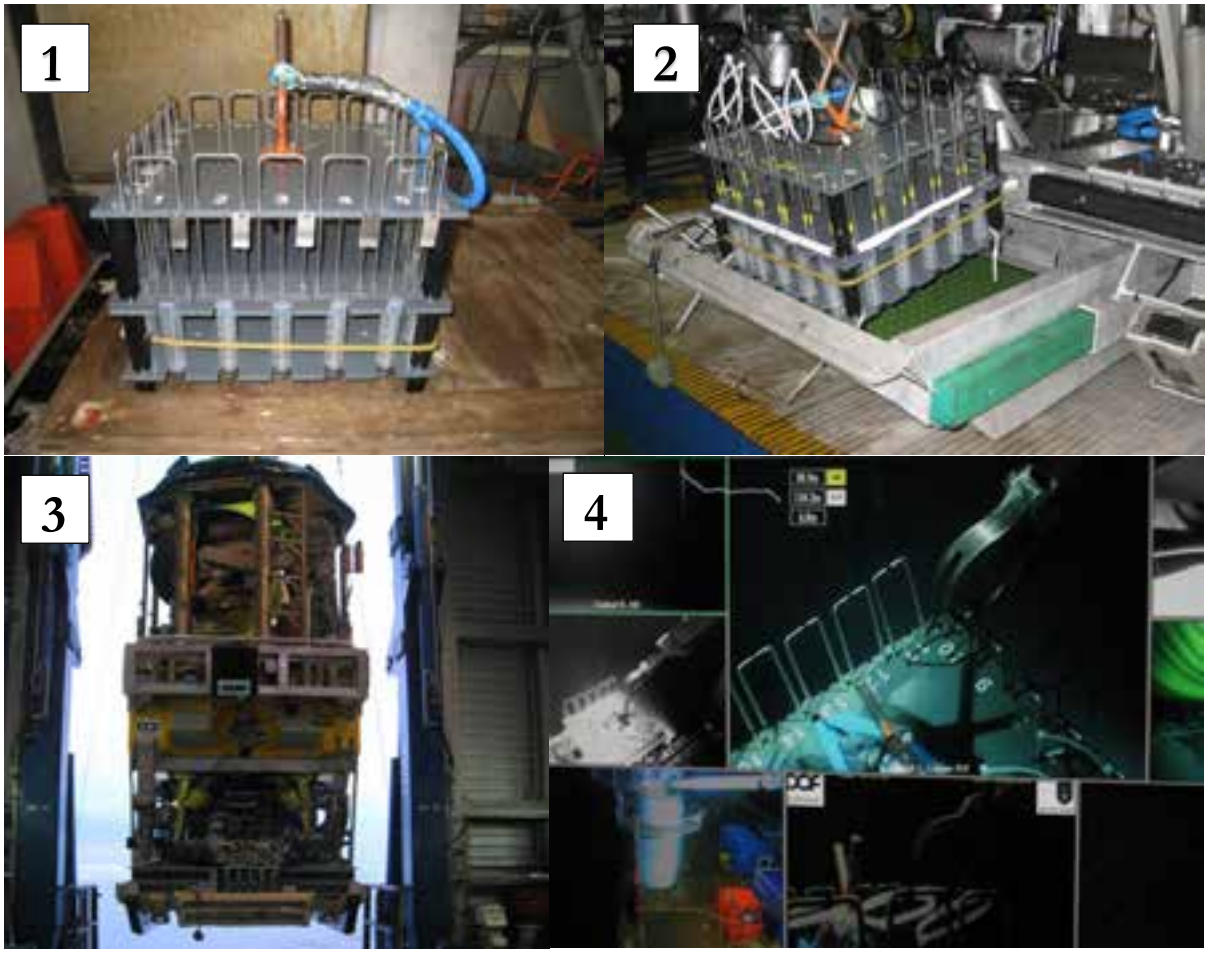
- Seal-in the polluted area, utilizing sand with special characteristics
- Retrieve the mercury cans from the keel section and seal-in the polluted area

In January 2014 NIVA participated on a survey to provide the NCA (Kystverket) with information to identify different risks and gain information on the feasibility of salvaging Hg canisters from the wreck of the U-864. NIVA did environmental investigations and monitoring during the survey.

2. Materials and methods

2.1 Water sampling

Water samples were taken with a water sampler made at NIVA, designed for taking 20 water samples in 60 ml syringes (Pictures 1-4). The water sampler was mounted on a ROV and operated by the ROV crew.



Pictures 1-4. The water samples were taken with a water sampler mounted on a ROV (photos: Sigurd Øxnevad, NIVA).

Water samples were taken at four stations (WSL-1, to WSL-4, Figure 1). Samples were taken at two depths, 3 and 10 meters above the seabed. Samples were taken at station WSL-5 on 13.1.2014 since there were only limited access to the stations due to the position of the vessel.

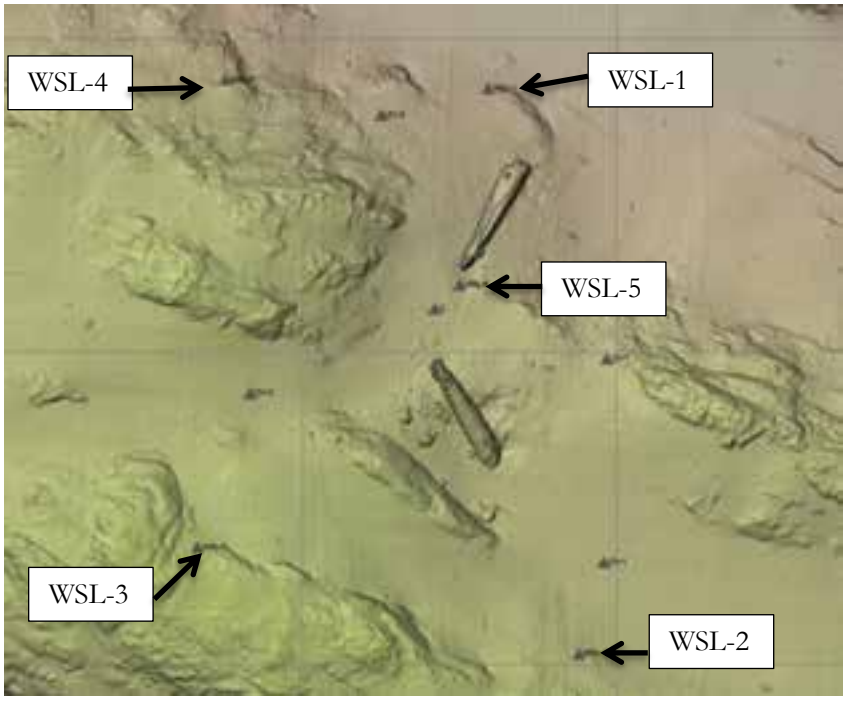


Figure 1. Water samples were collected around the wreck of submarine U-864 for analysis of mercury.

2.2 Measurements for mercury in air as part of HSE procedures

For safety reasons, equipment that had been used on the seabed or near the seabed was checked for mercury pollution when it was placed on deck. Personal protective equipment class 2 (including half face mask respirator with filters type HgP3) was used until the equipment and area was declared safe (picture 5). A portable Lumex Zeeman Mercury Analyzer was used to check for mercury vapour. The instrument is a multifunctional atomic absorption spectrometer with Xeeman background correction, which eliminates the effect of interfering impurities. It does not require gold amalgam pre-concentration and subsequent regeneration steps. This enables the user to conduct real time monitoring and detection of mercury vapour. The detection limit was 2 ng/m^3. Administrative norm for mercury vapour is 0.02 mg/m^3 (20 000 ng/m^3, veiledning om administrative normer for forurensning i arbeidsatmosfære, http://www.arbeidstilsynet.no/artikkel.html?tid=78880).

Picture 5. Measurement of mercury in air around a ROV that had just been landed on deck (photo: Fillip Andersen, Franzefoss).

2.3 Analysis of mercury in water samples

Water samples were analysed with a portable Lumex Zeeman Mercury Analyzer RA-915+, with a RP-91 attachment for liquid samples (Picture 6). The analytical principle is atomic absorption spectrometry using cold vapour technique. Mercury in the water sample is reduced with tin chloride to metallic mercury, and the vapour is flushed into an analytical cell of 10 meter optical path. This ensures high sensitivity and a detection limit of 0,5 - 1 ng/l could be achieved. A 10 ml water sample was used for the analysis of mercury.

Picture 6. Water samples were analysed with a portable Lumex Zeeman Mercury Analyzer RA-915+, with a RP-91 attachment (photo: Sigurd Øxnevad, NIVA).

The results were classified according to the classification system of the Norwegian Environmental Agency for classification of environmental quality in fjords and coastal water (Table 1, from Bakke *et al.* 2007).

Table 1. Classification system for concentration of mercury in water (from Bakke *et al.* 2007).

	Class I Background	Class II Good	Class III Moderately polluted	Class IV Bad	Class V Very bad
Mercury (µg Hg/l)	**<0.001**	**0.001 – 0.048**	**0.048 – 0.071**	**0.071 – 0.14**	**>0.14**

2.4 Analysis of mercury in sediment from sediment traps

Sediment was analysed with a Lumex RA-915+ Mercury Analyzer with pyrolyzer PYRO-915+. Combined with a two-chamber atomizer (PYRO-915+), the instrument can determine mercury content in solid samples such as sediment. The detection limit is 1.0 µg/kg in solid samples. A certified marine sediment reference material (MESS-3) was used as standard for the analysis of sediment samples.
The results were classified according to the classification system of the Norwegian Climate and Pollution Agency for classification of environmental quality in fjords and coastal water (Table 2) (Bakke et al. 2007).

Table 2. Classification system for concentration of mercury in marine sediments (from Bakke et al. 2007).

	Class I Background	Class II Good	Class III Moderately polluted	Class IV Bad	Class V Very bad
Mercury (mg/kg) dry weight	**<0.15**	**0.15 – 0.63**	**0.63 – 0.86**	**0.86 – 1.6**	**>1.6**

2.5 Monitoring of turbidity and water current

On January 8th to 9th seven rigs with instruments for monitoring of turbidity was deployed around the wreck of submarine U-864 (Figure 2). The intention was to deploy 8 rigs, but one rig got damaged during the lifting operation.

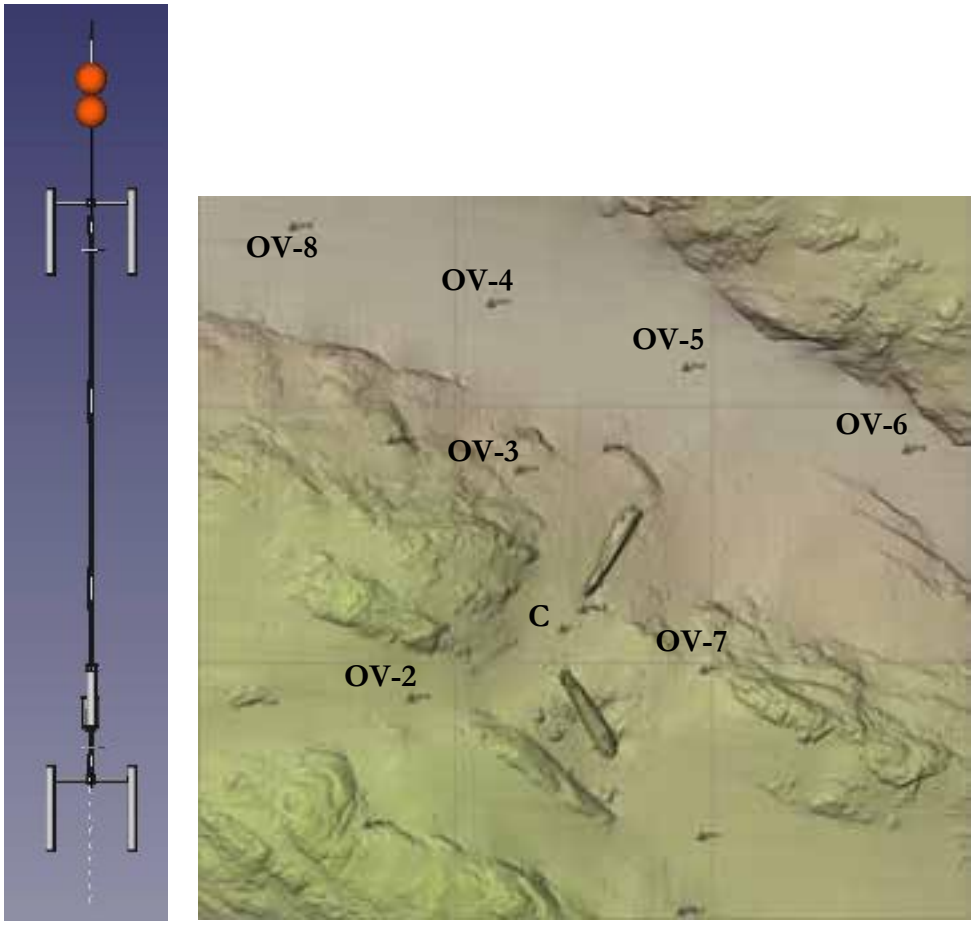


Figure 2. Turbidity rigs were deployed on 7 stations (OV-2 - OV-8) around the submarine wreck, and one turbidity sensor was mounted on the water current meter rig (C).

Turbidity was monitored at seven stations and water current was monitored at one station (Figure 2). The turbidity rigs were designed with turbidity sensors and sediment traps 3 and 10 meters above the seabed. Each rig had underwater modem and battery housing for transferring on-line measurements. The rigs also had a 100 kg anchor and buoyancy. Turbidity was acquired with AML MicroX Turbidity sensors (0-100 NTU).

Water current was measured through the whole water column in 5 m vertical cells with a Nortek Continental acoustic Doppler profiler. The water current profiler and turbidity sensor were deployed in a tripod frame (Picture 7). The turbidity sensor was installed at the same level as the profiler head. Measured deployment depth at profiler head was approximately 150 m. An IXSEA Oceano 2500 acoustic release was installed on the tripod. The tripod was retrieved up on deck, and logged data was unloaded. Extra battery was mounted to the tripod before it was deployed back to the same position for further logging of water currents.

Picture 7. Tripod with water current profiler and turbidity sensor being deployed (photo: Sigurd Øxnevad, NIVA).

A surface buoy with acoustic modem, battery and GPRS router was deployed for transfer of online measurements (Figure 3).

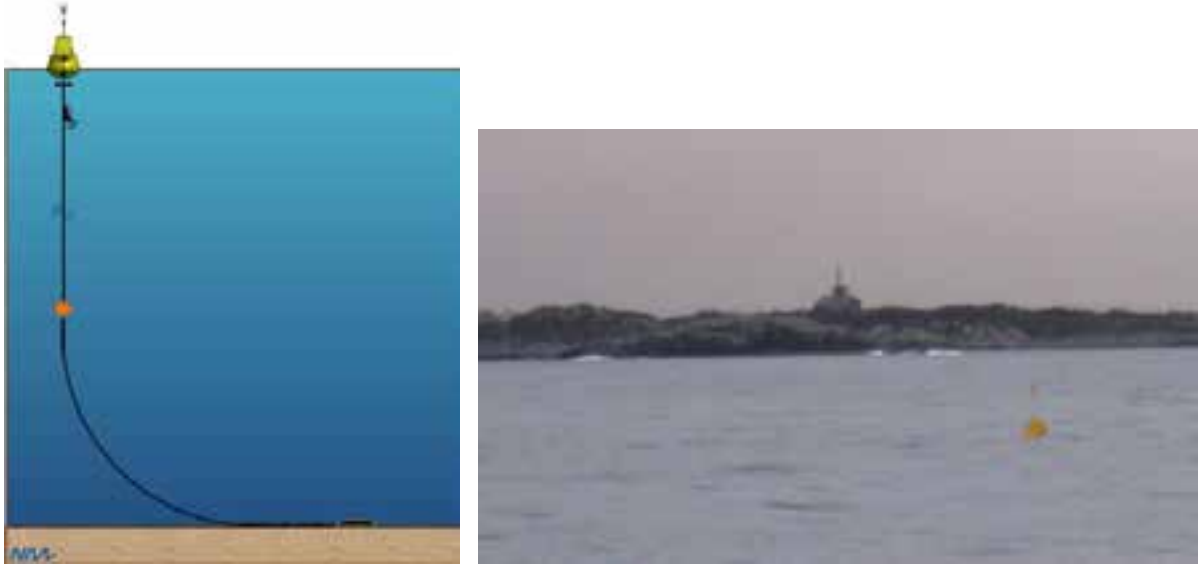


Figure 3. Figure of surface buoy with mooring, and picture of surface buoy outside Fedje (photo: Sigurd Øxnevad, NIVA).

