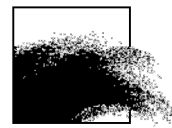




KONINKLIJK BELGISCH INSTITUUT VOOR NATUURWETENSCHAPPEN
OD NATUUR – BEHEERSEENHEID VAN HET MATEMATISCH MODEL



MONitoring en MODellering van het cohesieve sedimenttransport en evaluatie van de effecten op het mariene ecosysteem ten gevolge van bagger- en stortoperatie (MOMO)



Activiteitsrapport (1 juli 2016 - 31 december 2016)

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MOMO/7/MF/201706/NL/AR/6

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Photo voorpagina: Vervanging tripode op 20/05/2016 met de Sea Beluga

1. Inleiding

1.1. Voorwerp van deze opdracht

Het MOMO-project (MONitoring en MODellering van het cohesieve sedimenttransport en de evaluatie van de effecten op het mariene ecosysteem ten gevolge van bagger- en stortoperatie) maakt deel uit van de algemene en permanente verplichtingen van monitoring en evaluatie van de effecten van alle menselijke activiteiten op het mariene ecosysteem waaraan België gebonden is overeenkomstig het Verdrag inzake de bescherming van het mariene milieu van de noordoostelijke Atlantische Oceaan (1992, OSPAR-Verdrag). De OSPAR Commissie heeft de objectieven van haar huidige "Joint Assessment and Monitoring Programme" (JAMP) gedefinieerd tot 2010 met de publicatie van een holistisch Quality Status Report Noordzee en waarvoor de federale overheid en de gewesten technische en wetenschappelijke bijdragen moeten afleveren ten laste van hun eigen middelen.

De menselijke activiteit die hier in het bijzonder wordt beoogd, is het storten in zee van baggerspecie waarvoor OSPAR een uitzondering heeft gemaakt op de algemene regel "alle stortingen in zee zijn verboden" (zie OSPAR-Verdrag, Bijlage II over de voorkoming en uitschakeling van verontreiniging door storting of verbranding). Het algemene doel van de opdracht is het bestuderen van de cohesieve sedimenten op het Belgisch Continentaal Plat (BCP) en dit met behulp van zowel numerieke modellen als het uitvoeren van metingen. De combinatie van monitoring en modellering zal gegevens kunnen aanleveren over de transportprocessen van deze fijne fractie en is daarom fundamenteel bij het beantwoorden van vragen over de samenstelling, de oorsprong en het verblijf ervan op het BCP, de veranderingen in de karakteristieken van dit sediment ten gevolge van de bagger- en stortoperaties, de effecten van de natuurlijke variabiliteit, de impact op het mariene ecosysteem in het bijzonder door de wijziging van habitats, de schatting van de netto input van gevaarlijke stoffen op het mariene milieu en de mogelijkheden om deze laatste twee te beperken.

Een samenvatting van de resultaten uit de vergunningsperioden 2012-2016 kan gevonden worden in het "Synthesis report on the effects of dredged material dumping on the marine environment (Lauwaert et al. 2016) die gepubliceerd werden conform art. 10 van het K.B. van 12 maart 2000 ter definiëring van de procedure voor machtiging van het storten in de Noordzee van bepaalde stoffen en materialen.

1.2. Algemene doelstellingen

Het onderzoek uitgevoerd in het MOMO project kadert in de algemene doelstellingen om de baggerwerken op het BCP en in de kusthavens te verminderen en om een gedetailleerd inzicht te verwerven van de fysische processen die plaatsvinden in het mariene kader waarbinnen deze baggerwerken worden uitgevoerd. Dit impliceert enerzijds beleids-ondersteunend onderzoek naar de vermindering van de sedimentatie op de baggerplaatsen en het evalueren van alternatieve stortmethoden. Anderzijds is onderzoek naar knelpunten voor het plannen en schatten van de effecten van de baggerwerken vereist. Dit is specifiek gericht op het dynamische gedrag van silb in de waterkolom en op de bodem en zal uitgevoerd worden met behulp van modellen en in situ metingen. De specifieke acties die binnen dit onderzoek uitgevoerd worden om de algemene doelstellingen in te vullen zijn:

1. Streven naar een efficiënter stortbeleid door:

- optimalisatie van de stortlocaties. Gebaseerd op onderzoek uitgevoerd in de voorbije jaren (zie vorige synthesesrapporten) zal een terreinproef worden uitge-

voerd om de efficiëntie van een stortlocatie ten westen van Zeebrugge te bepalen;

- gebruik te maken van een operationeel stortmodel. Dit model zal geïntegreerd worden in de binnen BMM beschikbare operationele modellen. Het model zal gebruikt worden om in functie van de voorspelde fysische (wind, stroming, golven, sedimenttransport, recirculatie), economische (afstand, grootte baggerschip) en ecologische aspecten op korte termijn een keuze te kunnen maken tussen de beschikbare stortlocaties. Hiervoor zal binnen de huidige periode het slibtransportmodel gevalideerd worden op de geografische variabiliteit van de turbiditeitszones en de flocculatie van het slib.

2. Continue monitoring van het fysisch-sedimentologische milieu waarbinnen de baggerwerken worden uitgevoerd en aanpassing van de monitoring aan de nog op te stellen targets voor het bereiken van de goede milieutoestand (GES), zoals gedefinieerd zal worden binnen MSFD;

3. Uitbouw en optimalisatie van het numerieke modelinstrumentarium, ter ondersteuning en verfijning van acties 1 en 2.

1.3. Onderzoek Januari 2014 – December 2016

In het bijzonder is bij het opstellen van de hieronder vermelde taken rekening gehouden met de aanbevelingen voor de minister ter ondersteuning van de ontwikkeling van een versterkt milieubeleid zoals geformuleerd in het “Syntheserapport over de effecten op het mariene milieu van baggerspeciéstoringen (2011)” dat uitgevoerd werd conform art. 10 van het K.B. van 12 maart 2000 ter definiëring van de procedure voor machtiging van het storten in de Noordzee van bepaalde stoffen en materialen

Taak 1: In situ metingen en data analyse

Monitoring moet gericht zijn op het begrijpen van processen, zodoende dat de waargenomen variabiliteit in een correcte kader geplaatst kan worden. In vele kustzones is er een gebrek aan langdurige en hoogfrequente data over sleutelparameters die de milieutoestand beschrijven, zoals turbiditeit en SPM concentratie. De tripodemetingen in het kader van het MOMO project te MOW1 vormen een uitzondering hierop gezien hun langdurig karakter. De eerste verankeringen werden in 2004 uitgevoerd, vanaf november 2009 worden er continue metingen gedaan. Deze data laten toe om zowel de natuurlijke variabiliteit, de langdurige trends en de effecten van menselijke ingrepen op de turbiditeit te achterhalen. Een groot deel van de activiteiten is daarom gericht op zowel het uitvoeren van de metingen, het garanderen van kwalitatief hoogwaardige data en het archiveren, rapporteren en interpreteren ervan.

Taak 1.1 Langdurige metingen

Sinds eind 2009 worden er continue metingen uitgevoerd te MOW1 met behulp van een meetframe (tripode). Met dit frame worden stromingen, slibconcentratie, korrelgrootteverdeling van het suspensiemateriaal, saliniteit, temperatuur, waterdiepte en zeebodem altimetrie gemeten. Om een continue tijdreeks te hebben, wordt gebruik gemaakt van 2 tripodes. Na ongeveer 1 maand wordt de verankerde tripode voor onderhoud aan wal gebracht en wordt de tweede op de meetlocatie verankerd.

In 2013 werd gestart met langdurige metingen met behulp van een OBS-5 sensor vastgemaakt aan de AW boei; deze metingen zullen verdergezet worden. De data geven informatie over de SPM concentratie aan het oppervlak en zijn aldus complementair aan de bodem nabije metingen met de tripode. De data zijn ook van belang voor het calibreren en valideren van de oppervlakte SPM concentraties uit satellietbeelden.

Taak 1.2 Calibratie van sensoren tijdens in situ metingen

Tijdens 4 meetcampagnes per jaar met de R/V Belgica zullen een voldoende aantal 13-uursmetingen uitgevoerd worden met als hoofdoel het calibreren van optische of akoestische sensoren en het verzamelen van verticale profielen. De metingen zullen plaatsvinden in het kustgebied van het BCP. De optische metingen (transmissometer, Optical Backscatter Sensor) zullen gecalibreerd worden met de opgemeten hoeveelheid materie in suspensie (gravimetrische bepalingen na filtratie) om te komen tot massa concentraties. Naast de totale hoeveelheid aan suspensiemateriaal (SPM) wordt ook de concentratie aan POC/PON, chlorophyl (Chl-a, Chl-b) en phaeofytine (a, b) bepaald. Stalen van suspensiemateriaal zullen genomen worden met de centrifuge om de samenstelling ervan te bepalen.

Taak 1.3: Data archivering en rapportage

De meetdata worden gearchiveerd en er wordt een kwaliteitsanalyse uitgevoerd, zodat de goede data onderscheiden kunnen worden van slechte of niet betrouwbare data. Slechte data kunnen bv optreden doordat het instrument slecht heeft gewerkt en verkeerd werd ingesteld. Niet betrouwbare data zijn typisch geassocieerd met bv biofouling. De data en metadata worden gearchiveerd.

Taak 1.4: Verwerking en interpretatie van metingen

De metingen vergaard tijdens de 13-uursmetingen aan boord van de Belgica en met de tripod worden verwerkt en geïnterpreteerd. Hiervoor werden in het verleden reeds heel wat procedures (software) toegepast of ontwikkeld, zoals de berekening van de bodemschuifspanning uit turbulentiemetingen, entropieanalyse op partikelgrootteverdelingen, de opsplitsing van multimodale partikelgrootteverdeling in een som van lognormale verdelingen, het groeperen van de data volgens getij, meteorologie, klimatologie en seizoenen. Deze methodes (zullen opgenomen worden) zijn opgenomen in de standaardverwerking van de data. De aldus verwerkte data dienen als basis voor het verder gebruik binnen- in wetenschappelijke vragen (zie taak 2.2, 2.3 en 4.2, 4.4).

Taak 2: Onderzoek en monitoring alternatieve stortstrategie onderhoudsbaggerwerk voorhaven Zeebrugge

De BMM is auteur van de voorbereidende studies voor de terreinproef en zal de terreinproef mee opvolgen. BMM-OD Natuur zal verantwoordelijk zijn voor het uitvoeren van de langdurige frame metingen (lopen tot eind april 2014) en de statistische verwerking van de resultaten (Taak 2.1). De resultaten van de metingen zullen gebruikt worden bij de analyse van de efficiëntie van de baggerproef (Taak 2.3). Door de BMM-OD Natuur zullen ook met behulp van het Automatic Underway Monitoring System (AUMS) op het onderzoeksschip Belgica opnames gemaakt worden van de sedimentconcentratie binnen de haven (Taak 2.2). Deze gegevens zullen ter beschikking gesteld worden voor verdere verwerking. BMM-OD Natuur zal deel uitmaken van de stuurgroep.

Taak 2.1: Uitvoeren van lange termijn metingen in de omgeving van de haven van Zeebrugge voor het opvolgen van de terreinproef, en het bestuderen van de interne sedimentdynamiek in de haven

Voor dit deel van de opdracht is de BMM-OD Natuur verantwoordelijk voor het uitvoeren van de metingen en het aanleveren van de gevalideerde data voor verdere verwerking in de factual data rapportering en omzetting naar het standaardformaat. Het betreft twee meetframes, een ter hoogte van de meetpaal MOW 1 (als achtergrondwaarde, zie Taak 1.1) en een ander ter hoogte van de ingang van de haven van Zeebrugge (WZ-boei). Deze meetframes dienen afdoend de saliniteit, stromingen, sedimentconcentratie en korrel-

grootteverdeling te meten.

Taak 2.2: Beschrijving van de omgevingscondities

Gedurende de meetperiode van de langdurige metingen dienen ook de verschillende externe factoren die een invloed kunnen hebben op de interne slibdynamiek in de haven nauwkeurig bijgehouden worden en dit gedurende dezelfde periode als de metingen in taak 2.1. De BMM-OD Natuur is verantwoordelijk voor het opleveren van informatie over de sedimentconcentraties uit het AUMS aan boord van de Belgica.

Taak 2.3: Analyse efficiëntie baggerproef

Na afloop van de baggerproef dient de efficiëntie van de uitgevoerde proef geschat te worden. Hiervoor dient als eerste een T0 toestand gedefinieerd te worden, waarbij op basis van de binnen Taak 2.1 en Taak 2.2 verzamelde data een inschatting kan gemaakt worden van de mogelijke events die tijdens de proef hebben plaatsgevonden, en hun invloed op de resultaten van de baggerproef. De BMM-OD Natuur zal een statistische benadering van de efficiëntie van de baggerproef uitvoeren, waarbij nagegaan wordt in hoeverre de tijdens de baggerproef gemeten waardes op de twee frames afwijken van de waardes die gemeten werden buiten de stortproef. Deze analyse werd reeds toegepast bij de evalueren van de baggerproef in het Albert II dok.

Taak 3: Uitbouw en optimalisatie van het modelinstrumentarium

Taak 3.1: Validatie van het slibtransportmodel

Het tijdens de voorbije jaren verbeterde en aangepaste slibtransportmodel zal worden gevalideerd met behulp van de langdurige meetreeksen en de satellietbeelden. Hierbij zal dezelfde methode als in Baeye et al. (2011) en zoals in taak 1.4 worden gebruikt om de modelresultaten te groeperen en te klasseren volgens windrichting, weertype en getij. Het voordeel van deze werkwijze is dat niet zozeer gekeken wordt of de correlatie tussen meting en modelresultaat in één of meerder punt goed is, maar dat globaal nagegaan wordt of het model de SPM dynamica op het BCP goed kan reproduceren. Deze taak zal in nauwe samenwerking met het WLH gebeuren die eenzelfde benadering zullen toe passen op hun model (contacten zijn gelegd met B De Maerschak).

Taak 3.2: Operationeel stortmodel

Dit model zal geïntegreerd worden in de binnen BMM-OD Natuur beschikbare operationele modellen. Het model zal gebruikt worden om in functie van de voorspelde fysische (wind, stroming, golven, sedimenttransport, recirculatie), economische (afstand, grootte baggerschip) en ecologische aspecten op korte termijn een keuze te kunnen maken tussen de beschikbare stortlocaties. Hiervoor zal binnen de huidige periode het slibtransportmodel gevalideerd worden op de geografische variabiliteit van de turbiditeitszones en de flocculatie van het slib.

Taak 4: Oplossingen voor knelpunten

Taak 4.1: Kwaliteitscontrole van de data en de integratie ervan in de monitoring voor de KRMS

Taak 4.1.1: KRMS monitoring

De data verzameld in Taak 1, zullen worden opgenomen in de nog op te zetten monitoringsverplichtingen van de Belgische Staat (07/2014) in het kader van de Kaderrichtlijn Mariene Strategie (MFSD). De KRMS monitoring zal in 2015 starten en zal dienen om de toestand van het mariene milieu te evalueren aan de goede milieutoestand (GES), zoals opgetseld door de Belgische Staat in 2012 (Belgische Staat 2012a, 2012b).

Er zal verder geëvalueerd worden of het MOMO meetprogramma aan de monitorings-

verplichtingen die voor de KRMS (MFSD) moeten worden opgesteld zal voldoen en/of er aanpassingen nodig zijn. De wetenschappelijke vragen die hier bekeken worden hebben vooral betrekking op de geografische spreiding van de data. Is het voldoende om – zoals nu gebeurt – te berusten op satellietbeelden voor de geografische en in situ meetreeksen voor de temporele spreiding of dienen we te opteren voor één vast meetpunt (MOW1) en bijkomend een aantal andere punten (Nieuwpoort, Kwintebank, Gootebank) waar random in de tijd gemeten wordt met een tripode gedurende telkens een periode van ongeveer 1 maand. Hiervoor zou bv de tripode die nu ingezet wordt voor de terreinproef gebruikt kunnen worden.

Taak 4.1.2: Kwaliteitscontrole

Een belangrijk aandachtspunt bij deze langdurige datareeksen is het garanderen van een gelijke kwaliteit in de tijd van de verzamelde data. De vraag die zich bij onze SPM concentratiemetingen stelt is niet zozeer het opmeten van hogere of lagere waarden, mogelijks veroorzaakt door het toepassen van een andere stortstrategie, maar het garanderen dat deze waarden inderdaad veroorzaakt worden door menselijke activiteiten (bv storten) en niet het effect zijn van natuurlijke fluctuaties. De natuurlijke variabiliteit van SPM concentratie is groot en wordt veroorzaakt door de getijwerking, doodtij-springtijcyclus en meteorologische en klimatologische fenomenen. De tijdschalen gaan van seconden tot seizoenen, met mogelijks langere fluctuaties voor (nodale cyclus, klimaatsverandering, zeespiegelstijging,...). Langdurige variaties kunnen bv geïdentificeerd worden als een trend of een cosinusfunctie met lage frequentie. Om kwaliteitsvolle data te kunnen leveren over een lange periode, die gebruikt kunnen worden om langdurige trends te identificeren, is het nodig om een rigoureuze kwaliteitscontrole uit te voeren. OBS alsook akoestische sensoren zijn gevoelig aan de samenstelling en korrelgrootte van het gesuspendeerde materiaal. Dit kan variëren in functie van de boven vermelde frequenties, maar hieromtrent is er nog geen afdoende duidelijkheid wat de metingen te MOW1 betreft.

- Hoe veranderen de calibratieconstanten i.f.v. externe parameters (doodtij-springtij, zomer-winter)? Hoe dikwijls moeten de sensoren in situ gecalibreerd worden om de rekening te kunnen houden met de mogelijke fluctuaties in samenstelling van het suspensiemateriaal?
- Wat is de fout op de metingen? Het uitvoeren van directe (waterstaal) en indirecte metingen (OBS, akoestische backscatter) van SPM concentratie gaat inherent gepaard met onzekerheden (meetfouten). In situ metingen zijn steeds onderhevig aan onzekerheden tengevolge van random meetfouten (gebrek aan precisie), systematische fouten (onnauwkeurigheid), menselijke fouten, en de statistische variabiliteit van de parameter. De fouten hebben hun oorsprong in de onnauwkeurigheid en het gebrek aan precisie van het meetinstrument of de procedures (bv. waterstaalname en filtratie). Doel is om de fout op de verschillende onderdelen van de metingen (filtratie, calibratie, langdurige trends...) te schatten.

Taak 4.1.3: Aanvulling van ontbrekende data met behulp van statistische methodes

Het gebeurt regelmatig in de metingen te MOW1 dat de OBS sensoren verzadigen (vooral deze op 0.2 m) of uitvallen en er aldus gedurende een korte of langere perioden geen (betrouwbare) data beschikbaar zijn. In de statistiek bestaan technieken de ontbrekende data te reconstrueren. Er zal nagegaan worden wat de meests geschikte methode is om de tijdseries te vervolledigen.

Taak 4.2: Biologische effecten en de seizoensale variaties in SPM concentratie

De correlatie tussen biomassa (zoals o.a. POC en chlorophyl) en vloggrootte en vorm wordt dikwijls aangehaald in de literatuur, maar dit bleek sterk plaatsgebonden te zijn en dikwijls gebaseerd op korte meetperioden. De lange tijdsreeks te MOW1 werd geanaly-

seerd in combinatie met satelliet data, de omgekeerde correlatie tussen de chlorophyll en de SPM concentratie is opvallend. Er werd de hypothese opgesteld, dat door de algenbloei in de lente de concentratie aan kleverige organische moleculen (TEPs) wordt verhoogd, waardoor meer macrovlokken gevormd worden, het SPM sneller bezinkt en moeilijker kan eroderen en aldus de SPM concentratie gaat afnemen. Erder onderzoek richt zich naar:

- 1) Analyse van TEP concentraties. Tot nu toe worden geen TEP analyses uitgevoerd, nochtans is dit noodzakelijk om deze hypothese te toetsen. Er zal nagegaan worden hoe de TEPs geanalyseerd kunnen worden in waterstalen, wat en hoe dit meetprogramma uitgevoerd kan worden. Er wordt geopteerd om tegen 2015 met de eerste metingen te kunnen beginnen.
- 2) De invloed van lichthoeveelheid op de start van de algenbloei in de lente en de afname van de SPM concentratie;
- 3) Wat gebeurt er met het SPM dat uit de waterkolom verdwijnt door snellere sedimentatie in de zomer? Heeft dit een effect op de frequentie van hooggeconcentreerde sliksuspensies en mogelijks aanslibbing van vaargeulen en havens?
- 4) Verdere ontwikkeling van het flocculatiemodel zodat seizoenale effecten in rekening gebracht kunnen worden. Simulatie in 2D/3D met dit flocculatiemodel teneinde het model te valideren.

Taak 4.3: Alternatieve Stortstrategie Nieuwpoort

Er zal ondersteuning gegeven worden aan MDK in verband met het opzetten van een wetenschappelijke terreinproef om de impact van het verpompen van baggerspecie uit de haven van Nieuwpoort op een stortzone te evalueren. Details hiervan zullen op een vergadering van de technische werkgroep besproken worden.

Taak 4.4: Golfsystemen en hun impact op de zeebodem en de SPM concentratie

Er bestaan verschillende soorten golven en golfsystemen (korte golven, deining) die een impact hebben op de zeebodem. Tot nu toe werd dit aspect nog niet in rekening gebracht in de analyse van de data. Wat is de impact van deining of korte golven op de resuspensie van sedimenten? Wat zijn de belangrijkste parameters en wat is hun belang voor waterbouwkundige werken (baggeren)?

1.4. Gerapporteerde en uitgevoerde taken

Periode Januari 2014 – Juni 2014

- Taak 1.1: De meetreeks te MOW1 werd verdergezet.
- Taak 1.2: Calibratie van sensoren werd uitgevoerd tijdens RV Begica campagnes 2014/01 en 2014/11
- Taak 1.4: Verwerking en interpretatie van OBS meetdata (gerapporteerd in activiteitsrapport MOMO/7/MF/201408/NL/AR/1)
- Taak 2.1: De metingen aan de WZ boei werden beëindigd eind maart 2014.

Periode Juli 2014 – December 2014

- Taak 1.1: De meetreeks te MOW1 werd verdergezet.
- Taak 1.2: Calibratie van sensoren werd uitgevoerd tijdens RV Begica campagnes 2014/22, 2014/28 en 2014/31
- Taak 1.4: Verwerking en interpretatie van LISST meetdata (gerapporteerd in activiteitsrapport MOMO/7/MF/201501/NL/AR/2).
- Taak 2.2: ADCP data gemeten aan boord van de Belgica en de satellietbeelden tijdens de stortproef werden verwerkt en de data opgeleverd.
- Taak 4.2: Wat gebeurt er met het SPM dat uit de waterkolom verdwijnt door snellere sedimentatie in de zomer? (gerapporteerd in activiteitsrapport MOMO/7/MF/201501/NL/AR/2, voorgesteld op PiE 2014, PECS 2014, VLIZ Young Scientist day 2015 en gepubliceerd in JGR in augustus 2015).