Turbidity sensors were set up to measure turbidity every 15 seconds and "pushed" these values directly to the underwater acoustic modem on the local station. The underwater modem was set up to be in "Data Logger mode" and would then store data continuously in records in its local memory.
The acoustic surface modem made queries towards all the underwater modems at regular intervals specified by LabView program running on a PC that was locally at the NIVA office in Oslo. The acoustic surface modem communicated with a GPRS modem in the buoy which communicated with the PC at NIVA, Oslo. The queries from the PC in Oslo started on 9 January at 14.42, and the last query was executed on 16 January at 18:28 The LabView program in Oslo was programmed to ask for data every 15 minutes for turbidity and every 30 minutes for current.

2.6 Modelling sedimentation of particles

2.6.1 Objectives and general assumptions

Digging activity in sediments will whirl up a cloud of suspended particles. This cloud will be transported with the currents while the particles sink down until they settle at the sea bed some distance downstream. The objective of the model is to describe the lateral transport and sedimentation of Hg-contaminated particles suspended in the water column from activities undertaken during the operation described in this report.

Current in the water column as well as turbidity near the sea bed was measured at a station close to where the activity took place. The current was measured every 10 minutes with a vertical resolution of 5 m. The turbidity is a measure of suspended particles, and it is frequently assumed that a turbidity of 1 NTU correspond to a particle concentration of 1 g/m³ (Sørensen et al. 1993). This assumption applies also to this work.

Since current measurements only are available at one site, we assume no horizontal variation in the current field. This approximation is acceptable if the particles settle within a few hundred meters from the release point.

The Lagrangian particle tracking model described below, is referred to as NIVATRAC in the following.

2.6.2 Mathematical description of the model

Initially we have a particle released at a position ($x^{n=1}$, $y^{n=1}$ and $z^{n=1}$) at the time $t^{n=1}$ at the first timestep, $n = 1$, of the simulation. We have the relations

$$\frac{dx}{dt} = u$$

$$\frac{dy}{dt} = v \qquad (1)$$

$$\frac{dz}{dt} = w$$

By using a forward in time numerical scheme, we can calculate the position based on the relations (1) if the velocities u, v and w are known

$$x^{n+1} = x^n + u^n \cdot \Delta t$$

$$y^{n+1} = y^n + v^n \cdot \Delta t \qquad (2)$$

$$z^{n+1} = z^n + w^n \cdot \Delta t$$

The horizontal velocities, u and v are interpolated to the correct time and depth from the current measurements.

2.6.3 Sinking velocity

The vertical velocity,w, is calculated based on Stokes law

$$w = \frac{\rho_s - \rho}{18\mu} g d^2 \qquad (3)$$

Here ρ_s is the density of the particle (2.7 g/ml), ρ and μ are the density and viscosity of the sea water, g is the acceleration of gravity and d is the particle diameter.

2.6.4 The shape of the initial particle cloud

In the model, the initial cloud is represented by particles released at ten different depths above the seabed. The concentration of particles in the cloud is assumed to vary linearly from the measured value at the bottom to the background value at 10 m above the seabed. The shape of the cloud is assumed to be a cone, with a radius of 7.5 m at the seabed and a height of 10 m.

The unknown shape of the initial cloud is the largest source of uncertainty in the calculations, but this will only affect the absolute values of the sedimentation rate, and not the horizontal distribution pattern. The volume and particle distribution in the cone was scaled to fit the amount of particles collected in the sediment trap recovered 200 m away from the position of the cone. Particles are released every 10 minutes, but only if the concentration is above the background value, which was set to the lowest turbidity measured at station C.

For each class of particles it is assumed that the measured turbidity is a result of a cloud of uniform particles, all with size d.

2.6.5 Calculating sedimentation

The trajectories of the different particles are calculated until they reach the seabed because of sinking. The position is then stored, and the mass of all the particles that land within grid cells of size 50 x 50 m^2 are summed up. This is used to estimate the sedimentation rate. The density of the particles (ρ_s) are set to 2.7 g/ml in this calculation.

3. Results

3.1 Measurements for mercury vapour

Results from the measurements of mercury in air are presented in Appendix A.. No high concentrations of mercury were found in the ROV hangar. The Deep C excavator and dredger got very polluted with mercury, and cleaning turned out to be time consuming and difficult.

Liquid mercury was found on the Deep C machine on several places. After thorough flushing of the Deep C machine, liquid mercury and sediment was caught in the silt cloth (picture 8), but a few drops of mercury were also found on the wooden deck (picture 9).

Pictures 8 and 9. Mercury and sediment on the silt cloth (8), and mercury on the wooden deck (9) (photos: Sigurd Øxnevad, NIVA).

After the equipment was unloaded from deck, some of the wooden beams were removed. No liquid mercury was spotted on deck underneath the beams.

3.2 Mercury in sediment samples

Sediments were collected from the most contaminated area close to the submarine and from an area north of the contaminated site. In the area close to the wreck, approximately 50L of sediment was collected in two bags using the ROV and a steel shovel. The purpose of this sampling was to supply sediment for methylation experiments run at NIVA, Solbergstrand and in U.S. The bags were shipped to Solbergstrand in a metal barrel and three replicate subsamples were collected and analysed for total and methyl mercury. The results are shown in Table 3.The concentrations were 5-6 times higher than the boundary value for environmental class V "Very bad". The relatively low concentrations of methyl Hg confirmed previous conclusions that the environmental conditions at the U-864 site are not favourable for the methylation process.

Table 3. Total and methyl mercury in sediment collected near the submarine. The sediment was collected with a shovel operated by the ROV, and three replicate subsamples (A, B and C) were taken from the batch sample after arrival at NIVAs research station at Solbergstrand.

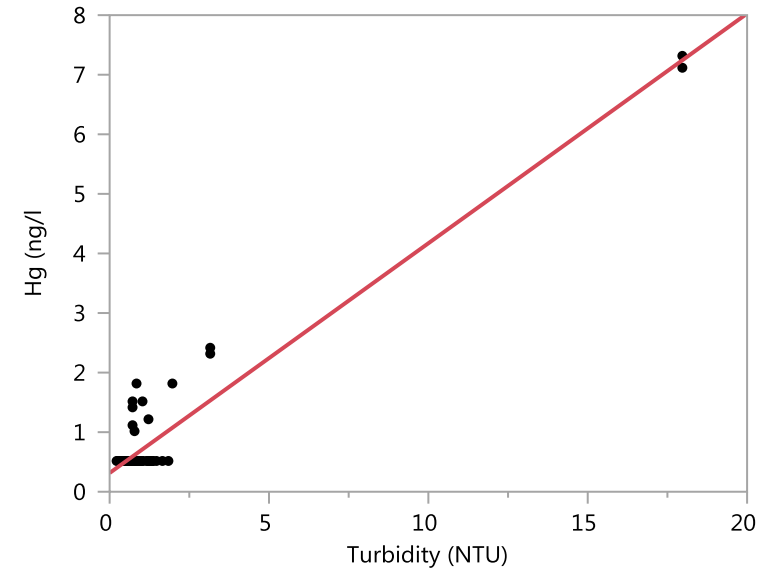
Sample	Total Hg (mg/kg dw)	Methyl Hg (mg/kg dw)
A	8,0	0,0012
B	8,8	0,0003
C	10,0	0,0003

Core samples from the area to the north were sampled by the ROV, but the cores were violently shaken and tipped over several times during handling both by the ROV and winching onboard. This caused severe vertical mixing of the sediments inside the core. The objective was to compare with previously collected samples to assess potential changes in the concentration of Hg within the top 0-2 cm layer, but the cores were not suitable for addressing this question. It was intended to collect new core samples later during the cruise, but this task was not given priority towards the end of the cruise

3.3 Mercury in water samples

The results from analysis of water samples are presented in Appendix B. The majority of the 74 water samples collected in syringes mounted on the ROV were below detection limit of 1 ng/l total Hg. 12 samples had detectable levels of Hg, the highest concentration was 7,3 ng/l in a sample collected on January, 12th. All of the 12 samples with detectable levels of Hg were classified as class II "good". The statistical analyses in figure 4 shows a positive correlation between turbidity and total concentration of mercury determined in the water samples.

Bivariate Fit of Hg (ng/l) By Turbidity (NTU)



Linear Fit

Hg (ng/l) = 0,3147138 + 0,3855845*Turbidity (NTU)

Summary of Fit

RSquare	0,917468
RSquare Adj	0,916321
Root Mean Square Error	0,331546
Mean of Response	0,82973
Observations (or Sum Wgts)	74

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	87,980179	87,9802	800,3842
Error	72	7,914415	0,1099	**Prob > F**
C. Total	73	95,894595		<,0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0,3147138	0,042624	7,38	<,0001*
Turbidity (NTU)	0,3855845	0,013629	28,29	<,0001*

Figure 4. Correlation between turbidity and concentration of mercury in all (n=74) syringe samples. Concentrations less than the detection limit was assigned 0,5 ng/l in this analyses.

The samples taken behind the dredger hose while dredging, had higher turbidity and a little higher concentrations of mercury, but were still not very polluted. The concentrations of mercury found in water close to the dredger was at the same level as found during dredging operations in 2006 (Uriansrud *et al.* 2006).

Dissolved fractions may spread far from the dredging site without showing up neither on turbidity sensors nor in sediment traps. However, filtration of samples with suspended sediments has shown that most of the mercury occurs in the particulate fractions (Schaanning et al. 2007).

3.4 Mercury in sediment from sediment trap at OV8

One sediment trap (10 m above the seabed) from rig OV8 was recovered. The sediment in this trap contained 4.20 mg Hg/kg dry weight. This is classified as class V (very bad). 98 % of the sediment particles were smaller than 63 μm in size. The high concentration of mercury in the sediment showed beyond reasonable doubt that the material trapped at OV8 originated in the digging and dredging activities at the submarine.

In two water samples with elevated concentrations of mercury, the concentrations were 7 ng/l and turbidity 18. The NTU scale is approximately correspondent with particle concentration so that 1 NTU equals 1 mg/l. Thus the two water samples had a sediment concentration of 7 ng Hg/18 mg sediment or 0,4 mg Hg/kg which is less than the concentration found in the trap. Sediment concentrations will vary from one location to another and with sediment depth so that the concentrations in the suspended particles are likely to vary during the operation. Also the concentration will vary with particles size so that the concentrations on the finest fractions which are carried the longest distance may be different from the bulk sediment suspended at the operation site. Thus, we would not expect a close match, and concludes that particles with similar or higher content of Hg than those found in the water samples have been transported in the water a distance of at least 200 m from the operation site to OV8.

3.5 Monitoring of turbidity and water current

Water current profiles are shown in Figure 5. The water current was mainly in northern direction, and the current speeds decreased from 50-100 cm/s.

The turbidity sensor on the tripod rig (C) was nearest to the work site by the aft section of the submarine. The turbidity monitoring showed that there were some turbidity peaks the 10th and 11th of January, a longer period with high turbidity the 12th of January, and some high peaks the 13th and 14th of January (Figure 6). Typical current speed was about 20 cm/s with variation between 0 and 50 cm/s.

The available turbidity data from stations OV2, OV3, OV6 and OV8 are shown in Appendix C. The registrations showed that there were no high peaks from 8th to 9th of January. On station OV2 there were only low turbidity values from the sensor 3 meters above the seabed, however on the sensor 10 meters above the seabed the turbidity increased from 2 to a maximum of 48 NTU during 9th to 11th of January. There is no apparent rationale to explain the difference between this and the other sensors. The registrations appear spurious and care should be taken when interpreting the data. On station OV6 there were no peaks in turbidity during 9th to 11th of January.

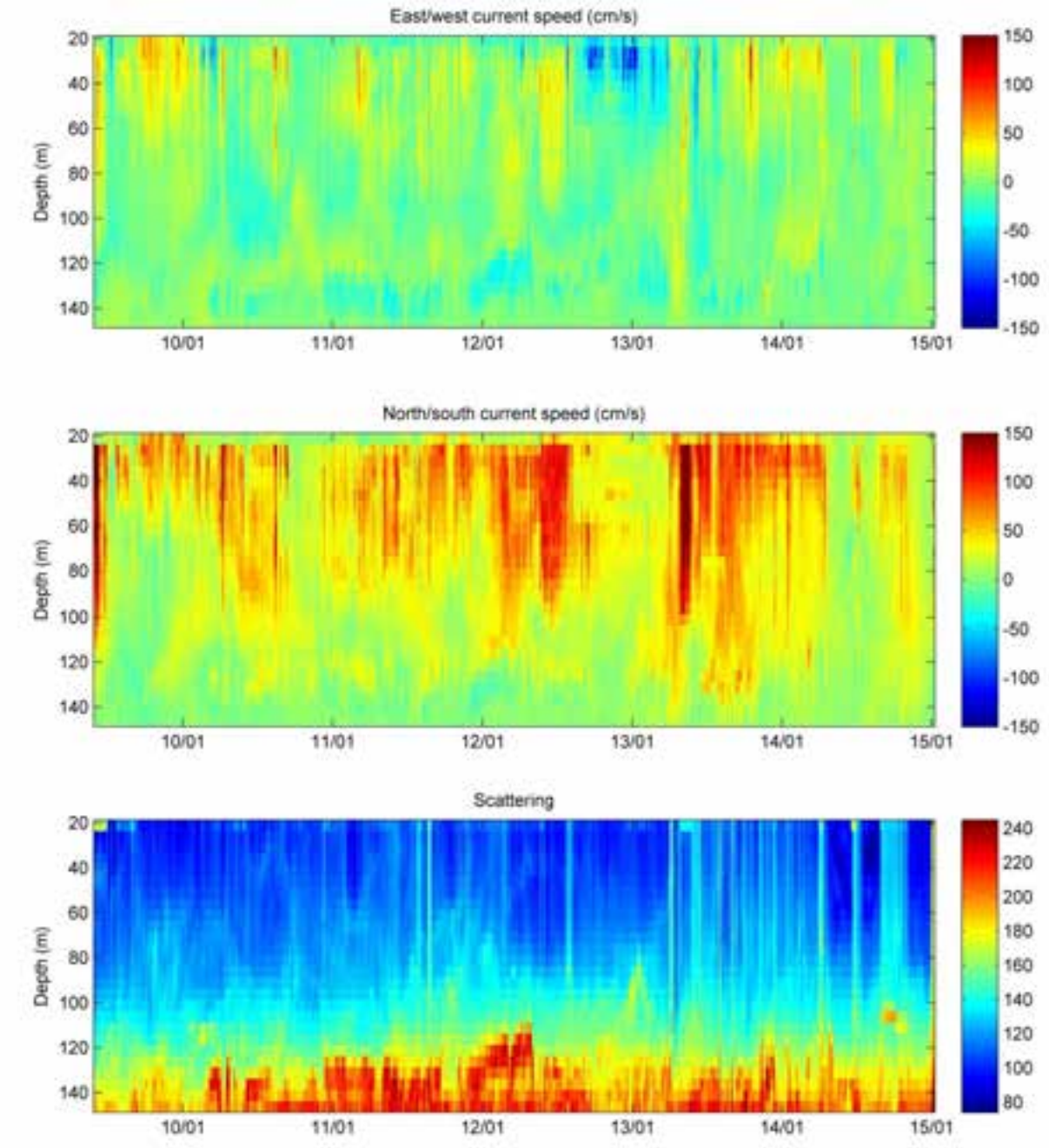


Figure 5. Upper panel: Current speed in the east-west direction. The color scale indicates the current speed in cm/s. Middle panel: Current speed in the north-south direction. The color scale indicates the current speed in cm/s. Bottom panel: Scattering from the ADCP current meter, indicating the particle concentration in the water column.

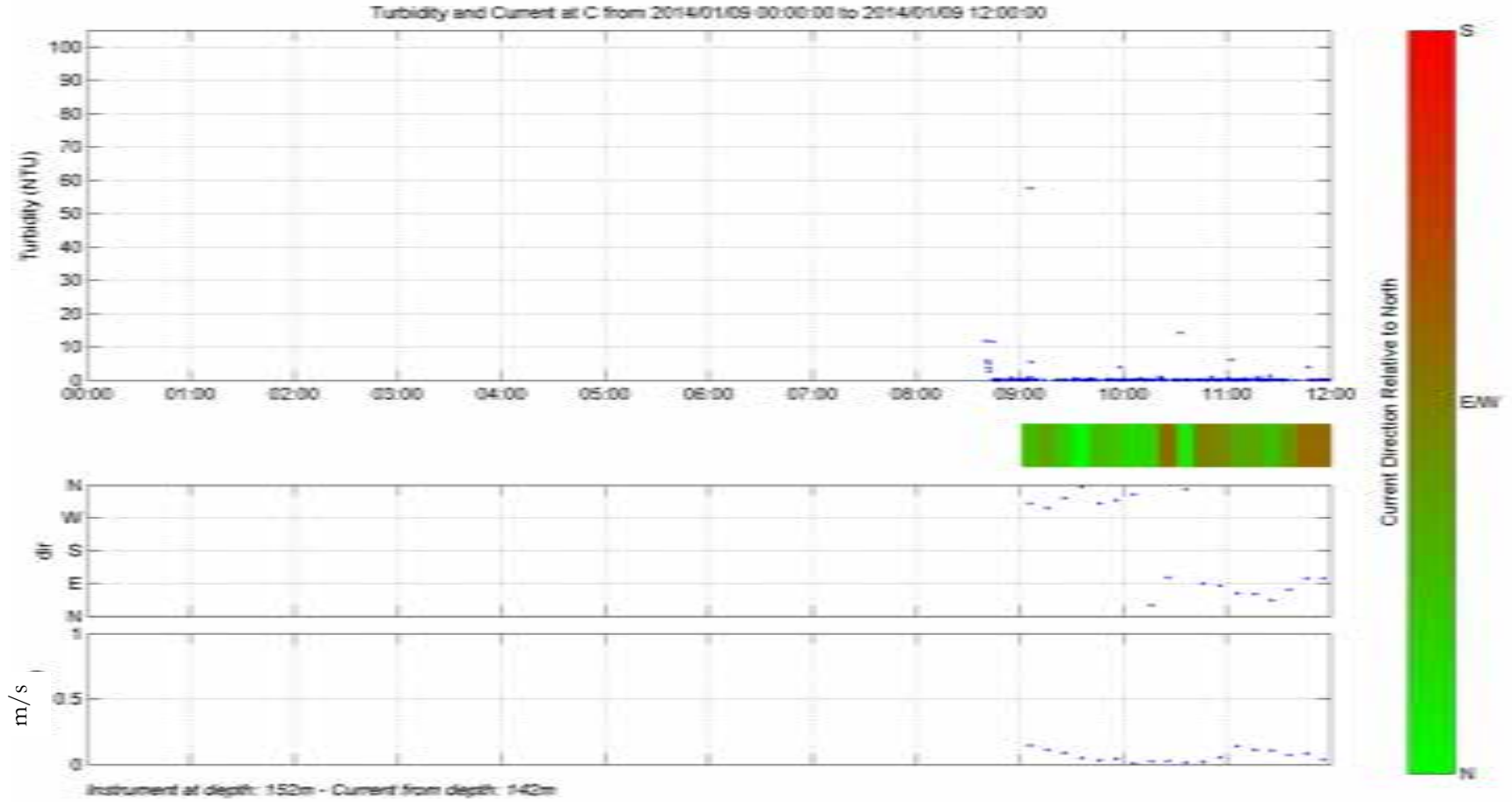
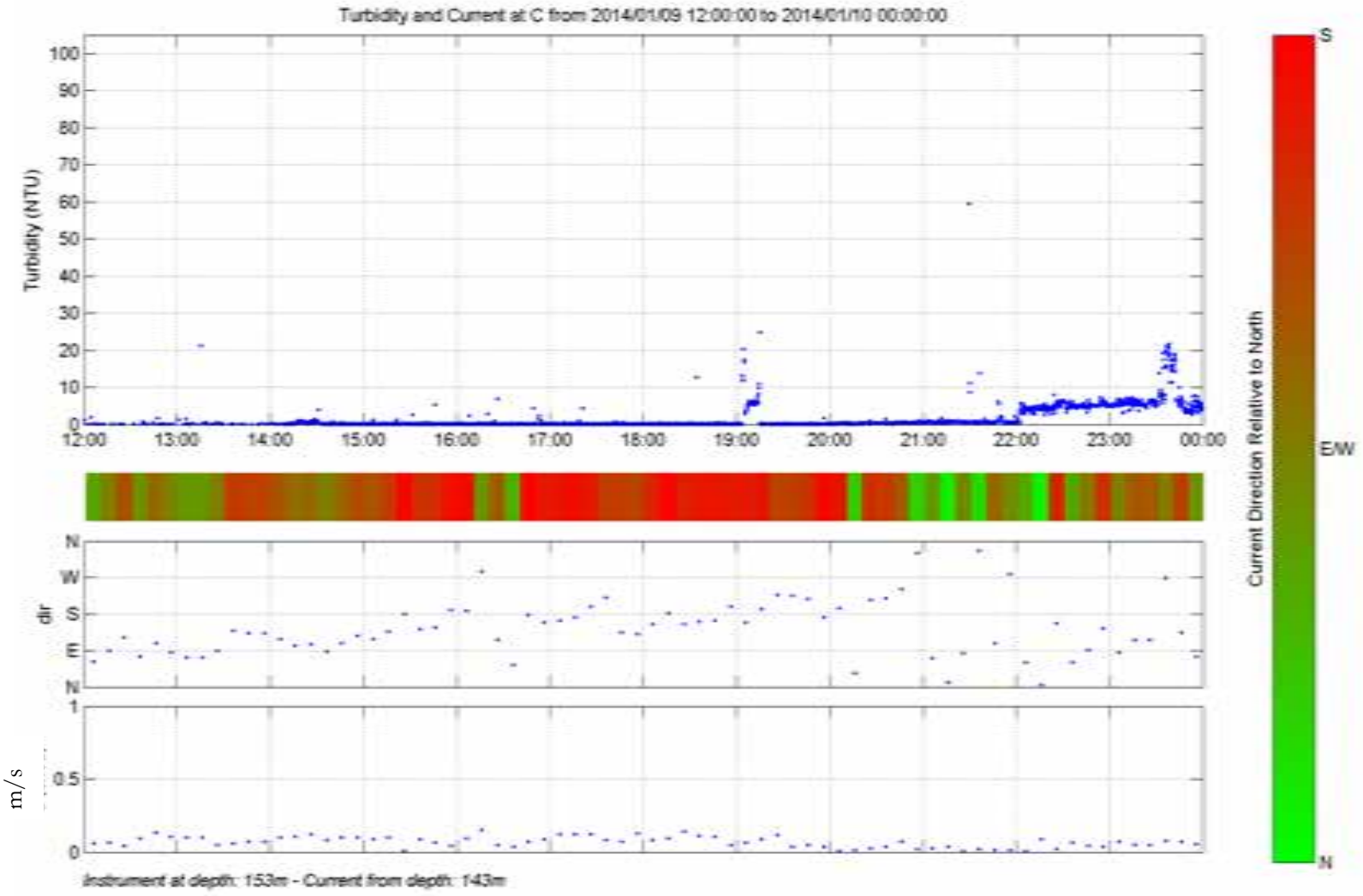
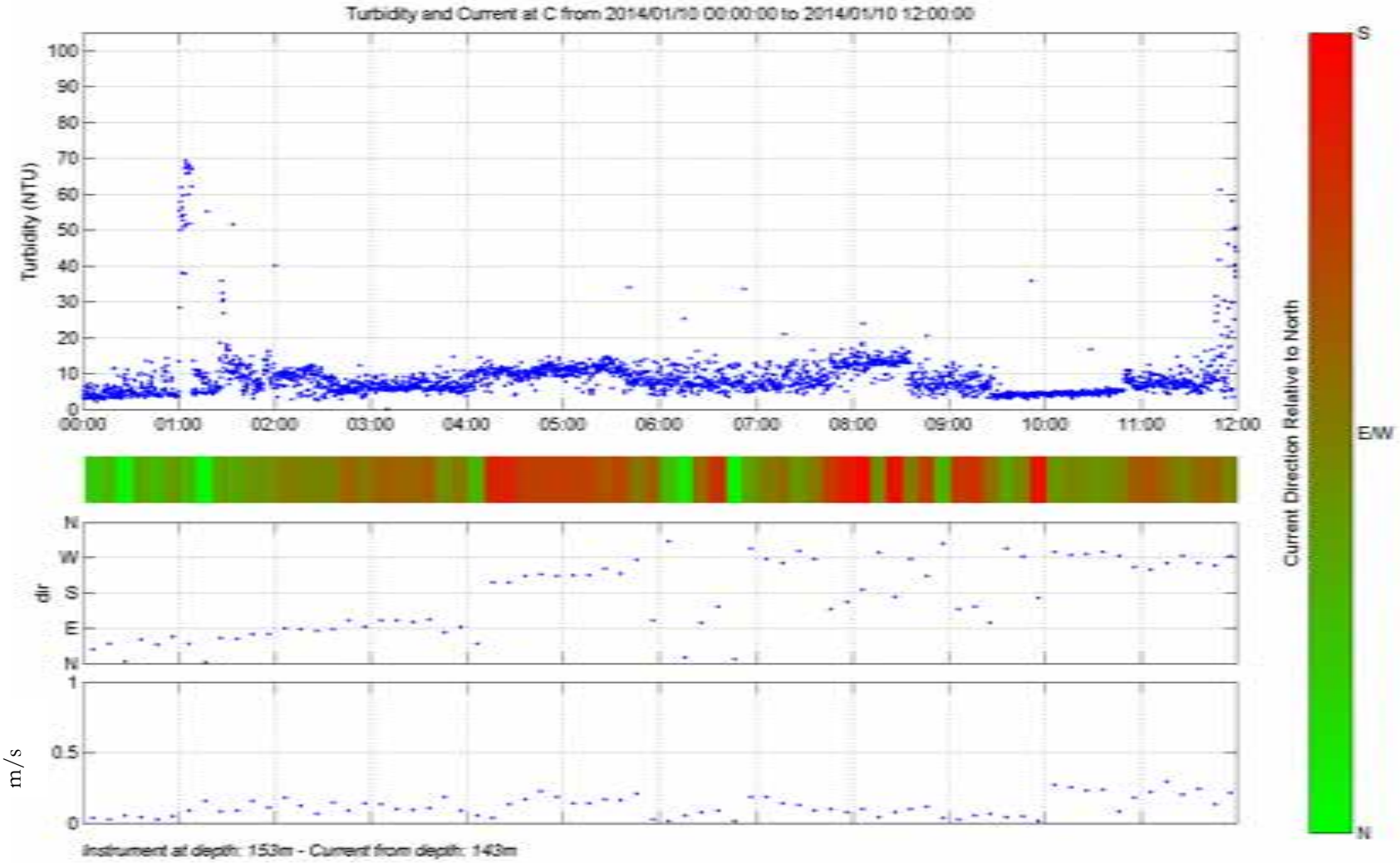
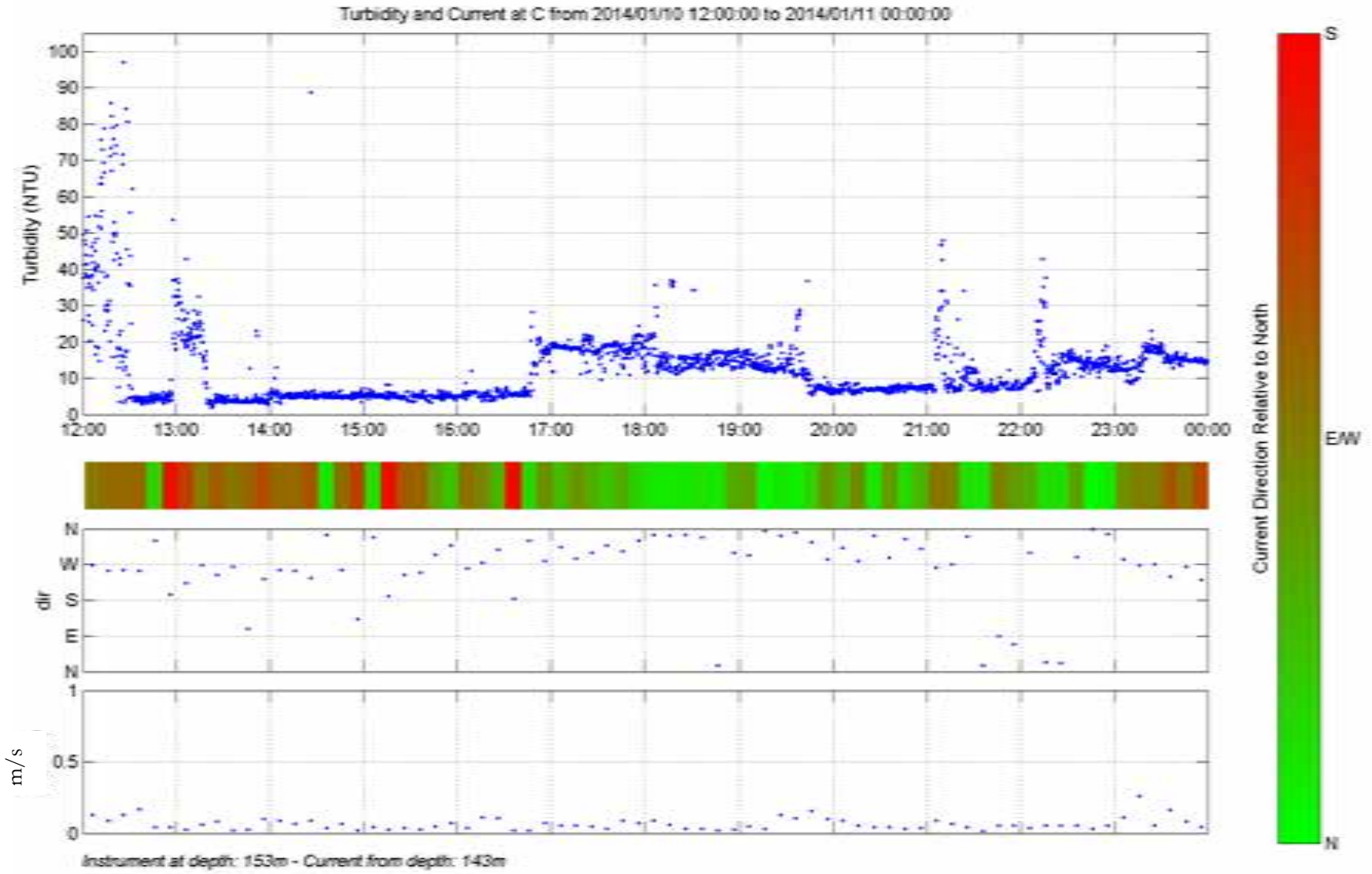
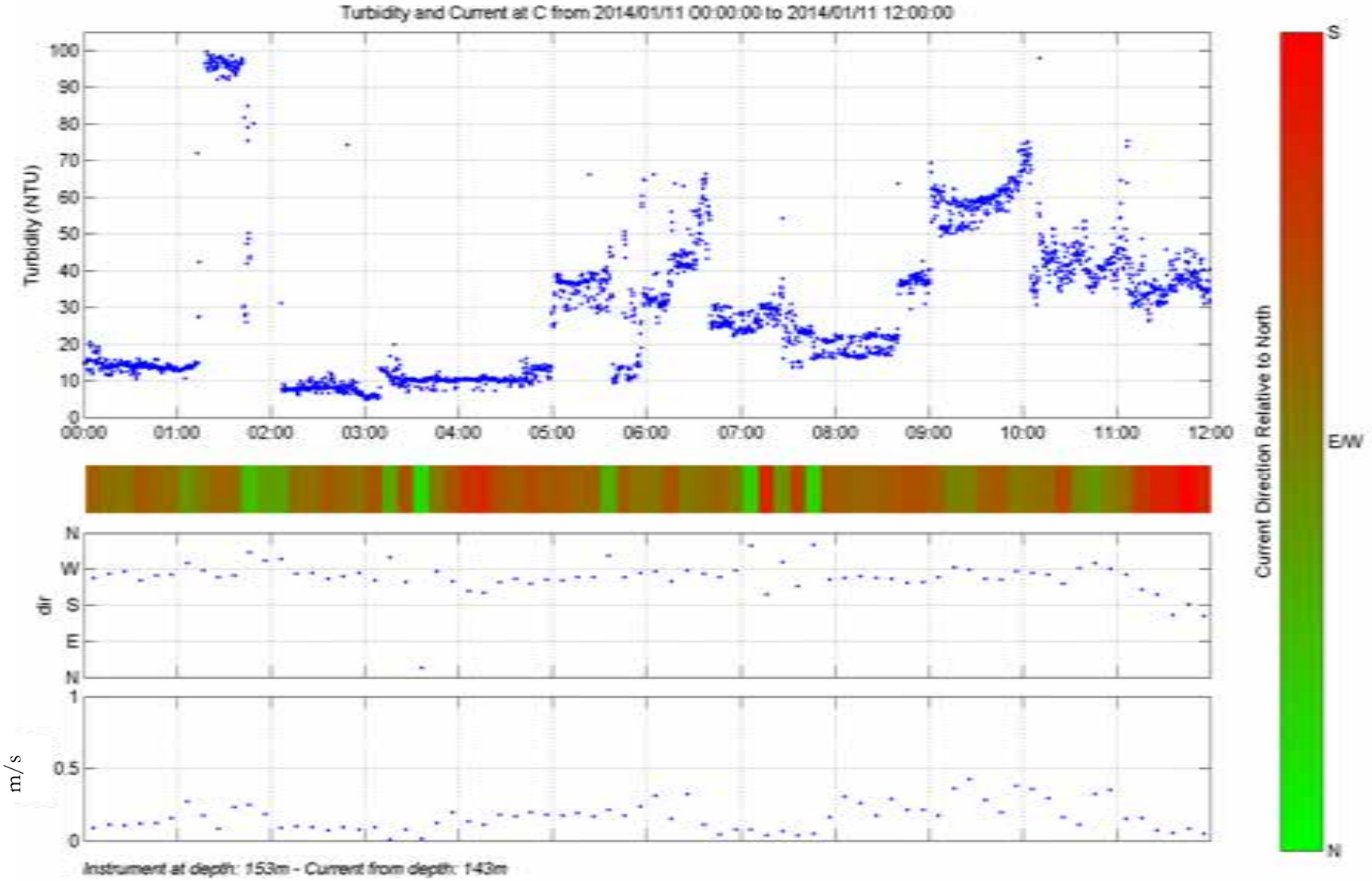