Periode Januari 2015 – Juni 2015

- Taak 1.1: De meetreeks te MOW1 werd verdergezet.
- Taak 1.2: Calibratie van sensoren werd uitgevoerd tijdens RV Begica campagnes 2015/01 en 2015/10.
- Taak 2 Terreinproef, analyse efficiëntie baggerproef (zie activiteitsrapport MOMO/7/MF/201508/NL/AR/3).

Periode Juli 2015 – December 2015

- Taak 1.1: De meetreeks te MOW1 werd verdergezet.
- Taak 1.2: Calibratie van sensoren werd uitgevoerd tijdens RV Begica campagnes 2015/32.
- Taak 2 Resultaten over de terreinproef werd voorgesteld op INTERCOH 2015.
- Taak 4.1.2 Eerste resultaten van de kwaliteitscontrole van de meetdata werd voorgesteld op INTERCOH 2015.
- Taak 4.4 Golfsystemen en hun impact op de zeebodem en de SPM concentratie (gerapporteerd in activiteitsrapport MOMO/7/MF/201603/NL/AR/4, voorgesteld INTERCOH 2015).

Periode Januari 2016 – Juni 2016

- Taak 1.1 De meetreeks te MOW1 werd verdergezet. AW boei data gerapporteerd in activiteitsrapport MOMO/7/MF/201608/NL/AR/5
- Taak 1.2 Calibratie van sensoren werd uitgevoerd tijdens RV Begica campagnes 2016/03 en 2016/11.
- Taak 4.1.2 Kwaliteitscontrole van de meetdata: Op 24-25 februari 2016 werd te Brussel een internationale workshop over 'Best practice in generating long-term and large-scale data sets of suspended particulate matter concentration' met experts uit Duitsland, Nederland, Frankrijk en België georganiseerd met als doel de kwaliteitscontrole van SPM oconcentratiemetingen te bespreken. Er werden concrete afspraken gemaakt betreffende het rapporteren van bestaande procedures en het ontwikkelen van 'best practices'.
- Taak 4.1.3 Aanvulling van ontbrekende data met behulp van statistische methodes (gerapporteerd in activiteitsrapport MOMO/7/MF/201608/NL/AR/5).

Periode Juli 2016 – December 2016 en overzicht 2014-2016

Taak 1 In situ metingen en data analyse

- Taak 1.1 De meetreeks te MOW1 werd verdergezet.
- Taak 1.2 Er werden geen calibraties van sensoren uitgevoerd tijdens het laatste semester wegens het niet beschikbaar zijn van de Belgica (april t.e.m. december 2016).
- Taak 1.3 Data archivering en rapportage: de data voor 2013, 2014 en 2015 werden gerapporteerd in de datarapporten BMM-MDO/2016-03/MOMO/2015, BMM-MDO/2016-03/MOMO/2014, BMM-MDO/2014-10/MOMO/2013.
- Taak 1.4 Verwerking en interpretatie van metingen, zie activiteitsrapporten MOMO/7/MF/201408/NL/AR/1, MOMO/7/MF/201501/NL/AR/2, MOMO/7/MF/201706/NL/AR/6

Taak 2 Onderzoek en monitoring alternatieve stortstrategie

Uitgevoerd, zie activiteitsrapport MOMO/7/MF/201508/NL/AR/3. Een samenvatting van de terreinproef werd gepubliceerd in Ocean Dynamics, zie appendix 7 van dit rapport.

Taak 3 Uitbouw en optimalisatie van het modelinstrumentarium

- Een nieuwe modellenreeks (van het Noordwest Europees Continentaal Plat tot de Belgische kustzone) werd opgesteld met behulp van Coherens V2. Voor de Belgische kustzone (BeC model) werd een nieuwe bathymetrie geïmplementeerd met een resolutie van 250m en inclusief wetting/drying. Het bimodale flocculatiemodel van BJ Lee werd in Coherens V2 geïmplementeerd.
- Taak 3.1 Validatie van het slibtransportmodel. Deze taak zal uitgevoerd worden tijdens de volgende vergunningsperiode.

- Taak 3.2 Operationeel stortmodel. Deze taak wordt overgedragen naar de volgende vergunningsperiode.
- Taak 4 Oplossingen voor knelpunten**
- Taak 4.1 Kwaliteitscontrole van de data en de integratie ervan in de monitoring voor de KRMS
- Taak 4.1.1 Integratie monitoring in KRMS werd uitgevoerd, zie hoofdstuk 7 van het “Syntheserapport vergunningsperiode 2012-2016” alsook appendix 6 van dit rapport.
- Taak 4.1.2 Kwaliteitscontrole. Een procedure voor de kwaliteitscontrole van de meetdata (tripode) is in ontwikkeling. Eerste resultaten werden voorgesteld op conferenties, zie appendix 3-5 van dit rapport. De taak wordt verdergezet tijdens de volgende vergunningsperiode.
- Taak 4.2 Biologische effecten en de seizoenale variatie van het SPM. Deze taak werd voor een deel uitgevoerd (zie rapport MOMO/7/MF/201603/NL/AR/4). Wegens problemen bij de analyse van de stalen en het nog niet beëindigen van de modellering van de seizoenale effecten wordt deze taak deels opgenomen in de taken voor de volgende vergunningsperiode.
- Taak 4.3 Alternatieve stortstrategie Nieuwpoort
Niet uitgevoerd. Deze taak wordt verschoven naar de taken voor de volgende vergunningsperiode.
- Taak 4.4 Golfsystemen en hun impact op de zeebodem en de SPM concentratie: werd uitgevoerd (zie rapport MOMO/7/MF/201603/NL/AR/4).

1.5. Publicaties (januari 2014 – december 2016)

Hieronder wordt een overzicht gegeven van publicaties met directe betrokkenheid van het KBIN waar resultaten en data uit het MOMO project in werden gebruikt.

Activiteits-, Meet- en Syntheserapporten

- Fettweis M, Baeye M, Francken F, Van den Eynde D. 2017. MOMO activiteitsrapport (1 juli – 31 december 2016). BMM-rapport MOMO/7/MF/201706/NL/AR/6, 23pp + app.
- Lauwaert B, Fettweis M, De Witte B, Devriese L, Van Hoei G, Timmermans S, Martens C. 2016. Synthesis report on the effects of dredged material disposal on the marine environment (licensing period 2012-2016). RBINS-ILVO-AMT-AMCS-FHR report BL/2016/09, 107pp.
- Fettweis M, Baeye M, Francken F, Van den Eynde D. 2016. MOMO activiteitsrapport (1 januari – 30 juni 2016). BMM-rapport MOMO/7/MF/201607/NL/AR/5, 30pp + app.
- Backers J, Hindryckx K, Vanhaverbeke W. 2016. Rapport van de RV Belgica Meetcampagnes en Verankering van Meetsystemen MOMO – 2015. BMM-rapport BMM-MDO/2016-03/MOMO/2015, 89pp.
- Backers J, Hindryckx K, Vanhaverbeke W. 2016. Rapport van de RV Belgica Meetcampagnes en Verankering van Meetsystemen MOMO – 2014. BMM-rapport BMM-MDO/2016-03/MOMO/2014, 165pp.
- Fettweis M, Baeye M, Francken F, Van den Eynde D, Thant S. 2016. MOMO activiteitsrapport (1 juli – 31 december 2015). BMM-rapport MOMO/7/MF/201603/NL/AR/4, 25pp + app.
- Fettweis M, Baeye M, Francken F, Vn den Eynde D. 2015. MOMO activiteitsrapport (1 januari – 30 juni 2015). BMM-rapport MOMO/7/MF/201508/NL/AR/3, 76pp + app.
- Van den Eynde D, Fettweis M. 2015. Modellering van een alternatieve stortstrategie voor de onderhoudsbaggerwerken in de voorhaven van Zeebrugge. Technisch rapport MOMO/7/DVDE/201506/NL/TR01, 17pp.
- Fettweis M, Baeye M, Francken F. 2015. MOMO activiteitsrapport (1 juli – 31 december 2014). BMM-rapport MOMO/7/MF/201501/NL/AR/2, 41pp + app.
- Backers J, Francken F, Hindryckx K, Vanhaverbeke W. 2014. Rapport van de RV Belgica Meetcampagnes en Verankering van Meetsystemen MOMO – 2013. BMM-rapport BMM-MDO/2014-10/MOMO/2013, 213pp.

- Fettweis M, Baeye M, Francken F, Van den Eynde D. 2014. MOMO activiteitsrapport (1 januari - 30 juni 2014). BMM-rapport MOMO/7/MF/201408/NL/AR/1, 43pp + app.
- Lauwaert B, Fettweis M, De Witte B, Devriese L, Van Hoei G, Timmermans S, Martens C. 2014. Vooruitgangsrapport (juni 2014) over de effecten op het mariene milieu van baggerspeciëstoringen (vergunningsperiode 01/01/2012 – 31/12/2016). Rapport uitgevoerd door KBIN-BMM, ILVO, CD, aMT. BL/2014/01, 20pp + app.

Conferenties/Workshops

- Van Hoey G, Devriese L, Dewitte B, Fettweis M, Lauwaert B, Parmentier K, Vanlede J, Hostens K, Martens C. 2016. Environmental impact assessment in line with the EU Nature Directives. North Sea Conference, 7-10 November, Ostend (Belgium).
- Fettweis M, Baeye M. 2016. SPM concentration measurements in low and high turbulent conditions. Particles in Europe, 3-5 October, Budapest (Hungary).
- Riethmüller R, Fettweis M, Verney R. 2016. Best-practice for long-term observations of total suspended particulate matter in coastal marine environments. ICES Annual Science Conference, 19-23 September, Riga (Latvia).
- Baeye M, Francken F, Fettweis M. 2016. Remote sensing of suspended particulate matter concentration, inter-comparison with surface buoy and tripod lander data. ECSA 56. 4-7 September, Bremen (Germany)
- Fettweis M., Baeye M. 2016. SPM concentration measurements in low and high turbulent conditions. ECSA56. 4-7 September, Bremen (Germany).
- Riethmüller R, Fettweis M, Verney R. 2016. On best-practice for long-term observations of total suspended particulate matter. ECSA 56, 4-7 September, Bremen (Germany).
- Fettweis M. 2016. Long-term observations of suspended particulate matter concentration. NewSTHEPS Follow-up Committee Meeting, 12 April, Brussels (Belgium).
- Backers J. 2016. Instrument related problems with optical backscatter sensors. Workshop Best practice in generating long-term and large-scale data sets of suspended particulate matter concentration, 24-25 February, Brussels (Belgium).
- Fettweis M. 2016. Long term measurements of SPM concentration in the Belgian near-shore: How to estimate the uncertainty? Workshop Best practice in generating long-term and large-scale data sets of suspended particulate matter concentration, 24-25 February, Brussels (Belgium).
- Fettweis M, Baeye M, Cardoso C, Dujardin A, Van den Eynde D, Van Hoestenbergh T, Vanlede J, Van Poucke L, Velez C, Martens C. 2016. The impact of disposal of fine grained sediments from maintenance dredging works on SPM concentration and fluid mud in and outside the harbor of Zeebrugge. VLIZ Marine Scientists' Day, 12 February, Brugge (Belgium).
- Dujardin A, Vanlede J, Van Hoestenbergh T, Van Poucke L, Fettweis M, Cardoso C, Velez C, Martens M. 2015. Factors influencing top sediment layer and SPM concentration in the Zeebrugge harbor. INTERCOH, 7-11 September, Leuven (Belgium).
- Fettweis M, Baeye M, Verney R. 2015. Uncertainty of in situ SPM concentration measurements. INTERCOH, 7-11 September, Leuven (Belgium).
- Fettweis M, Baeye M, Francken F, Van den Eynde D, Van Hoestenbergh T, Van Poucke L, Dujardin A, Martens C. 2015. In situ measurements of SPM concentration to evaluate the impact of the disposal of fine grained sediments from maintenance dredging. INTERCOH, 7-11 September, Leuven (Belgium).
- Lee BJ, Bi Q, Toorman EA, Fettweis M, Weilbeer H. 2015. Two-Class Flocculation kinetic model: Development and application to large-scale, multi-dimensional cohesive sediment transport. INTERCOH, 7-11 September, Leuven (Belgium).
- Thant S, Fettweis M, Baeye M, Monbaliu J. 2015. Wave systems and their impact on the seabed and water column turbidity in the Belgian coastal zone. INTERCOH, 7-11 September, Leuven (Belgium).
- Van den Eynde D, Baeye M, Fettweis M, Francken F, Van Lancker V. 2015. Validation of modelled bottom shear stress under the influence of currents and waves using long-term measurements. INTERCOH, 7-11 September, Leuven (Belgium).
- Fettweis M, Baeye M. 2015. Seasonality in concentration, size and settling velocity of muddy marine snow in the southern North Sea and their effects on the the sea bed.