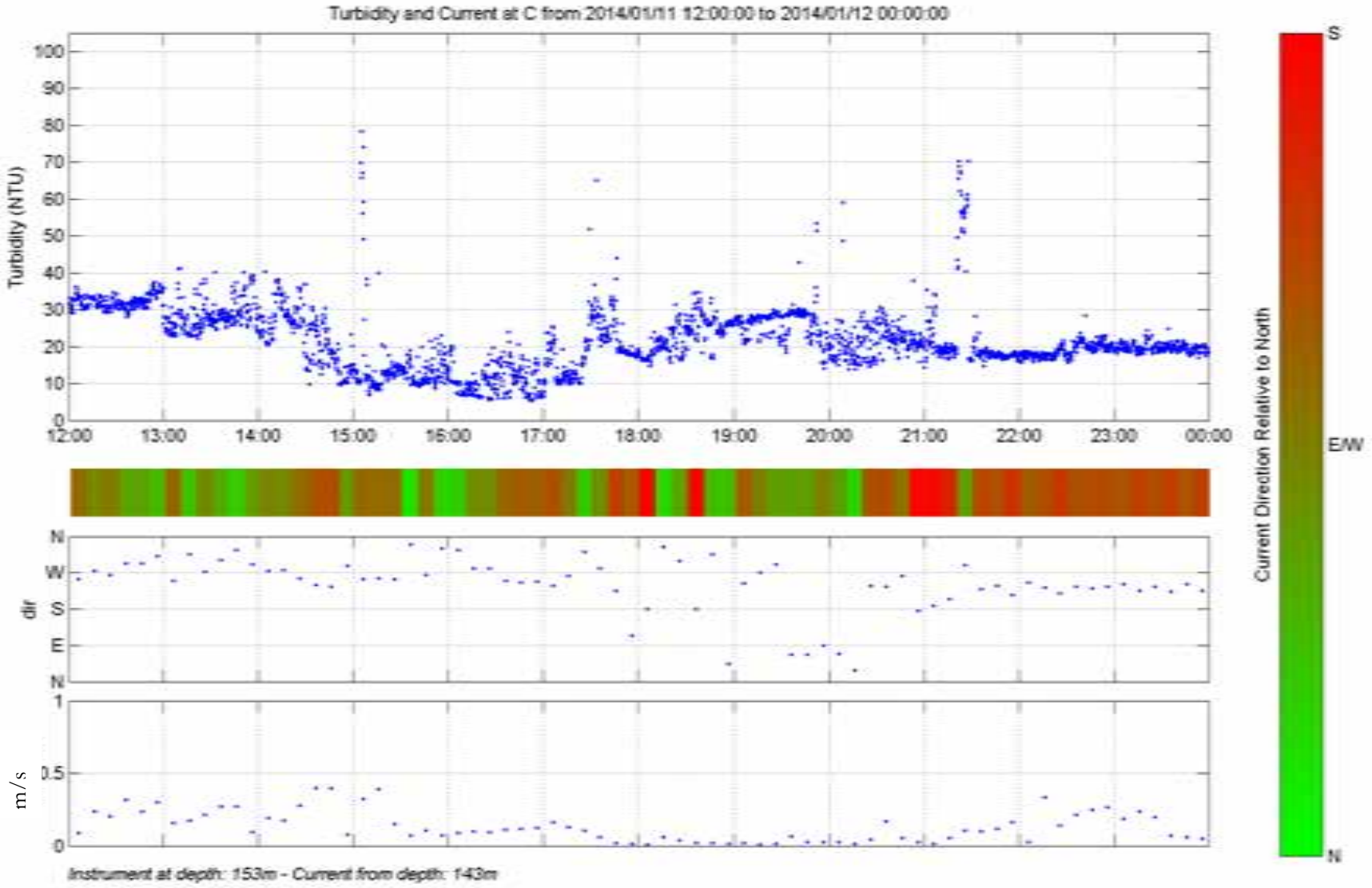
Figure 6. Turbidity and water current monitored at station C (between the two wreck sections). Data are presented in time series plot for turbidity, horizontal current direction and magnitude. Colour patches represent current direction relative to north. Assuming subsea operations were mainly located around the southern wreck part, position C for turbidity and current measurements can be found almost right north. Hence, the patches show whether the current is in the direction from subsea operations to position C (green) or opposite (red). Time is shown in UTC time. The figure continues on the following pages….

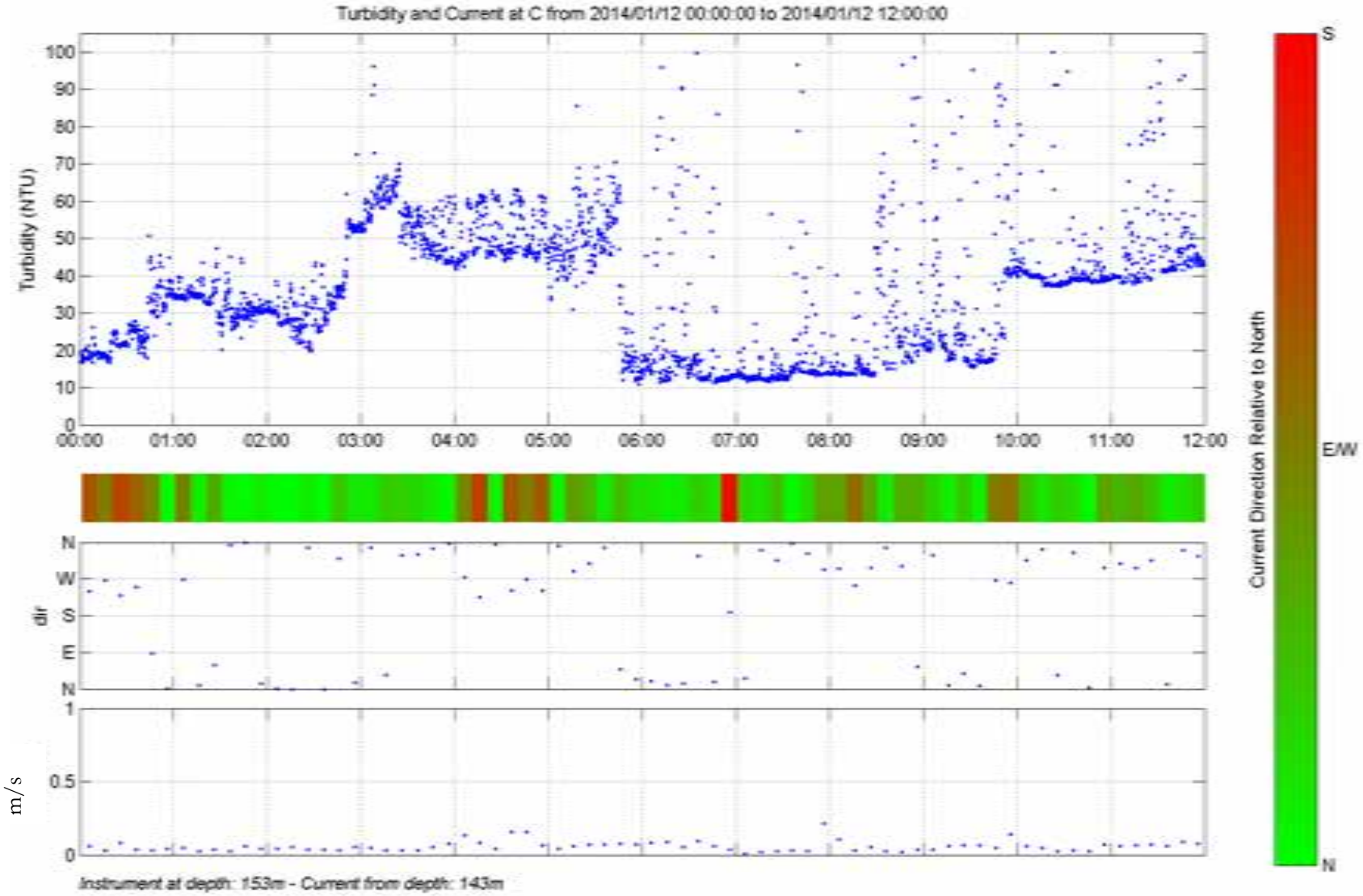

Turbidity and Current at C from 2014/01/09 12:00:00 to 2014/01/10 00:00:00
Turbidity (NTU)
100
90
80
70
60
50
40
30
20
10
0
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
00:00
dir
N
W
S
E
N
m/s
1
0.5
0
Instrument at depth: 153m - Current from depth: 143m
Current Direction Relative to North
S
E/W
N

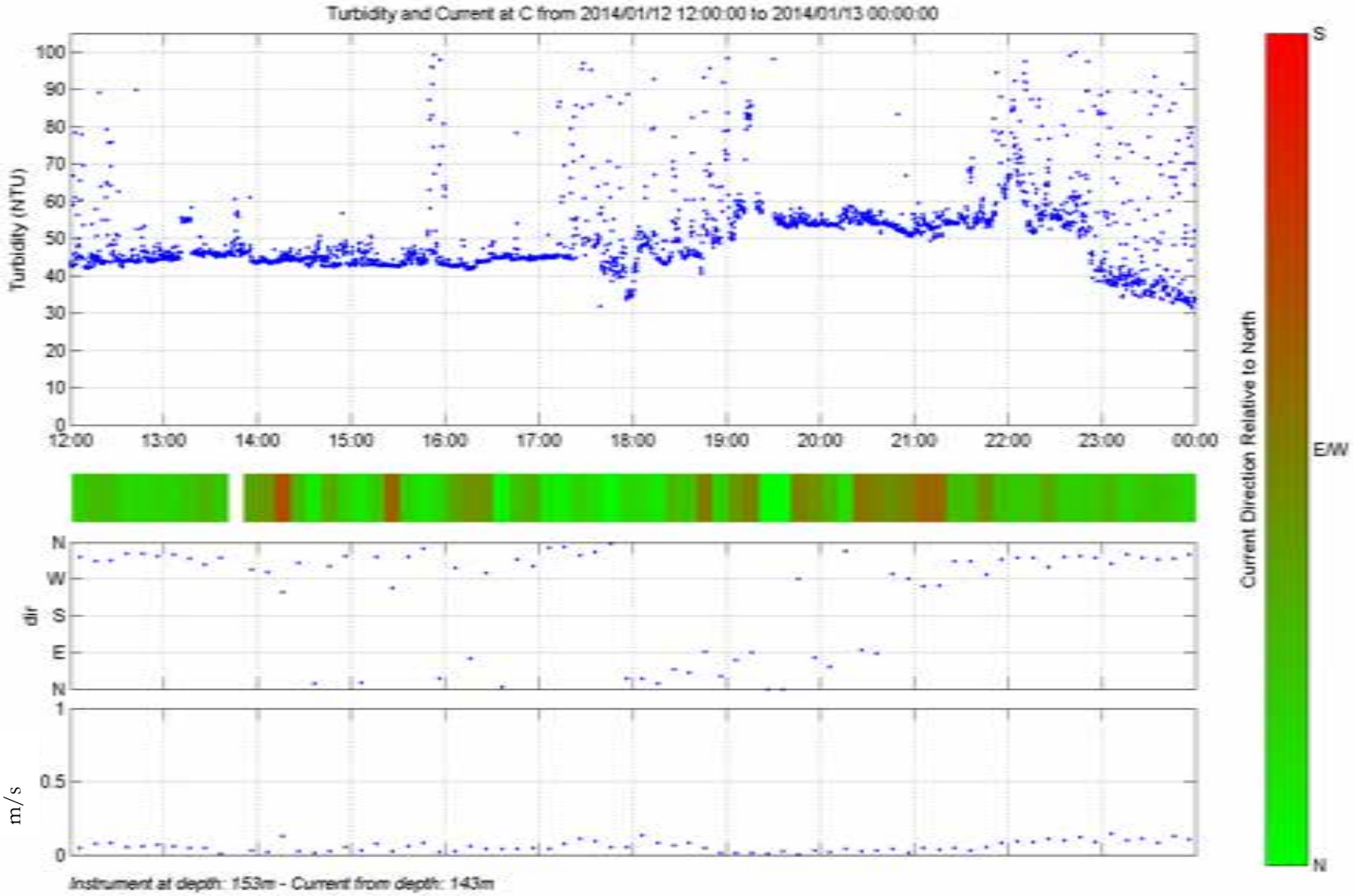

Turbidity and Current at C from 2014/01/10 00:00:00 to 2014/01/10 12:00:00
Turbidity (NTU)
100
90
80
70
60
50
40
30
20
10
0
00:00
01:00
02:00
03:00
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
12:00
dir
N
W
S
E
N
m/s
1
0.5
0
Instrument at depth: 153m - Current from depth: 143m
Current Direction Relative to North
S
E/W
N