- VLIZ Young Marine Scientists' Day, 20 February, Brugge (Belgium).
- Fettweis M, Baeye M. 2015. SPM dynamics at the marine limit of influence of the Westerschelde estuary. Ems-Scheldt workshop, 12-13 February, Delmenhorst (Germany).
- Fettweis M, Baeye M, Francken F. 2014. Seasonality of the near bed SPM dynamics in the southern North Sea. PECS, 20-24 October, Porto de Galinhas (Brazil).
- Fettweis M, Baeye M. 2014. Variability in concentration, size and settling velocity of muddy marine flocs from the southern North Sea. Particles in Europe, 7-9 October, Esbjerg (Denmark).
- Fettweis M, Lee B, Toorman E. 2014. Multimodal particle size distribution of fine-grained cohesive sediments: Observation and simulation. Reactive Transport Workshop, 20 May, Louvain-la-Neuve (Belgium).
- Baeye M, Francken F, Fettweis M, Van den Eynde D. 2014. The first buoy for continuous measuring of surface Suspended Particulate Matter concentration on the Belgian inner shelf. VLIZ Young Marine Scientists' Day, 7 March, Brugge (Belgium) (poster).
- Fettweis M, Baeye M, Van der Zande, Van den Eynde D, Lee BJ. 2014. Seasonality of near-shore marine snow in the southern North Sea. VLIZ Young Marine Scientists' Day, 7 March, Brugge (Belgium).
- Thant S, Baeye M, Fettweis M, Monbaliu J, Van Rooij D. 2014. Extreme values of Suspended Particulate Matter concentration and their relation to wave systems along the Belgian inner shelf. VLIZ Young Marine Scientists' Day, 7 March, Brugge (Belgium).

Papers en hoofdstukken in boeken

- Fettweis M, Baeye M, Cardoso C, Dujardin A, Lauwaerts B, Van den Eynde D, Van Hoesenberghe T, Vanlede J, Van Poucke L, Velez C, Martens C. 2016. The impact of disposal of fine grained sediments from maintenance dredging works on SPM concentration and fluid mud in and outside the harbor of Zeebrugge. *Ocean Dynamics*, 66, 1497–1516. doi:10.1007/s10236-016-0996-1
- Fettweis M, Baeye M. 2015. Seasonal variation in concentration, size and settling velocity of muddy marine flocs in the benthic boundary layer. *Journal of Geophysical Research Oceans*, doi: 10.1002/2014JC010644
- Van Lancker V, Deronde B, De Vos K, Fettweis M, Houthuys R, Martens C, Mathys M. 2015. Kust en Zee. In: Borremans M. (Ed.) *Geologie van Vlaanderen*. Academia Press/Genootschap van Gentse Geologen.
- Van den Eynde D, Fettweis M. 2014. Towards the application of an operational sediment transport model for the optimisation of dredging works in the Belgian coastal zone (southern North Sea). In: Dahlin H, Flemming NC, Petersson SE (Eds.). *Sustainable Operational Oceanography*, 250-260.
- Fettweis M, Baeye M, Van der Zande D, Van den Eynde D, Lee BJ. 2014. Seasonality of floc strength in the southern North Sea. *Journal of Geophysical Research Oceans*, 119, 1911-1926. doi:10.1002/2013JC09750
- Lee BJ, Toorman E, Fettweis M. 2014. Multimodal particle size distribution of fine-grained sediments: Mathematical modeling and field investigations. *Ocean Dynamics* 64, 429-441. doi: 10.1007/s10236-014-0692-y

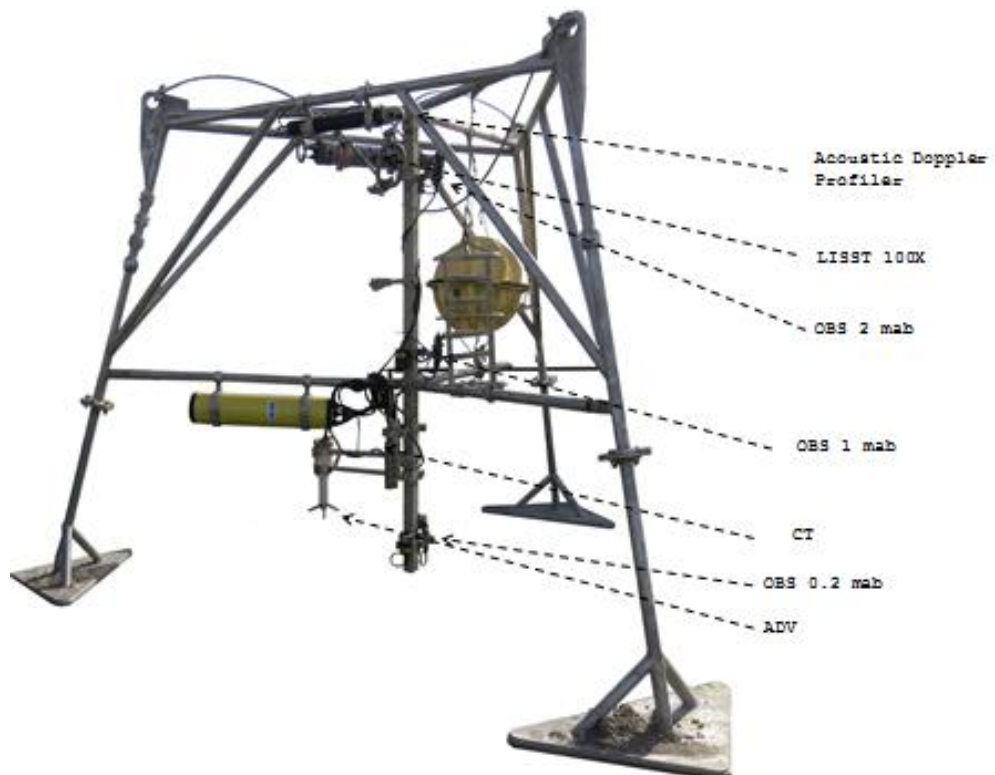
Thesis

- Nelson M. 2015. Soft sediment dynamics in a high-turbidity environment, Belgian coastal zone. Master thesis in Marine and Lacustrine Science and Management. UA, UGent and VUB. 38pp+app.
- Thant S. 2014. Study on wave systems and their impact on the seabed and water column turbidity in the Belgian coastal zone. Master thesis in Marine and Lacustrine Science and Management. UA, UGent and VUB. 43pp+app.

2. SPM concentratie te MOW1 in 2014-2015

2.1. Meetapparatuur

Stroming, saliniteit, temperatuur, SPM concentratie en partikelgrootteverdeling (PGV) werden gemeten met een tripode (Figuur 2.1). De tripode wordt gedurende een periode van 3-6 weken verankerd, waarna ze terug opgehaald en vervangen wordt met een gelijkwaardig tripodesysteem. De gemonteerde instrumentatie bestaat, onder andere uit drie D&A optical backscatter point sensors (OBSen), een Sea-bird SBE37 thermosalinograaf, een SonTek 5MHz ADVOcean puntstroommeter, een SonTek 3MHz ADP current profiler en een Sequoia Scientific LISST (laser in situ scattering and transmissometry) 100X type C. Alle data (uitgezonderd van de LISST) worden opgeslaan in twee SonTek Hydra data logging systemen (Backers et al., 2016a, 2016b). De LISST werd gemonteerd op ongeveer 2 meter boven de bodem (verder afgekort als mbb) en de OBSen op 0.2, 1 en 2 mbb. De OBS voltage werd omgezet naar SPM concentratie met behulp van gefiltreerde waterstalen genomen tijdens verschillende meetcampagnes. Vanaf 2014 werd de meetrange van de onderste OBS vergroot, zodat waarden tot 7 g/l kunnen worden gemeten.



Figuur 2.1: Frame dat gebruikt wordt in de langdurige metingen te MOW1. Afmetingen zijn ongeveer 2.5 m (hoogte) en 3 m (breedte).

2.2. Overzicht metingen

In tabellen 2.1-2.2 en Figuren 2.2-2.5 wordt een overzicht gegeven van de metingen 2014-2015 ter hoogte van MOW1. De details per verankering kunnen in appendix 1 en 2 worden gevonden. Er werden verschillende OBS instellingen gebruikt tijdens de verankeringen. Het meetinterval is afhankelijk of de OBS aan de ADP of de ADV bevestigd was. Voor de ADV, die hoog frequente metingen doet gedurende korte tijd, is het interval tussen twee metingen groter (15 minuten). Bij de ADP werd om de 2 minuten gemeten.

Tabel 2.1: Overzicht van OBS te MOW1.

Nr		measuring period	SPM conc. 2 mab		SPM conc. 2 mab	
			good data (julian day)	days	good data (julian day)	days
80	ADV	09/12/2013-27/03/2014	-	-	-	-
82	ADP	27/03/2014-28/04/2014	86.56-118.64	32.08	86.56-118.64	32.08
83	ADV	28/04/2014-21/05/2014	118.66-141.33	22.67	118.66-141.33	22.67
84	ADP	21/05/2014-04/07/2014	141.36-185.28	43.92	141.36-185.28	43.92
85	ADV	04/07/2014-09/09/2014	185.35-189.54	4.19	185.35-189.54	4.19
86	ADP	09/09/2014-17/10/2014	252.44-268.00	15.56	252.44-270.00	17.56
88	ADV	17/10/2014-20/11/2014	290.44-317.41	29.85	290.44-317.41	26.97
89	ADP	20/11/2014-16/12/2014	-	-	-	-
90	ADV	16/12/2014-27/01/2015	350.35-15.00	30.65	350.35-15.00	30.65
91	ADV	27/01/2015-16/03/2015	27.67-75.47	47.80	27.67-75.47	47.80
92	ADV	16/03/2015-13/04/2015	-	-	75.52-103.69	28.17
93	ADV	13/04/2015-08/05/2015	103.72-128.03	24.31	103.72-128.03	24.31
94	ADV	08/05/2015-22/06/2015	-	-	-	-
95	ADV	15/07/2015-21/10/2015	196.24-248.61	52.37	-	-
96	ADV	07/12/2015-19/01/2016	-	-		

Tabel 2.3: Overzicht van ADP metingen te MOW1.