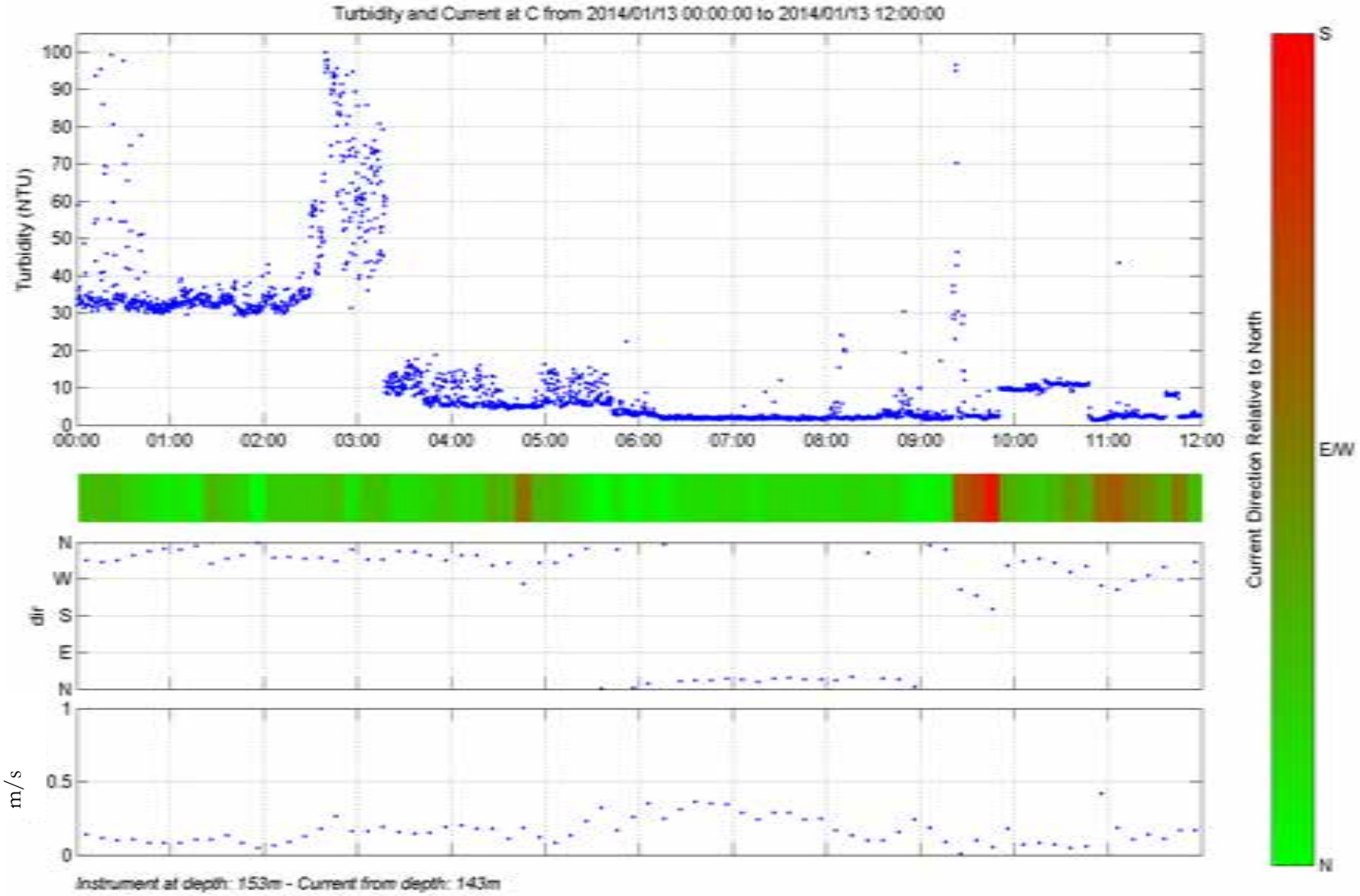

Turbidity and Current at C from 2014/01/10 12:00:00 to 2014/01/11 00:00:00
Turbidity (NTU)
100
90
80
70
60
50
40
30
20
10
0
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
00:00
dir
N
W
S
E
N
m/s
1
0.5
0
Instrument at depth: 153m - Current from depth: 143m
Current Direction Relative to North
S
E/W
N

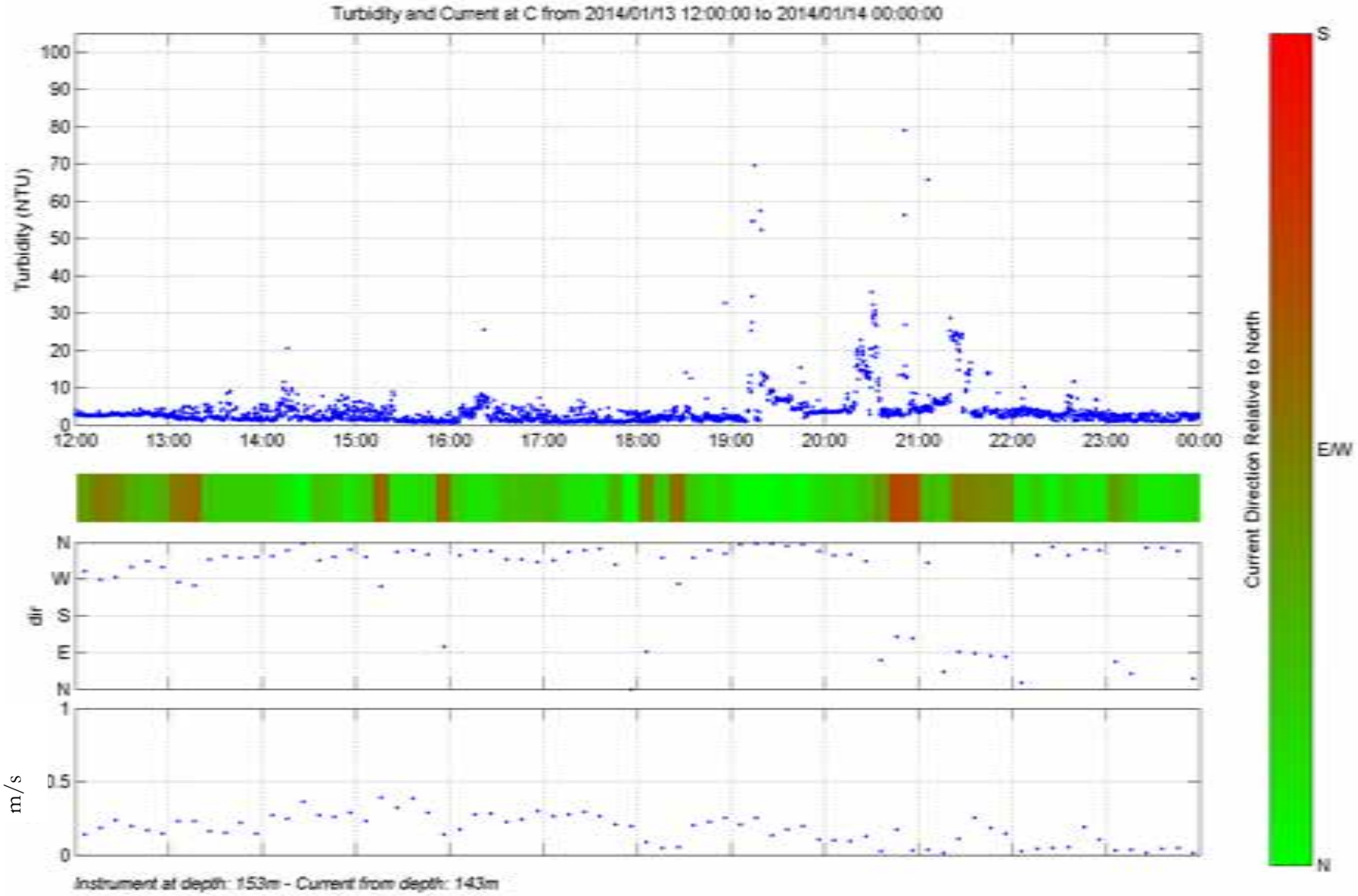

Turbidity and Current at C from 2014/01/11 00:00:00 to 2014/01/11 12:00:00
Turbidity (NTU)
0
10
20
30
40
50
60
70
80
90
100
00:00
01:00
02:00
03:00
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
12:00
dir
N
W
S
E
N
m/s
0
0.5
1
Instrument at depth: 153m - Current from depth: 143m
Current Direction Relative to North
S
E/W
N

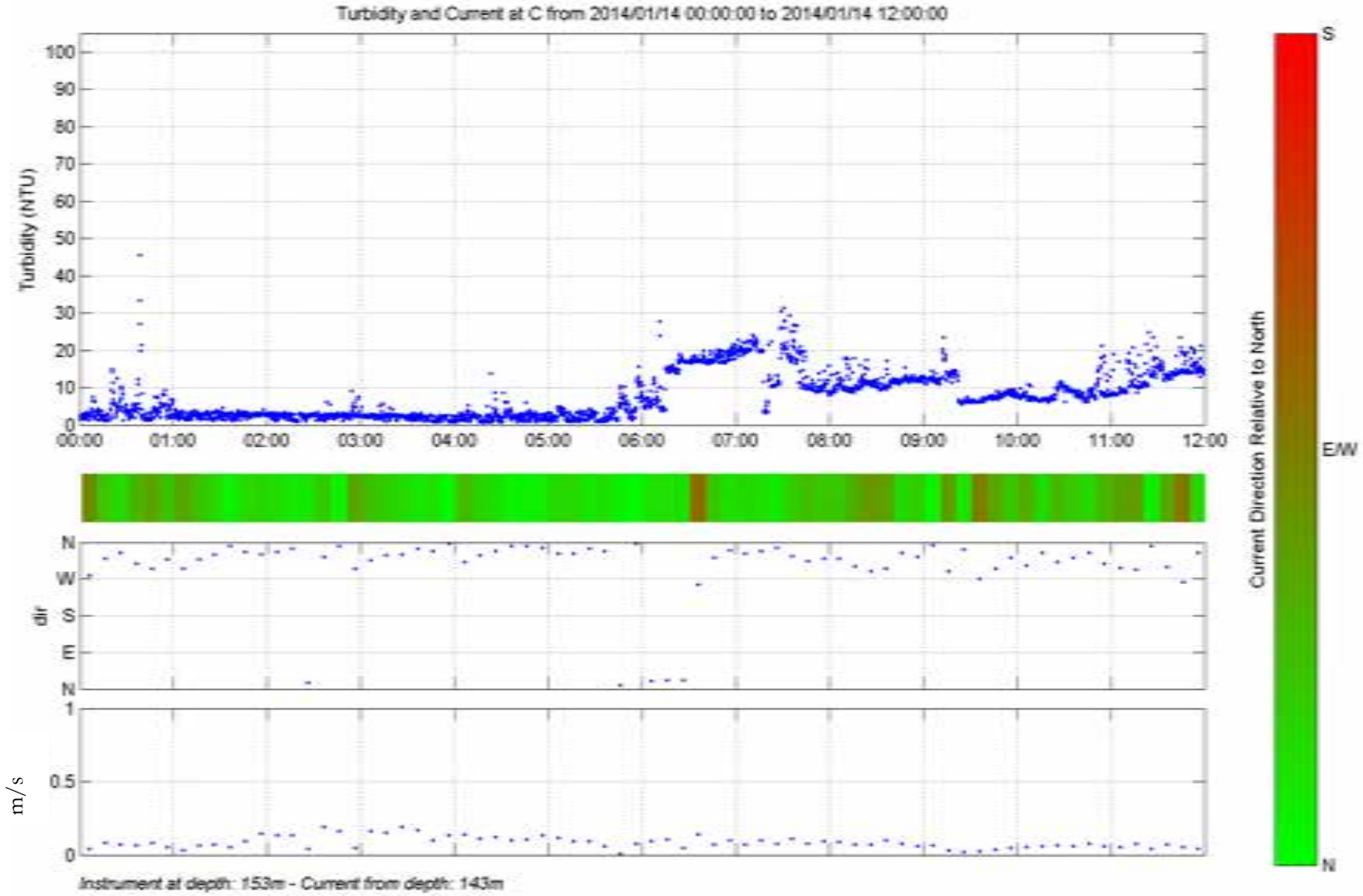

Turbidity and Current at C from 2014/01/11 12:00:00 to 2014/01/12 00:00:00
Turbidity (NTU)
100
90
80
70
60
50
40
30
20
10
0
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
00:00
dir
N
W
S
E
N
m/s
1
0.5
0
Instrument at depth: 153m - Current from depth: 143m
Current Direction Relative to North
S
E/W
N

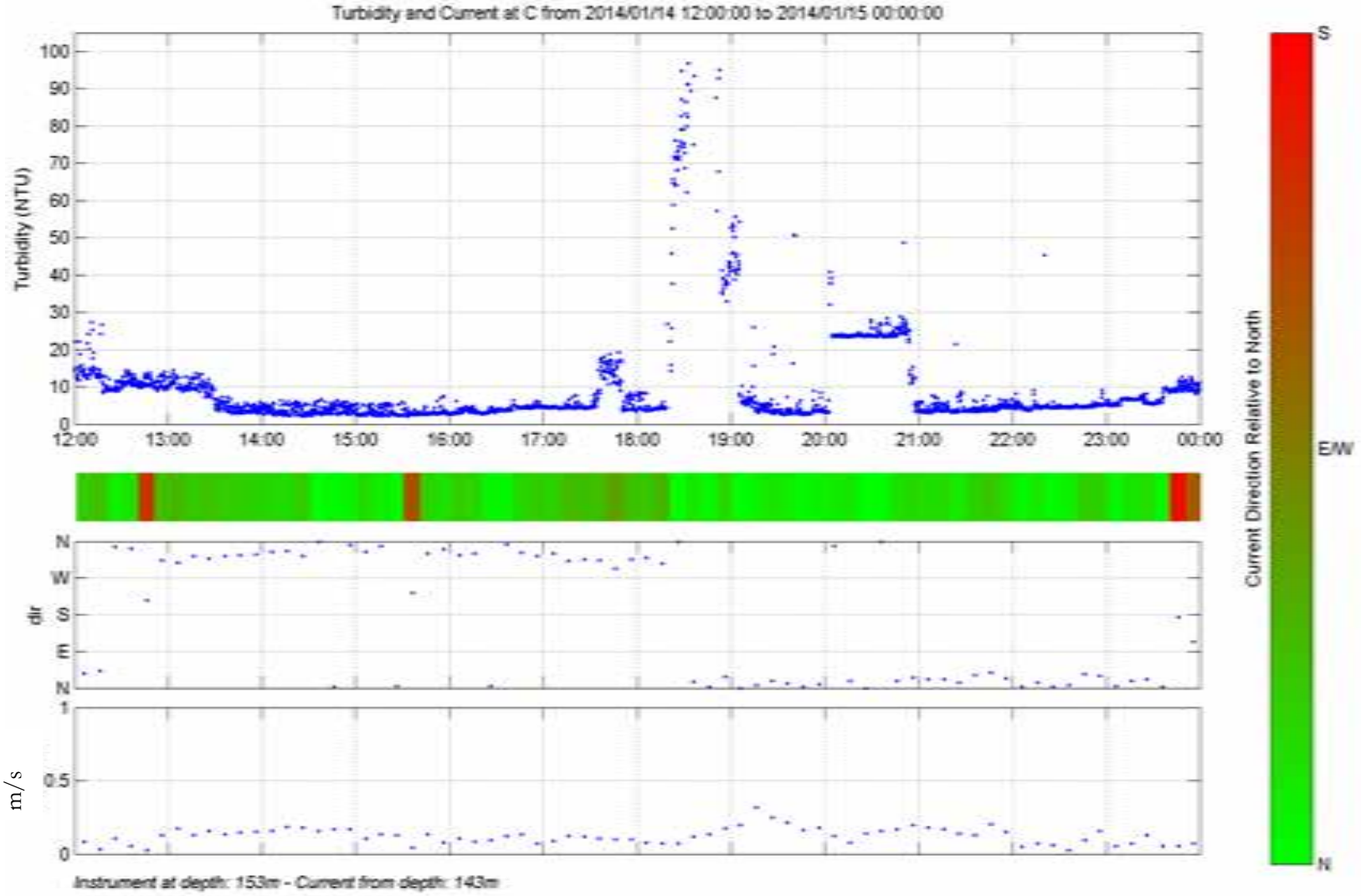

Turbidity and Current at C from 2014/01/12 00:00:00 to 2014/01/12 12:00:00
Turbidity (NTU)
100
90
80
70
60
50
40
30
20
10
0
00:00
01:00
02:00
03:00
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
12:00
dir
N
W
S
E
N
m/s
1
0.5
0
Instrument at depth: 153m - Current from depth: 143m
Current Direction Relative to North
S
E/W
N