Nr	measuring period	ADP		ADV	
		good data (julian day)	days	good data (julian day)	days
80	09/12/2013-27/03/2014	343.62-70	91.38	-	-
82	27/03/2014-28/04/2014	86.56-118.64	32.08	86.56-118.64	32.08
83	28/04/2014-21/05/2014	118.66-141.33	22.67	118.66-141.33	22.67
84	21/05/2014-04/07/2014	-	-	141.36-185.28	43.92
85	04/07/2014-09/09/2014	185.35-252.45	67.10	185.35-189.54	4.19
86	09/09/2014-17/10/2014	252.44-290.41	37.97	252.44-290.41	37.97
88	17/10/2014-20/11/2014	290.44-324.33	33.89	290.44-317.41	26.97
89	20/11/2014-16/12/2014	-	-	324.38-350.38	26.00
90	16/12/2014-27/01/2015	350.35-27.62	43.27	350.35-15.00	30.65
91	27/01/2015-16/03/2015	27.67-75.47	47.80	27.67-75.47	47.80
92	16/03/2015-13/04/2015	75.52-103.69	28.17	75.52-103.69	28.17
93	13/04/2015-08/05/2015	-	-	103.72-128.03	24.31
94	08/05/2015-22/06/2015	128.24-173.76	45.52	128.24-159.64	31.40
95	15/07/2015-21/10/2015	196.24-294.46	98.22	196.24-248.61	52.37
96	07/12/2015-19/01/2016	341.50-19.39	43.89	-	-

2.3. Spanningstoevoer naar OBS

Het teruggekaatste signal uitgezonden door de OBS3+ wordt als Voltage opgeslaan. In zuiver water registreert een OBS 0 V, bij toenemende troebelheid neemt deze waarde lineair toe tot een maximum voltage van ongeveer 5 V wordt bereikt bij het maximale meetbereik. Voor hogere turbiditeiten satureert de OBS. De sensor heeft als input een constant spanning van minimum 6 V nodig om goede data te kunnen geven. Een lagere voedingspanning resulteert in een schijnbare afname in troebelheid, zie Figuur 2.6. De figuur toont de output van een OBS3+ ingesteld voor het lage (0-2000 BU) en het hoge (0-4000 BU) meetbereik die gevoed werd met verschillende inputspanningen terwijl de sensor geplaatst was in een standaardoplossing van 2000 Amco-Clear®-equivalente BU (Backscatter Unit). Voor een input voltage van meer dan 6 V registreert de OBS3+ in het lage meetbereik een constant waarde van 5.1 V (saturatie), terwijl in het hoge meetbereik een half zo grote waarde wordt opgeslaan (2.5 V). Indien de voedingsspanning afneemt, dan registreert ook de OBS3+ een afname. Een lagere voedingspanning kan voorkomen bij een afname van de batterijspanning of bij technische problemen met de meetapparatuur. Dit laatste werd opgemerkt in de tijdseries vanaf 2014, zie een voorbeeld in Figuur 2.7. De fi-

guur toont dat tengevolge van een slecht functionerend instrument (data logger van de SonTek Hydra) een lagere dan de vereiste 6 V naar de OBS3+ kwam, waardoor het output-signaal significant lager was. De tripod werd op dag 118 vervangen door een gelijkaardig systeem. Voor verankering 84 werd hetzelfde systeem gebruikt als voor verankering 82. Het foutieve signaal kon aan de hand van de curve in Figuur 2.6 gecorrigeerd worden, zie Figuur 2.8 voor een voorbeeld.

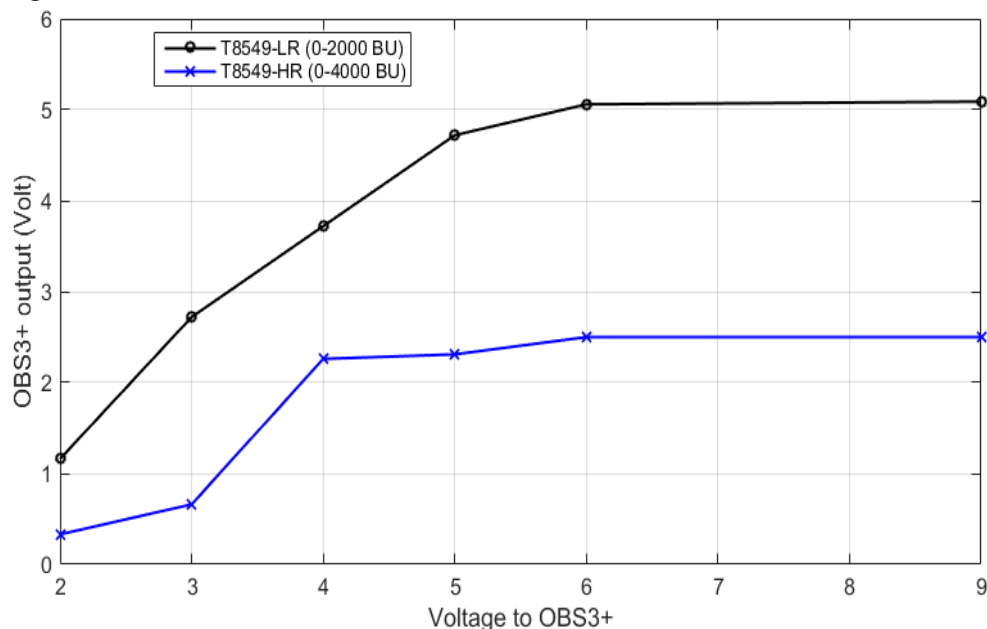


Figure 2.6: Voltage provided by an external source to a Campbell OBS3+ (T8549) measuring in a standard solution of 2000 AmcoClear® equivalent BU. When the voltage supply drops below 6 V, the sensor registers too low values.

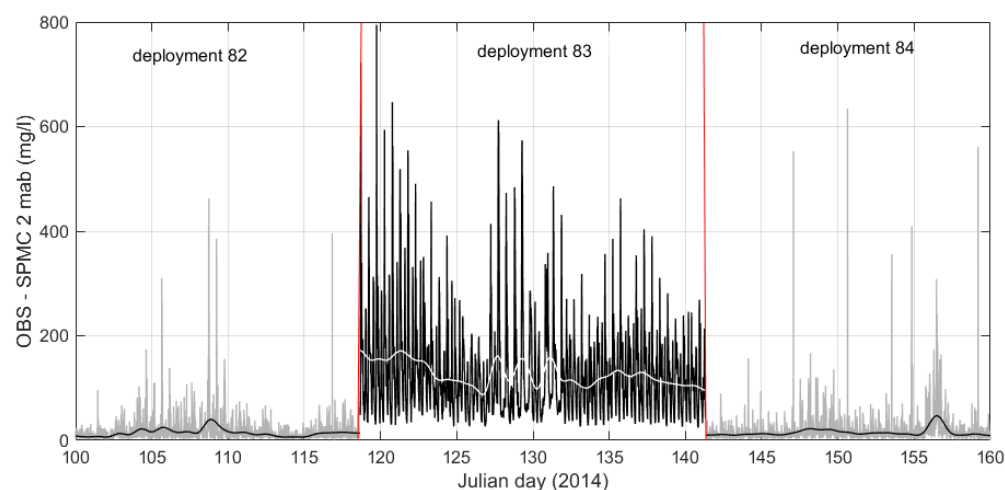


Figure 2.7: SPMC tijdseries tijdens verankeringen 82-84 gemeten met Campbell OBS3+ instrument (op 2 m boven bodem) die aangesloten waren op een SonTek Hydra data logging systeem voor dataopslag en batterijspanning: Foutieve data in verankering 82 en 84 en onder de gecorrigeerde data.

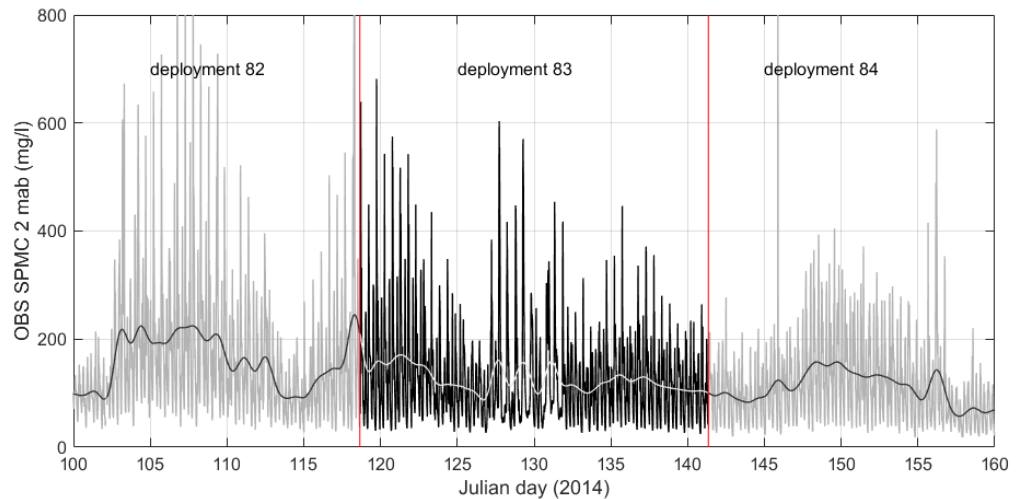


Figure 2.8: SPMC tijdseries tijdens verankeringen 82-84 gemeten met Campbell OBS3+ instrument (op 2 m boven bodem) die aangesloten waren op een SonTek Hydra data logging systeem voor dataopslag en batterijspanning: gecorrigeerde data.

2.4. Omrekening akoestische en optische backscatter naar SPM concentratie

Het OBS signaal werd gebruikt om de SPM concentratie te bepalen. De OBS voltages werden omgezet in SPM concentration via een sensor calibratie ($V \rightarrow \text{FNU}$) en nadien via een calibratie met gefiltreerde waterstalen verzameld gedurende enkele getijcycli per jaar (februari 2014, april 2014, 2×september 2014, 2×november 2014, december 2014, januari 2015, april 2015, december 2015). Een lineaire regressie werd gebruikt als correlatie tussen het OBS signaal (in FNU) en de SPM concentration uit de gefiltreerde waterstalen (in mg/l). De regressieve coefficient (R^2) was hoger dan 0.90 (Backers et al. 2016a, 2016b); de onzekerheid op de OBS-SPM concentratie werd geschat op 10% (Fettweis, 2008).