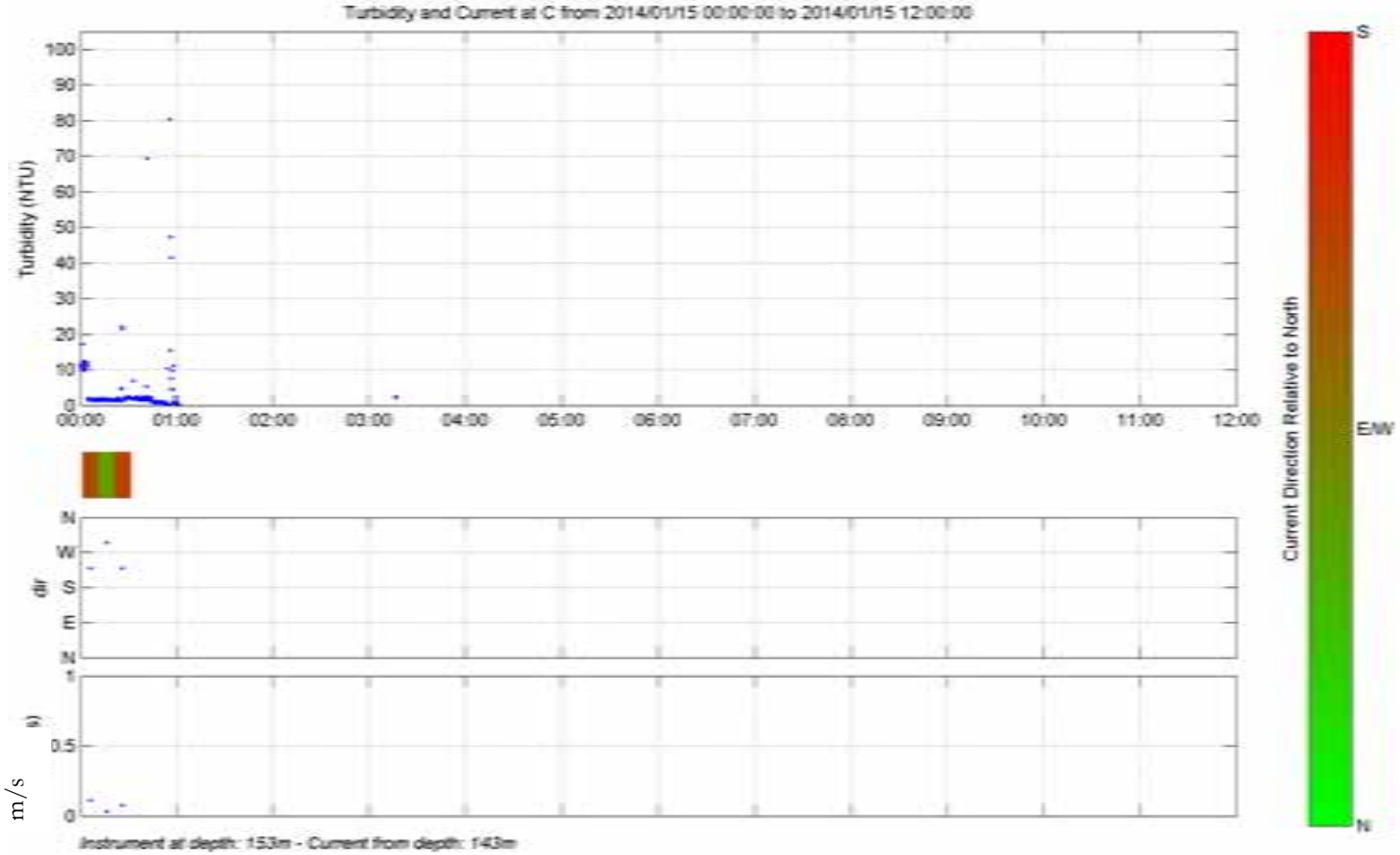

Turbidity and Current at C from 2014/01/12 12:00:00 to 2014/01/13 00:00:00
Turbidity (NTU)
100
90
80
70
60
50
40
30
20
10
0
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
00:00
dir
N
W
S
E
N
m/s
1
0.5
0
Instrument at depth: 153m - Current from depth: 143m
Current Direction Relative to North
S
E/W
N


Turbidity and Current at C from 2014/01/13 00:00:00 to 2014/01/13 12:00:00
Turbidity (NTU)
100
90
80
70
60
50
40
30
20
10
0
00:00
01:00
02:00
03:00
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
12:00
dir
N
W
S
E
N
m/s
1
0.5
0
Instrument at depth: 153m - Current from depth: 143m
Current Direction Relative to North
S
E/W
N


Turbidity and Current at C from 2014/01/13 12:00:00 to 2014/01/14 00:00:00
Turbidity (NTU)
100
90
80
70
60
50
40
30
20
10
0
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
00:00
dir
N
W
S
E
N
m/s
1
0.5
0
Instrument at depth: 153m - Current from depth: 143m
Current Direction Relative to North
S
E/W
N


Turbidity and Current at C from 2014/01/14 00:00:00 to 2014/01/14 12:00:00
Turbidity (NTU)
100
90
80
70
60
50
40
30
20
10
0
00:00
01:00
02:00
03:00
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
12:00
dir
N
W
S
E
N
m/s
1
0.5
0
Instrument at depth: 153m - Current from depth: 143m
Current Direction Relative to North
S
E/W
N


Turbidity and Current at C from 2014/01/14 12:00:00 to 2014/01/15 00:00:00
Turbidity (NTU)
100
90
80
70
60
50
40
30
20
10
0
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
00:00
dir
N
W
S
E
N
m/s
1
0.5
0
Instrument at depth: 153m - Current from depth: 143m
Current Direction Relative to North
S
E/W
N


Turbidity and Current at C from 2014/01/15 00:00:00 to 2014/01/15 12:00:00
Turbidity (NTU)
100
90
80
70
60
50
40
30
20
10
0
00:00
01:00
02:00
03:00
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
12:00
dir
N
W
S
E
N
m/s
1
0.5
0
Instrument at depth: 153m - Current from depth: 143m
Current Direction Relative to North
S
E/W
N

3.6 Modelled sedimentation

The regression curve calculated in Figure 4 (eq. 4) gives a relation between turbidity and concentration of mercury in the cloud of particles suspended in the water mass.

$$Hg(ng\ l^{-1}) = 0.315 + 0.386 \cdot Turbidty(NTU) \qquad (4)$$

This relation (4) was also shown to be reasonably consistent with the concentration of Hg found in the sediment trap at OV8 and can be used together with NIVATRAC to estimate the sedimentation of mercury around the operation area. Four different particle classes are modelled, where the sinking velocity is given by (3). For each of the particles classes shown in Figure 7, it is assumed that all of the particles in the initial cloud is uniform and of the given particle size.

Analysis of the sediments in the sediment trap at station OV-8 showed that 98 % of the particles were smaller than 63 μm. This is confirmed by the modelling that showed that particles bigger than 63 μm will sink to the seabed within 100 m from station C.

At station OV-8 the concentration of mercury was measured to 4.20 mg Hg/kg dry weight. Based on estimates of the total dry weight in the sample and the horizontal area of the sediment trap, the sedimentation of mercury will have been 0.7 ± 0.6 mg/m² in the area where the trap was located. The plots in Figure 7 were calibrated so that the concentration at station OV-8 was within this range for particle size 30, 40 and 63 μm. The last plot, with particle size 20 μm, was calibrated so that the maximum concentration was within the range of the measured value at station OV-8.

It can be seen from Figure 7 that the cloud of particles does not reach far beyond station OV-8 if all of the size of the particles are close to 63 μm. Smaller particles will spread over a considerably larger area. If for example a large amount of the particles in the initial cloud is of particle size 20 μm or smaller, the model suggests that sedimentation of Hg may have been as high as 100 mg/m² as far as 1000 m from the release point. This scenario is likely to represent maximum spreading during this operation. The particle size distribution within the trapped material is not known, but it appears unlikely that particles of size 20 μm or less constitute a significant fraction of the bulk sediment.

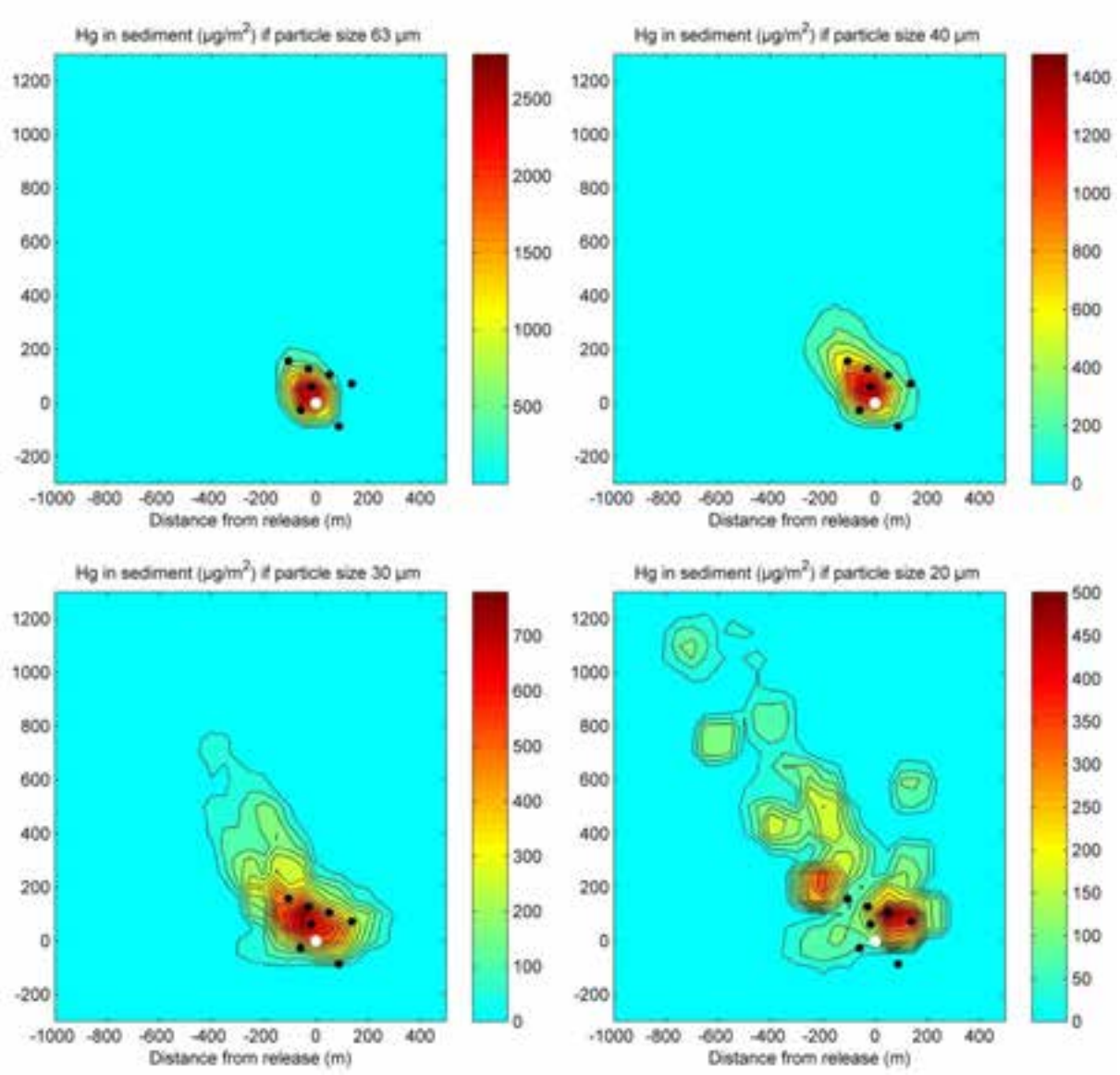


Figure 7. Results from the modelling of sedimentation of mercury (µg Hg/m² of the bottom) during the operation at Fedje 9.-15.01.2014. The model is based on measurements of currents and turbidity at station C (white circle) and sediments trapped at station OV8. The black points represent the positions of the OV stations, see Figure 2. Dispersion of particles is modelled for four different particle classes.

4. Conclusions and recommendation

No high concentrations of mercury were found in air in the ROV hangar. The Deep C excavator and dredger were found to be significantly contaminated with mercury during inspection on deck after the operation. Liquid mercury was found on the excavator and high concentrations of mercury vapour were detected on several places at the machine.

Mercury was detected in only small concentrations in the water samples. The concentrations of mercury in the water samples were in class I (background) and class II (good). The digging and dredging in the contaminated area caused some spreading of particles contaminated with mercury, but the concentrations in the water samples were low.

One sediment trap (10 m above the seabed) from rig OV8 was recovered. The sediment in this trap positioned approximately 200 m northwest of the operation center contained 4.2 mg Hg/kg dry weight. This is classified as class V (very bad). The high concentration of mercury in the sediment trap shows that the digging and dredging has caused spreading of contamination.

Due to loss of turbidity rigs there is not sufficient data to assess spreading of contamination with particles. Data for turbidity showed that there were several peaks of turbidity and some longer time periods with high turbidity measured on rig C a little north of the aft section were most of the digging and dredging operations were undertaken.

Model calculations based on current and turbidity measurements on rig C, water samples collected from ROV and sediment material trapped at station OV-8 showed that particles larger than 63 um will sediment less than 100m from the operation center. Most actually with the 50 m grid at the operation center. Typically, 60 to 90% of the sediments on the site is larger than 63 um. The model showed that silt and clay fractions will be spread further away from the operation site. Particles of 63 um will sediment mostly within 200m, whereas the smaller size fractions of 20 um may be transported up to 1 km through the water mass before settling on the sediment. Due to the prevailing current directions the particles will spread primarily towards northwest. It is assumed that particles smaller than 20 um constitute a very small fraction of the bulk sediment.

In order to verify the model results on spreading during this operation, it may be considered to collect new sediment cores in the operation area for comparison with mercury concentrations in previously collected samples. By fine sectioning of the top layer it should be possible to verify the spreading of mercury calculated by the model.

5. References

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Sørensen, K., Aas, E., Faafeng, B., Lindell, T. 1993. Fjernmåling av vannkvalitet – videreutvikling av optisk satelittfjernmåling som metode for overvåking av vannkvlitet. NIVA rapport 2860-1993.

Uriansrud, F., Skei, J., Mortensen, T., Dahl, I. & Wehde, H. 2006. Miljøovervåking, strømundersøkelser, sedimentkartlegging og vurdering av sedimenttildekking – Fase 2 kartlegging ved U-864 høsten 2006. NIVA rapport 5279-2006.

Appendix A. Measurements of mercury vapour

Concentrations of mercury detected in air during the survey.