The ADP profiler was gemonteerd op 2.3 m boven de bodem men heft stroomsnelheid en backscatterintensiteit gemeten met een resolutie van 15 cm beginnend op 1.9 m boven de bodem. De onderste bins die niet verstoord was door de bodem bevindt zich op 0.55 m boven de bodem. Het teruggekaatste akoestische signaal werd gebruikt om de SPM concentratie te berekenen. Na omzetting in decibels, werd de signaalsterkte gecorrigeerd voor de geometrische spreiding en verzwakking door het water. Verder werd een iteratief process toegepast (Thorne & Hanes 2002) om te corrigeren voor signaalafzwakking door het sediment in suspensie. De SPM concentratie afgeleid van de bovenste OBS werd gebruikt om de eerste bin van de ADP te calibreren. Terugkaatsing van het akoestisch signaal wordt beïnvloed door het type sediment, de kleur, partikelgrootte, samenstelling en turbulentie. Optische en akoestische terugkaatsing hebben een andere gevoeligheid voor deze parameter (Thorne et al. 1991; Fugate & Friedrichs 2002; Voulgaris & Meyers 2004; Downing 2006; Nauw et al. 2014). De echo intensiteit van het teruggekaatste akoestisch signaal geeft een goede achting van de SPM concentration zolang de partikelgrootte en karakteristieken hetzelfde blijven. Dit is dikwijls niet het geval in getijomgevingen waar fijnkorrelige sedimenten onderhevig zijn aan flocculatie an waar cohesieve en niet-cohesieve sedimenten tegelijkertijd in suspensie kunnen voorkomen (Baeye et al. 2011; Fettweis et al. 2012). Vlokken beïnvloeden de terugkaatsing minder sterk dan een zandkorrel van dezelfde grootte tengevolge van hun lagere densiteit (Ha et al. 2011). De sterkte van het door vlokken teruggekaatste signaal wordt vooral (maar niet uitsluitend) beïnvloed door de bouwstenen van de vlokken, dit zijn de primaire deeltjes en microvlokken (flocculi) (Fugate & Friedrichs 2002; MacDonalds et al. 2013; Rouhnia et al. 2014). De ver-

schillende gevoeligheid van akoestische en optische sensoren op veranderingen in SPM partikelgrootte en eigenschap weerspiegelt zich in de correlatie coëfficiënt tussen de ADP backscatter (in dB) en de OBS-SPM concentratie van $R^2=0.53$. De R^2 is beter bij lagere SPM concentraties en het regressie model houdt Aldus minder rekening met de variantie van de hoge SPM concentraties.

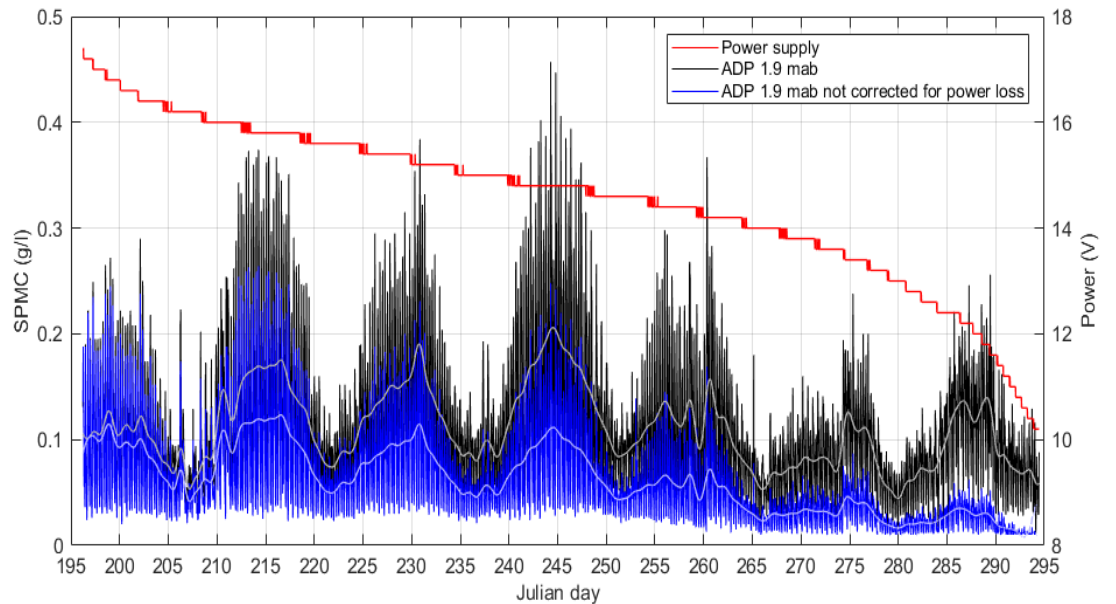
2.5. Spanningstoevoer naar ADP

De actieve sonar vergelijking wordt gebruikt om het teruggekaatste akoestische signal te relateren aan SPMC. De vergelijking kan omgevormd worden (zie b.v. Kim et al., 2004) naar

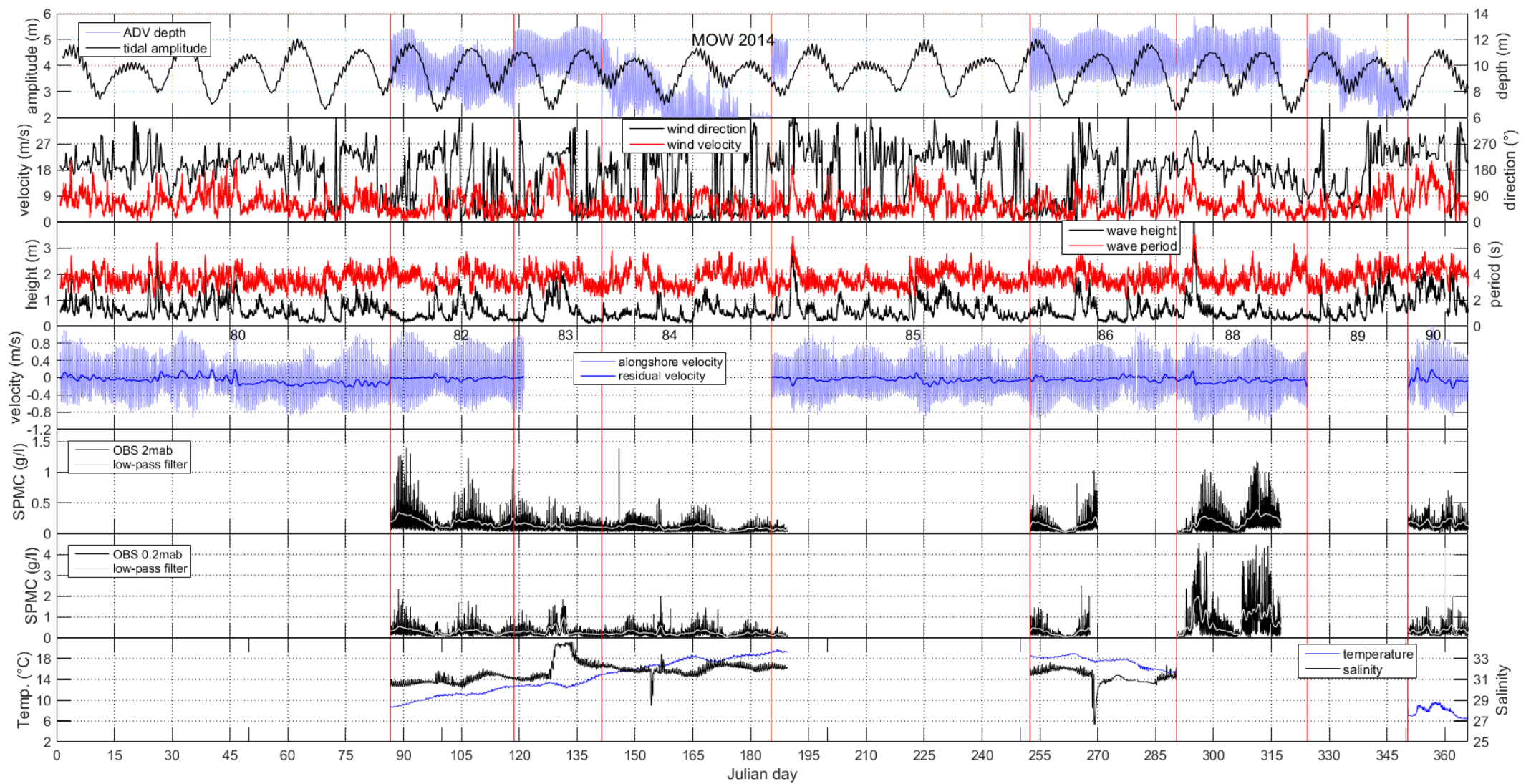
$$S_v = C + 10 \log(TR^2) - L_{DBM} - P_{DBW} + 2\alpha R + K_c(E - E_r)$$

waarbij L_{DBM} de $10\log_{10}(L)$ is, P_{DBW} de $10\log_{10}(P)$ met P het vermogen, K_c de Received Signal Strength Indicator (RSSI) factor (in dB counts⁻¹), E de echointensiteit (in counts), E_r het ontvangen ruis (in counts) en $C = 10 \log \frac{8 K F B_N \cos \theta}{\pi E_x^2 d^2}$. Verder zijn E_x de transducer efficiëntie, α de water absorptie (in dB m⁻¹), R de 'range to scatterers' langsheen de straal (in m), B_N de ruis bandbreedte (in Hz) en F de ontvanger ruis factor. C is afhankelijk van de specificaties van de akoestische sensor en P_{DBW} een factor die rekening houdt met het vermogen van het uitgezonden akoestisch signaal.

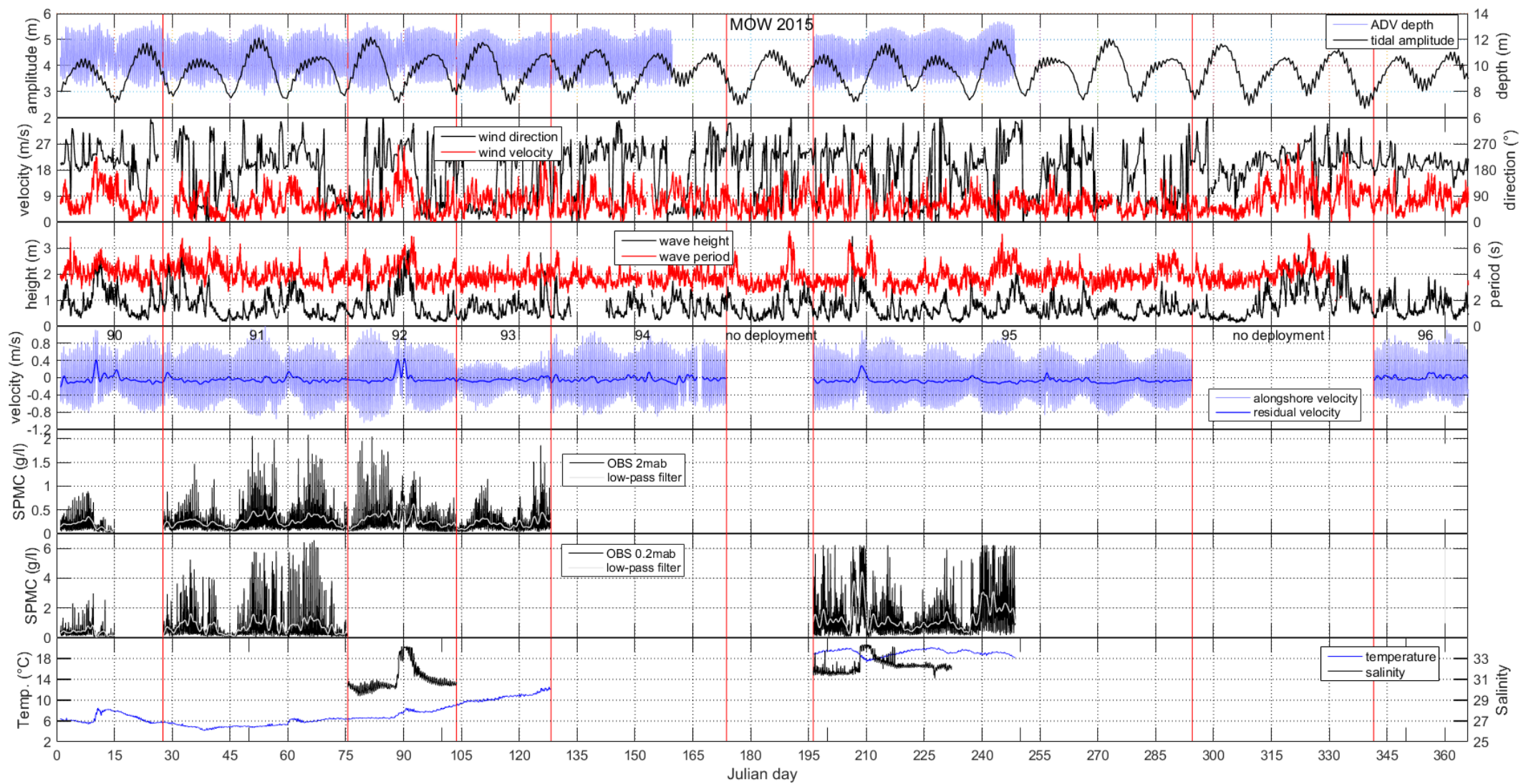
Het vermogen afgeven door de batterij neemt in functie van de tijd af (zie Figuur 2.9) en dient dus gecorrigeerd te worden. Voor een 3000 kHz system is P_{dbw} geschat op 0.7 (zie Kim et al., 2004), wat overeenkomt met een vermogen P van 1.1749 W. Uit de geregistreerde batterijspanning aan de ADP sensor kan dan de weerstand ($R=U^2/P^{-1}$) geschat worden die constant is. Uit de stroom ($I=U/R$) en het vermogen $P=U I$ kan de correctiefactor P_{dbw} worden berekend voor verschillende batterijspanningen en de SPMC berekend worden als $P_{dbw}=10\log_{10}(P^2)/R$. In Figuur 2.9 wordt een berekening met en zonder correctie getoond voor verankering 95. Volgende verankeringen werden aangepast voor afnemende spanningstoevoer: 80, 85, 95.