Date	Time	Location for Hg measurement	Concentration (ng Hg/m³)
7. Jan		In lab container	2-10
8. Jan	14:20	In ROV hangar (and on ROV)	1-10
	17:00	In ROV hangar (and on ROV)	1-8
9. Jan	15:00	In lab container	1-8
10. Jan	02:15	On deck before bringing up any equipment	3-5
	03:30	On deck	0-4
	07:20	In ROV hangar (and on ROV)	1-10
	08:00	By orange peel grab	1-10
	10:30	In ROV hangar (and on ROV)	1-10
	20.30	In lab container after measurements of water samples	1-5
	21:30	In ROV hangar (and on ROV)	0-8
	23:25	In ROV hangar (and on ROV)	0-7
11. Jan	03:15	In ROV hangar (and on ROV)	1-7
	07:00	In ROV hangar (and on ROV)	1-8
	09:10	In ROV hangar (and on ROV)	1-8
	15:40	In ROV hangar (and on ROV)	1-7
	16:00	By Deep C excavator	1-8
	18:45	In lab container	1-5
	21:00	By orange peel grab	1-10
	21:10	In ROV hangar (and on ROV)	1-7
12. Jan		On basket for sediment samples	0-10
	14:30	In lab container	1-8
	17:15	In ROV hangar (and on ROV)	1-10
	17:50	In ROV hangar (and on ROV)	1-8
	17:40	By basket for sediment samples after cleaning	1-10
	19:50	In lab container	Ca 150
		In lab container over garbage bin	380
	20:30	In lab container	47
13. Jan	13:45	In lab container	15-25
	15:50	In lab container	4-10
	16:05	In ROV hangar (and on ROV)	1-8
	22:00	In ROV hangar (and on ROV)	1-10
		Over damaged sediment corer in ROV hangar	675
14. Jan	07:30	In lab container	7-10
	07:50	In ROV hangar (and on ROV)	
		Over a "warm black box"	200-250
		On "cup" used for lifting Hg-canisters	425
	08:00	In ROV hangar (and on the other ROV)	2-7
	08:10-09:40	On Deep C excavator and dredging hose	
		On dredging hose	>50 000
		Several places on excavator	20 000-30 000
		On dredging hose after a lot of flushing	2000-3000
	09:45	On wooden deck	2-42
	10:50	On parts of ROV	120-150
	14:10	In ROV hangar (and on ROV)	2-260
		On warm components on ROV	260
	14:45	Found liquid Hg on wooden deck	

Date	Time	Location for Hg measurement	Concentration (ng Hg/m³)
	15:00	In ROV hangar (and on ROV)	1-20
		In lab container	15-20
	15:15	On excavator	20-6000
		On parts of dredging hose	225-460
	18:15	In lab container	40-60
		On air intake in lab container	120
	19:45	On deck	20-50
		On deck close to dredger	100-200
	21:30	In lab container	120-350
	23:10	On damaged sediment corer on ROV hangar	10-20
15. Jan	01:00	On basket with sediment samples	20-30
	05:00	In ROV hangar (and on ROV)	1-15
	09:10	On basket with sediment samples	67-165
	13:20	In Deep C container, floor	10-65
		on dirty strap	400-800
	14:20	By rig for current measurements	5-22
	14:30	On Deep C excavator, over gravel and clay	480-970
	18:40	In lab container	40
	23:20	In ROV hangar (and on ROV)	1-15
16. Jan	07:30	In ROV hangar (and on ROV)	5-32
		On warm component	975
	14:40	In ROV hangar (and on ROV)	
		On plate of steel from the submarine	107
		On grinder	24
	20:30	In ROV hangar (and on ROV)	5-20
	20:45	On excavator	10-50
		In cavities	650
	21:50	On excavator after cleaning	10-40
		In same cavities	1000
	22:45	On excavator after cleaning	
		In same cavities	1000-2000
	22:55	In ROV hangar (and on ROV)	5-40
	23:10	On excavator after more cleaning	
		In same cavities	2000
	23:30	In ROV hangar (and on ROV)	1-20
17. Jan	03:20	In blue dredger hose	>50 000
	03:50	In blue dredger hose after more flushing	10 000-30 000
	04:15	In blue dredger hose after more flushing	10 000-30 000
	04:50	In blue dredger hose after more flushing	20 000
	07:50	On working gloves of Deep C personnel	>50 000
	10:00	On basket and equipment on dirty area	25-950
		On sandbags	>50 000
	12:30	In ROV hangar (and on ROV)	0-24
		On warm component	235
	13:00	On equipment on ROV basket	3-510
	18-19	On Deep C machine, platform	30-98
		In dredger hose	50-380
	20:25-21:30	In ROV hangar (and on ROV)	0-70
18. Jan	04:55-5:30	On deck after unloading of equipment	5-280
		On marked area on wooden deck	200-340
	10:15	On marked area on deck	510

Date	Time	Location for Hg measurement	Concentration (ng Hg/m³)
	10.45	**On deck after removal of six wooden beams**	**100-1200**

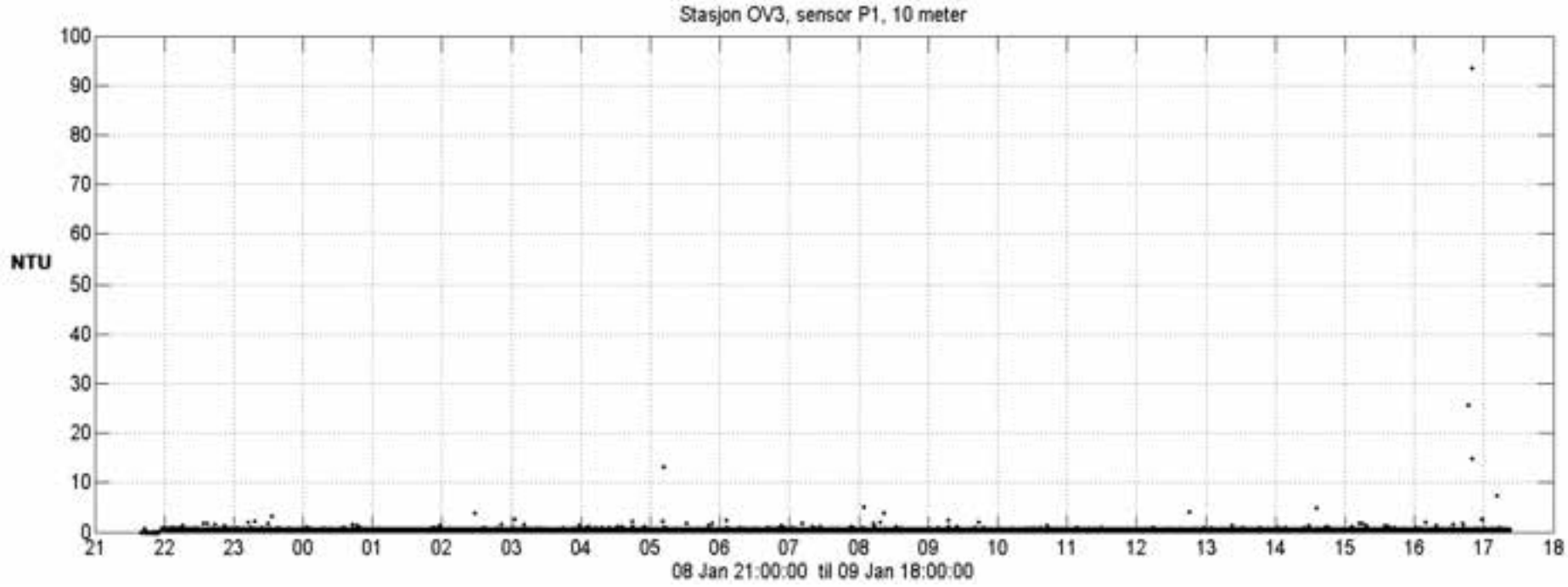
Appendix B. Mercury in water samples

Concentrations of mercury in water samples taken near submarine U-864 during the survey. The results are presented according to the classification system shown in table 1.

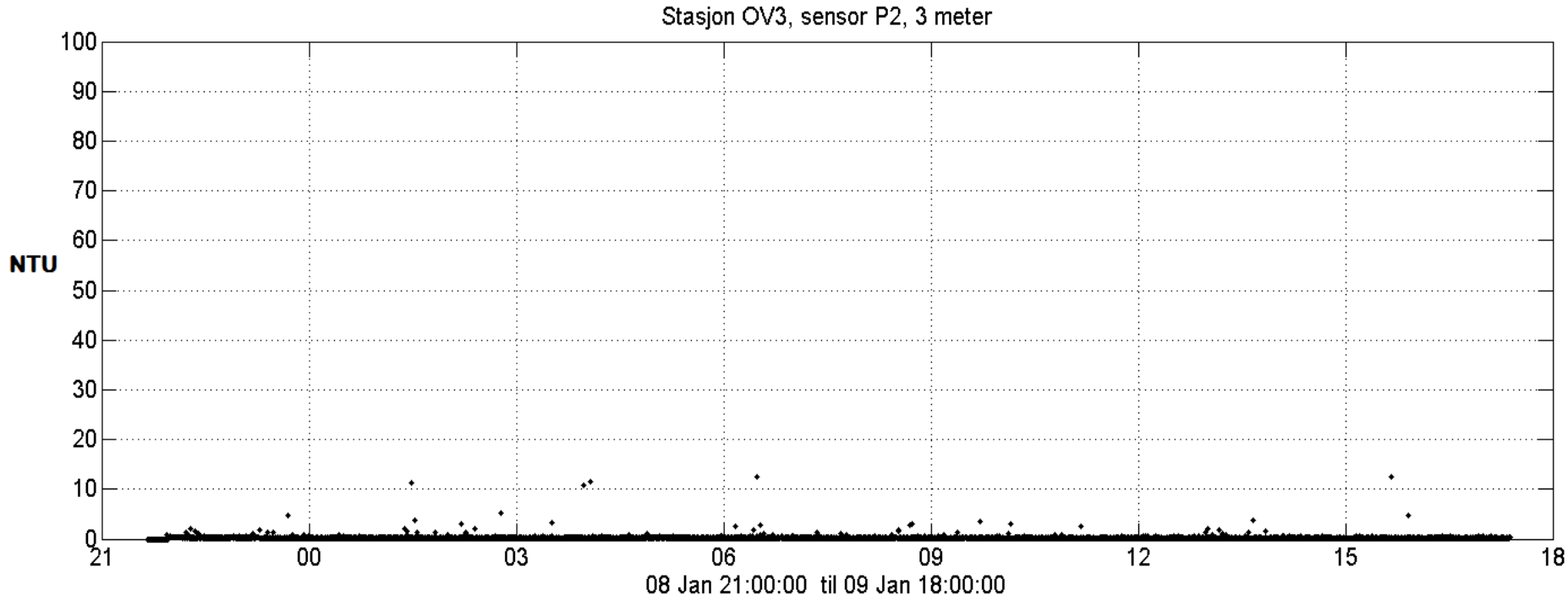
Date	Time	Station	Elevation over seabed	Turbidity	Concentration ng Hg/l
10. Jan	09-10	WSL-3	3 m	0.77	<1.0
	09-10	WSL-3	10 m	0.77	<1.0
	09-10	WSL-4	10 m	0.79	<1.0
	09-10	WSL-4	3 m	0.83	<1.0
	09-10	WSL-1	10 m	0.83	<1.0
	09-10	WSL-1	3 m	1.39	<1.0
	09-10	WSL-2	10 m	1.08	<1.0
	09-10	WSL-2	4 m	0.90	<1.0
	22:15-23:10	WSL-3	3 m	0.39	<1.0
	22:15-23:10	WSL-3	10 m	0.37	<1.0
	22:15-23:10	WSL-4	10 m	0.30	<1.0
	22:15-23:10	WSL-4	3 m	0.29	<1.0
	22:15-23:10	WSL-1	10 m	0.26	<1.0
	22:15-23:10	WSL-1	3 m	0.36	<1.0
	22:15-23:10	WSL-2	10 m	0.29	<1.0
	22:15-23:10	WSL-2	3 m	0.42	<1.0
11. Jan	07:45-08:40	WSL-3	3 m	0.43	<1.0
	07:45-08:40	WSL-3	10 m	0.44	<1.0
	07:45-08:40	WSL-4	10 m	0.92	<1.0
	07:45-08:40	WSL-4	3 m	0.53	<1.0
	07:45-08:40	WSL-1	10 m	0.64	<1.0
	07:45-08:40	WSL-1	3 m	0.58	<1.0
	07:45-08:40	WSL-2	10 m	0.47	<1.0
	07:45-08:40	WSL-2	3 m	0.53	<1.0
	21:40-22:35	WSL-2	10 m	0.86	<1.0
	21:40-22:35	WSL-2	3 m	1.20	<1.0
	21:40-22:35	WSL-3	10 m	0.48	<1.0
	21:40-22:35	WSL-3	3 m	0.55	<1.0
	21:40-22:35	WSL-1	10 m	0.59	<1.0
	21:40-22:35	WSL-1	3 m	0.40	<1.0
	21:40-22:35	WSL-4	10 m	0.44	<1.0
	21:40-22:35	WSL-4	3 m	0.46	<1.0
12. Jan	08:35-09:30	WSL-3	10 m	1.22	1.2
	08:35-09:30	WSL-3	3 m	1.40	<1.0
	08:35-09:30	WSL-2	10 m	1.33	<1.0
	08:35-09:30	WSL-2	3 m	1.71	<1.0
	08:35-09:30	WSL-4	10 m	1.23	<1.0
	08:35-09:30	WSL-4	3 m	0.95	<1.0
	08:35-09:30	WSL-1	10 m	1.36	<1.0
	08:35-09:30	WSL-1	3 m	1.25	<1.0
	18:15-19:15	WSL-1	10 m	0.79	<1.0
	18:15-19:15	WSL-1	3 m	0.78	1.1
	18:15-19:15	WSL-4	10 m	0.80	<1.0
	18:15-19:15	WSL-4	3 m	0.72	<1.0
	18:15-19:15	WSL-2	10 m	0.75	<1.0
12. Jan	18:15-19:15	WSL-2	3 m	0.73	1.4

Date	Time	Station	Elevation over seabed	Turbidity	Concentration ng Hg/l
	18:15-19:15	WSL-2	3 m	0.73	1.5
	18:15-19:15	Dredger exhaust	10 m	3.16	2.4
	18:15-19:15	Dredger exhaust	10 m	3.16	2.3
	18:15-19:15	Dredger exhaust	3 m	1.50	<1.0
	18:15-19:15	Dredger exhaust	3 m	18.0	7.3
	18:15-19:15	Dredger exhaust	3 m	18.0	7.1
	18:15-19:15	WSL-3	10 m	0.66	<1.0
	18:15-19:15	WSL-3	3 m	0.81	<1.0
13. Jan	16:30-17:05	WSL-2	10 m	0.92	<1.0
	16:30-17:05	WSL-2	3 m	1.09	<1.0
	16:30-17:05	WSL-5	10 m	1.31	<1.0
	16:30-17:05	WSL-5	3 m	0.86	<1.0
14. Jan	03:50-04:25	WSL-4	3 m	0,81	1.0
	03:50-04:25	WSL-4	10 m	0,72	<1.0
	03:50-04:25	WSL-1	3 m	1.04	1.5
	03:50-04:25	WSL-1	10 m	0.86	1.8
	03:50-04:25	WSL-2	3 m	0.91	<1.0
	03:50-04:25	WSL-2	10 m	0.79	<1.0
	03:50-04:25	WSL-3	3 m	1.02	<1.0
	03:50-04:25	WSL-3	10 m	0.98	<1.0
16. Jan	22:15-23:05	WSL-3	3 m	2.00	1.8
	22:15-23:05	WSL-3	10 m	1.85	<1.0
	22:15-23:05	WSL-2	10 m	0.31	<1.0
	22:15-23:05	WSL-2	3 m	0.40	<1.0
	22:15-23:05	WSL-4	10 m	0.54	<1.0
	22:15-23:05	WSL-4	3 m	0.80	<1.0
	22:15-23:05	WSL-1	3 m	0.54	<1.0
	22:15-23:05	WSL-1	10 m	0.49	<1.0

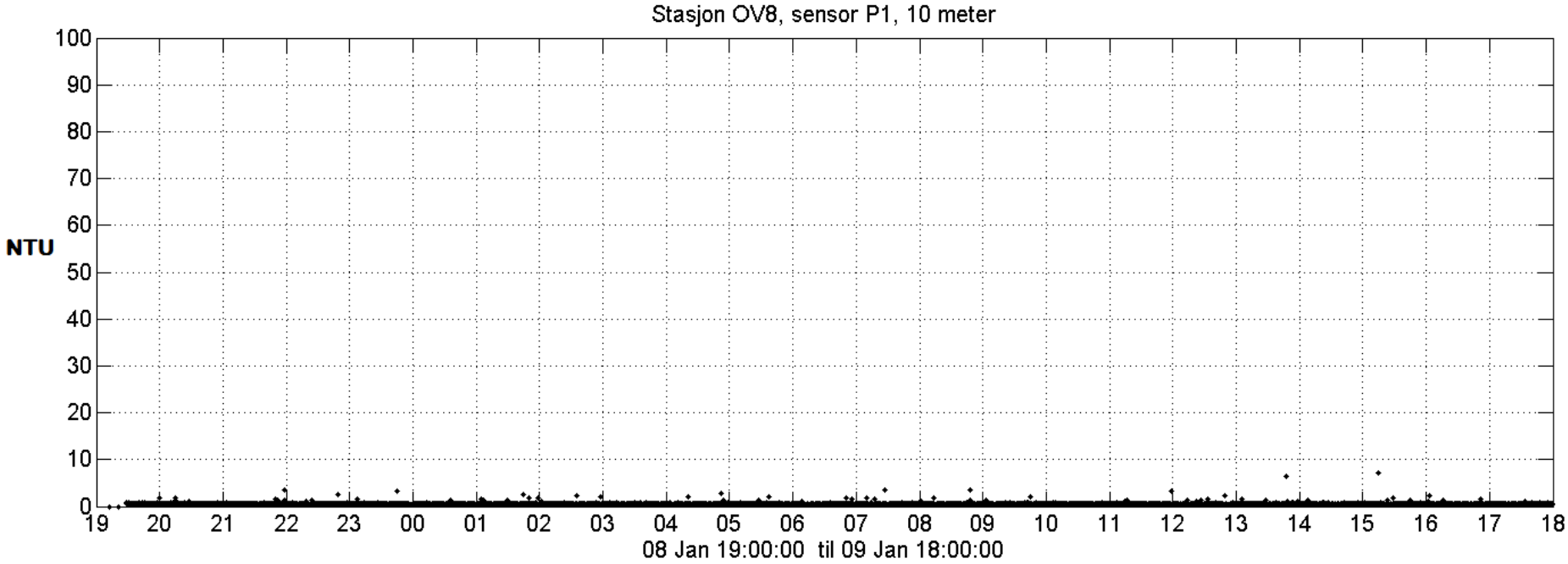
Appendix C. Turbidity data



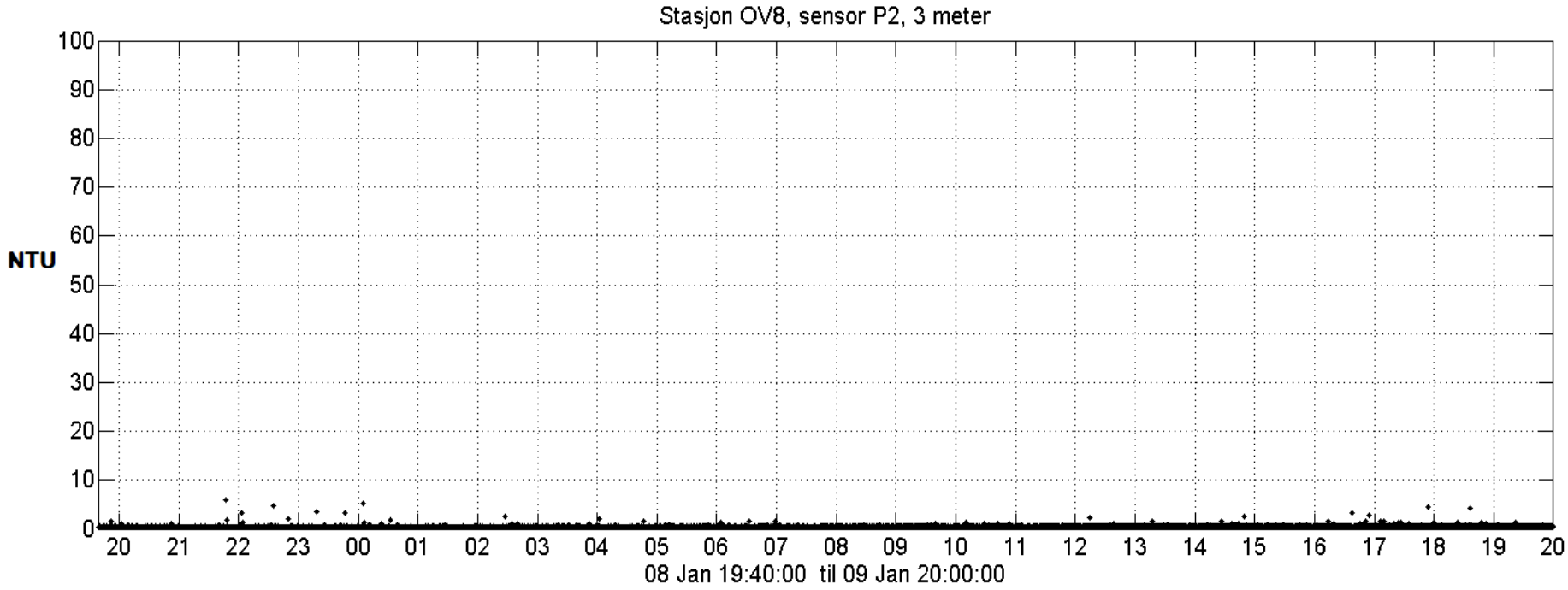
Turbidty measurements from station OV3 at 10 m above the seabed. Time is shown in UTC time.



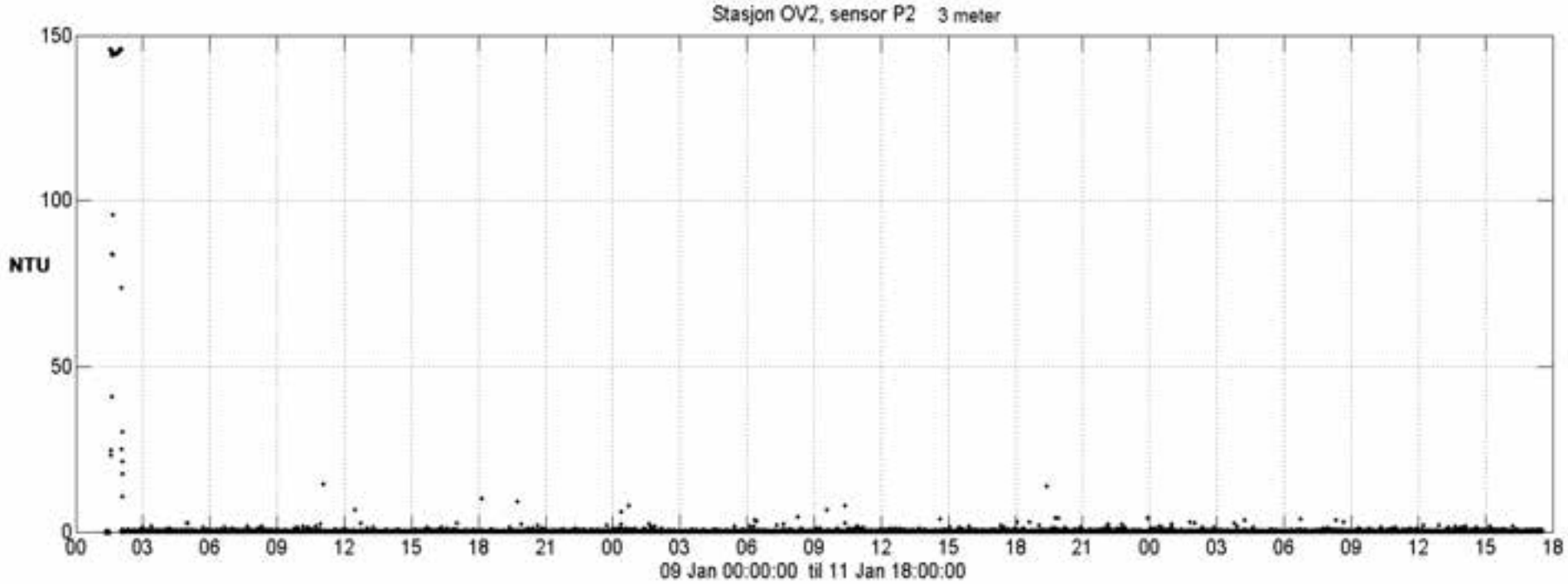
Turbidity monitored at station OV3 at 3 m above the seabed. Time is shown in UTC time.



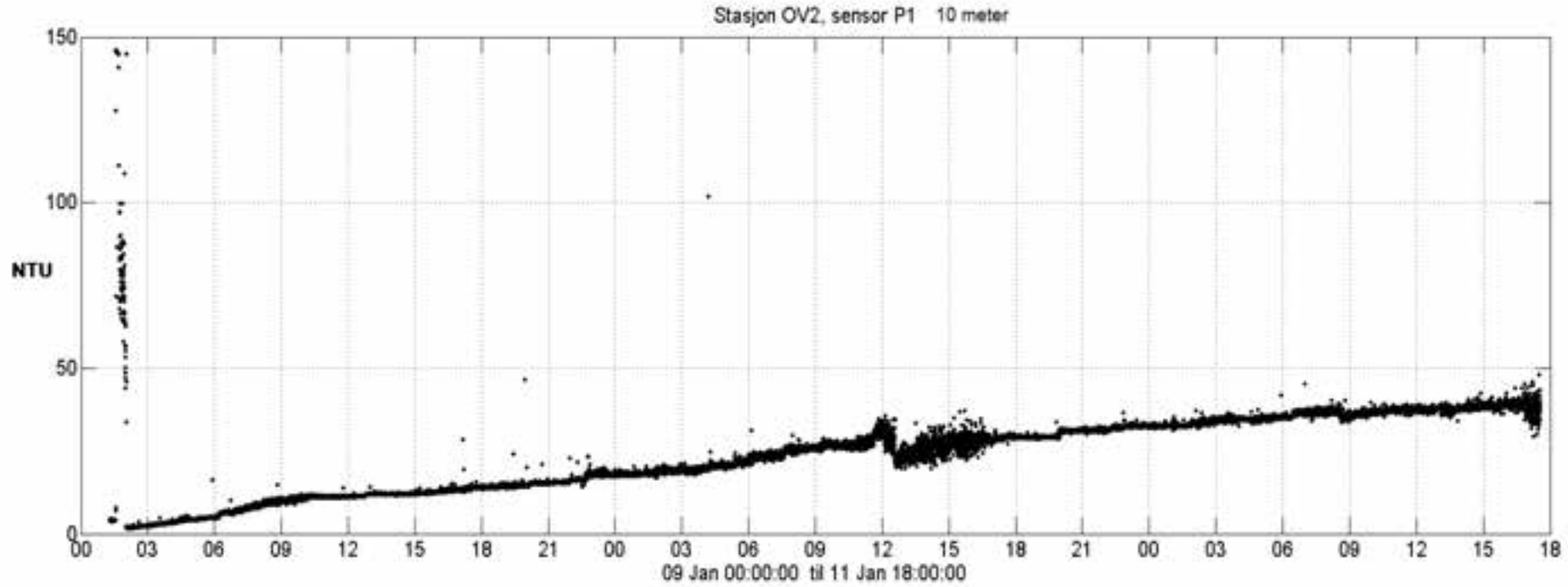
Turbidity monitored at station OV8 at 10 m above the seabed. Time is shown in UTC time.



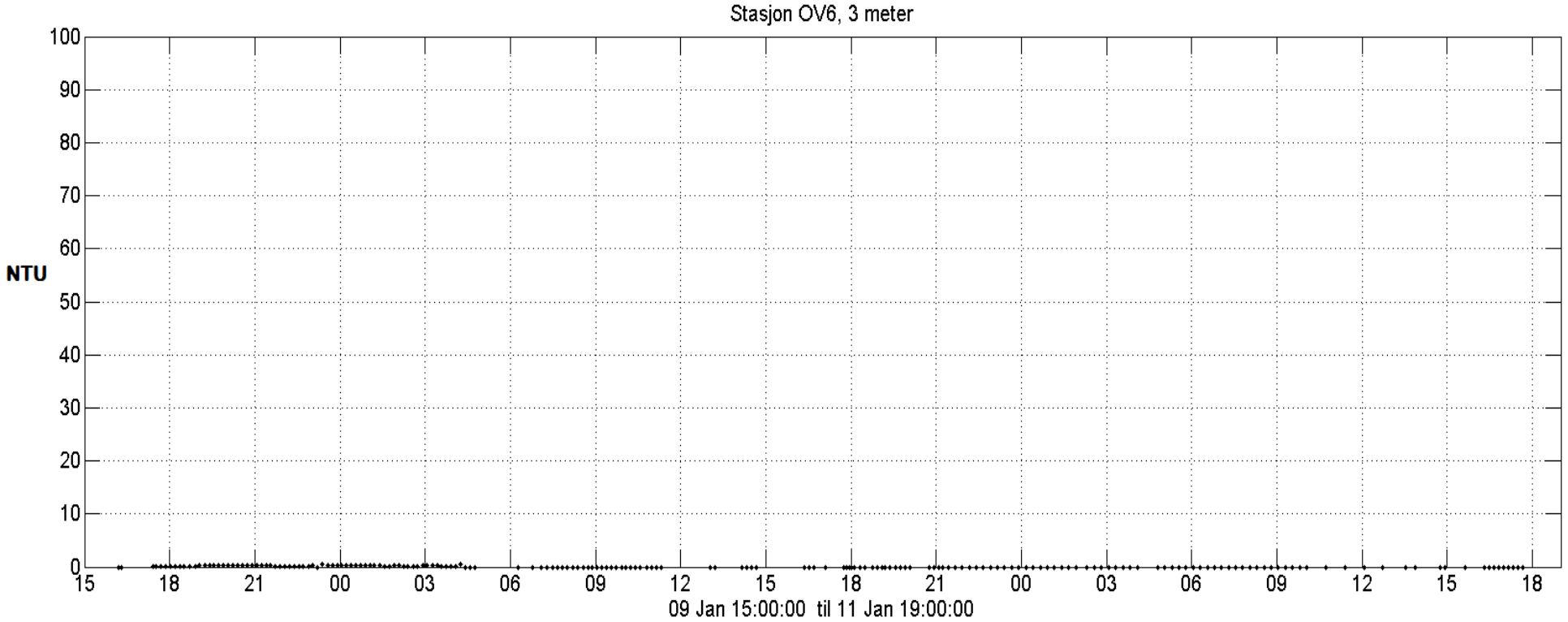
Turbidity monitored at station OV8 at 3 m above the seabed. Time is shown in UTC time.



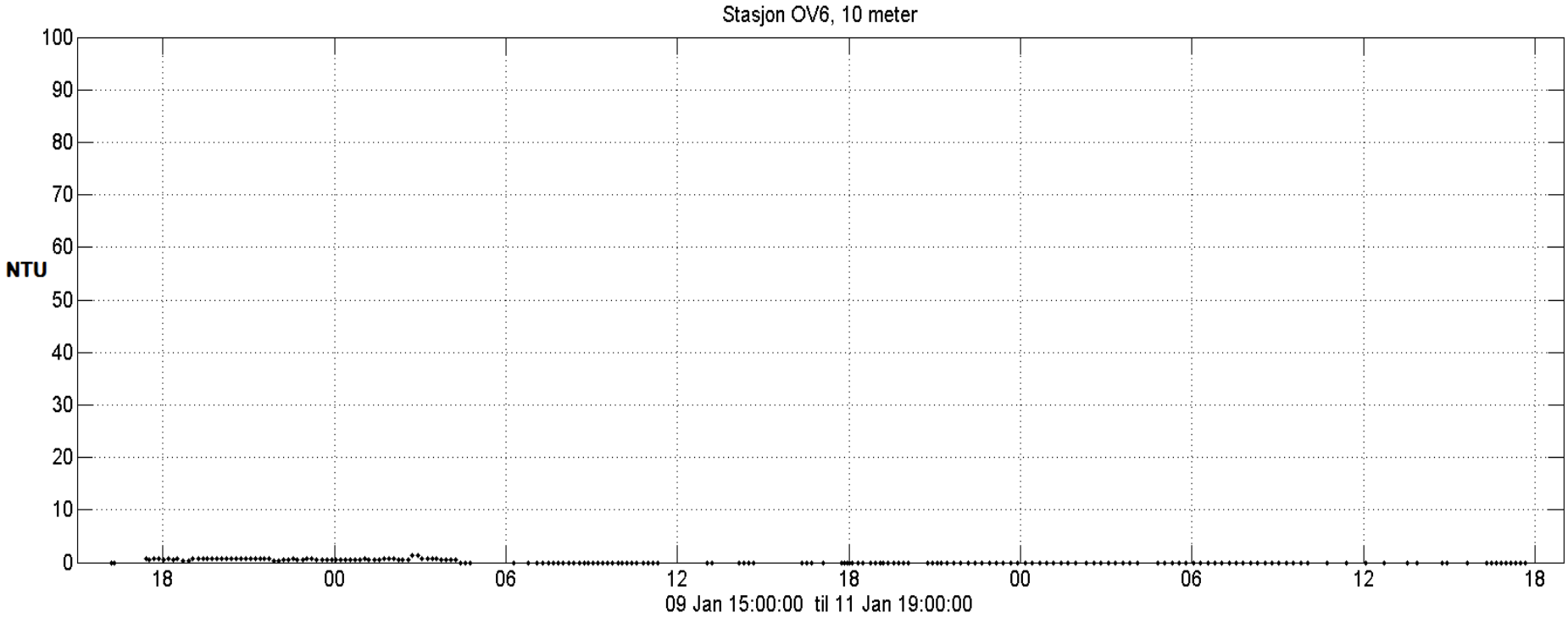
Turbidity monitored at station OV2 at 3 m above the seabed. Time is shown in UTC time.



Turbidity monitored at station OV2 at 10 m above the seabed. Time is shown in UTC time.



Turbidity monitored at station OV6 at 3 m above the seabed. Time is shown in UTC time.



Turbidity monitored at station OV6 at 10 m above the seabed. Time is shown in UTC time.

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