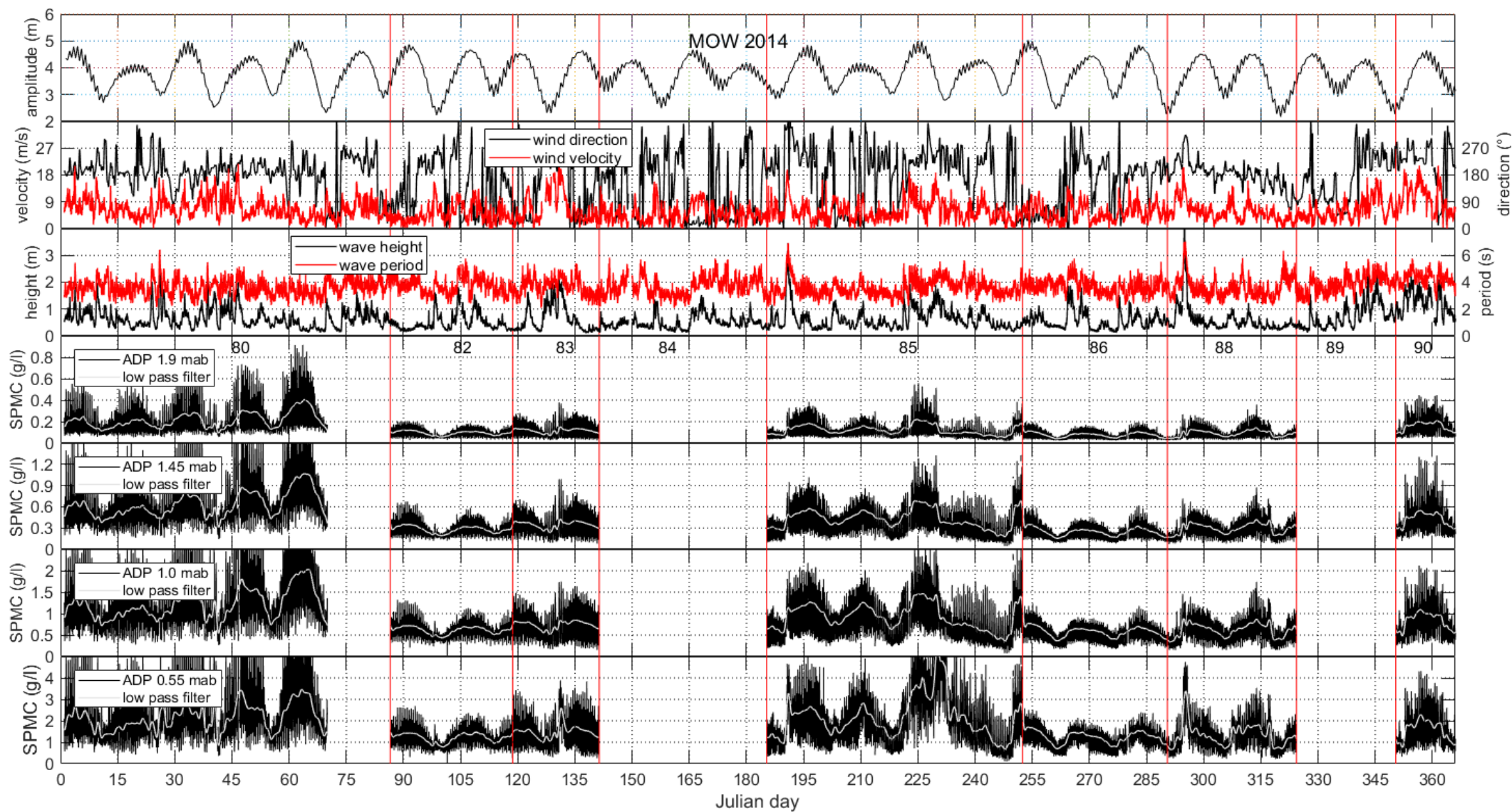
Figuur 2.9: Verankering 95, afname van de batterijspanning tijdens de verankering en het effect op de backscatter intensiteit en aldus ook op de SPMC van de ADP. De SPMC is deze op 1.9 m boven de bodem met en zonder correctie voor afnemende batterijspanning.



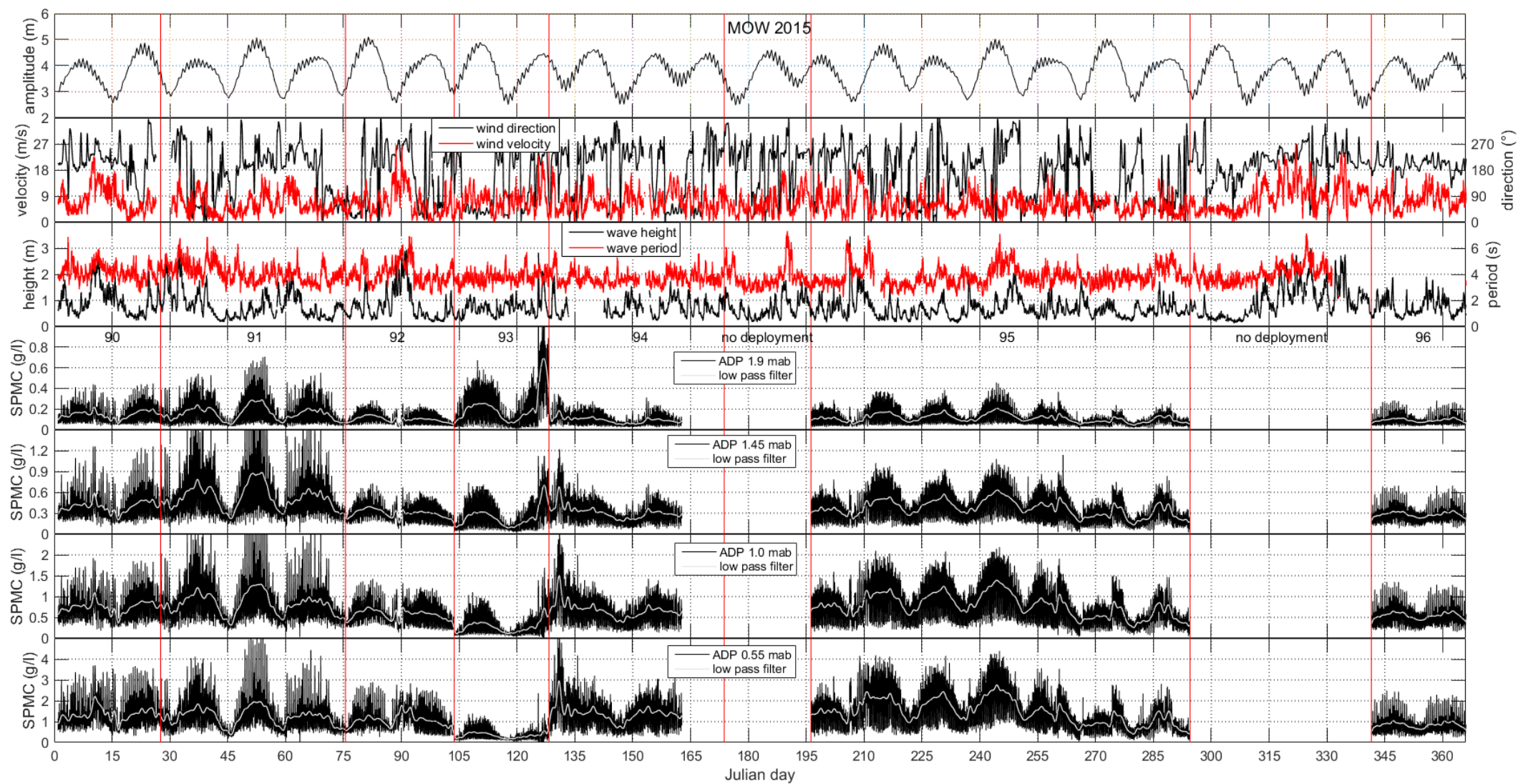
Figuur 2.2: MOW1 2014, getijamplitude en waterdiepte gemeten met de ADV, windrichting en snelheid, significante golfhoogte en gemiddelde golfperiode, residuele alongshore stroming, OBS SPM concentratie op 0.2 en 2 m boven de bodem, saliniteit en temperatuur.



Figuur 2.3: MOW1 2015, getijamplitude en waterdiepte gemeten met de ADV, windrichting en snelheid, significante golfhoogte en gemiddelde golfperiode, residuele alongshore stroming, OBS SPM concentratie op 0.2 en 2 m boven de bodem, saliniteit en temperatuur.



Figuur 2.4: MOW1 2014, getijamplitude, windrichting en snelheid, significante golfhoogte en gemiddelde golfperiode, ADP SPM concentratie op 1.9, 1.45, 1 en 0.55 m boven de bodem.



Figuur 2.4: MOW1 2014, getijamplitude, windrichting en snelheid, significante golfhoogte en gemiddelde golfperiode, ADP SPM concentratie op 1.9, 1.45, 1 en 0.55 m boven de bodem.

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COLOPHON

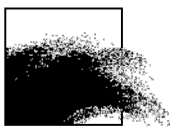
Dit rapport werd voorbereid door de BMM in juni 2017
Zijn referentiecode is .MOMO/7/MF/201706/NL/AR/6

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BEHEERSEENHEID VAN HET
MATHEMATISCH MODEL VAN DE NOORDZEE

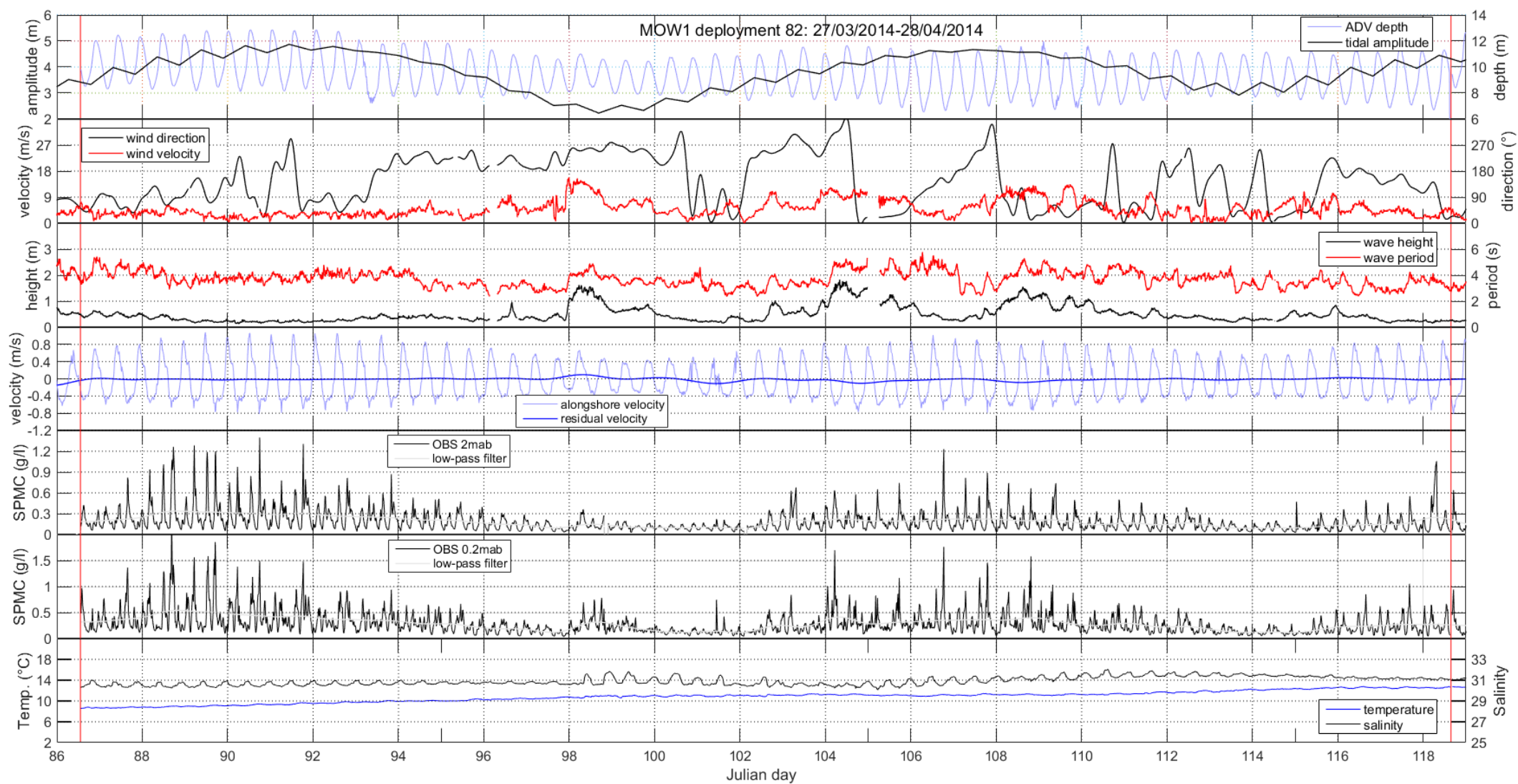


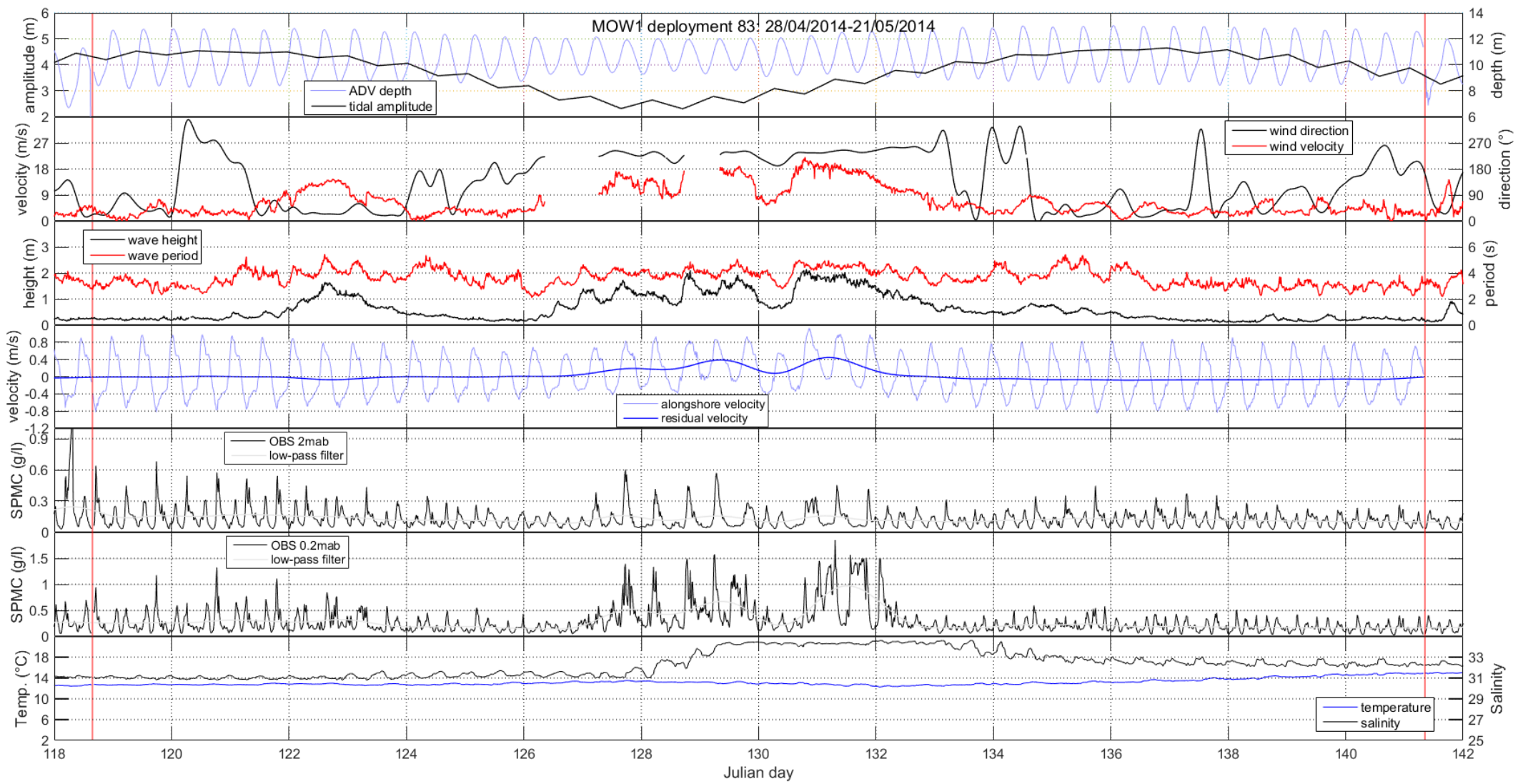
APPENDIX 1

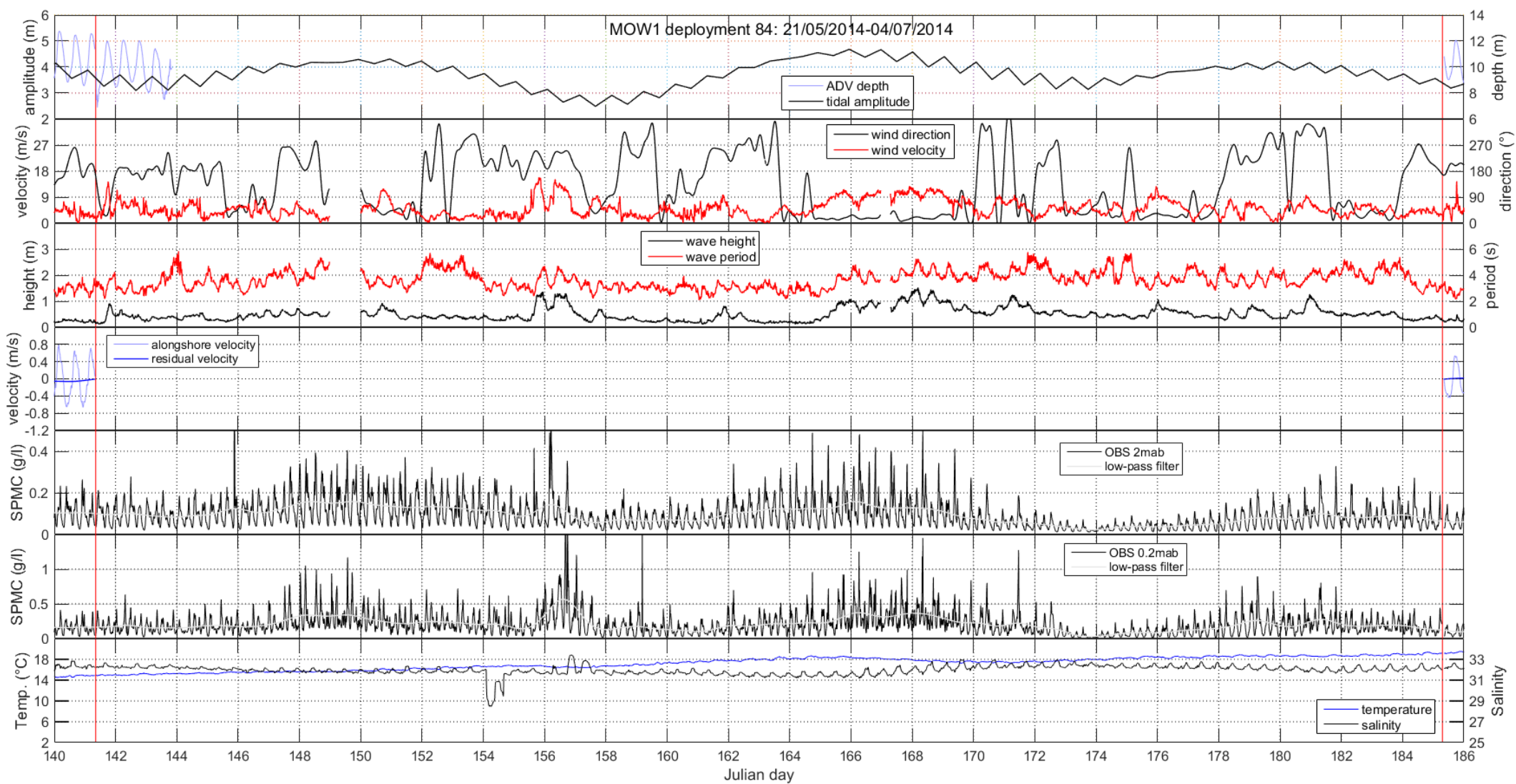
Time-series 2014-2015 MOW1 OBS-SPM concentration

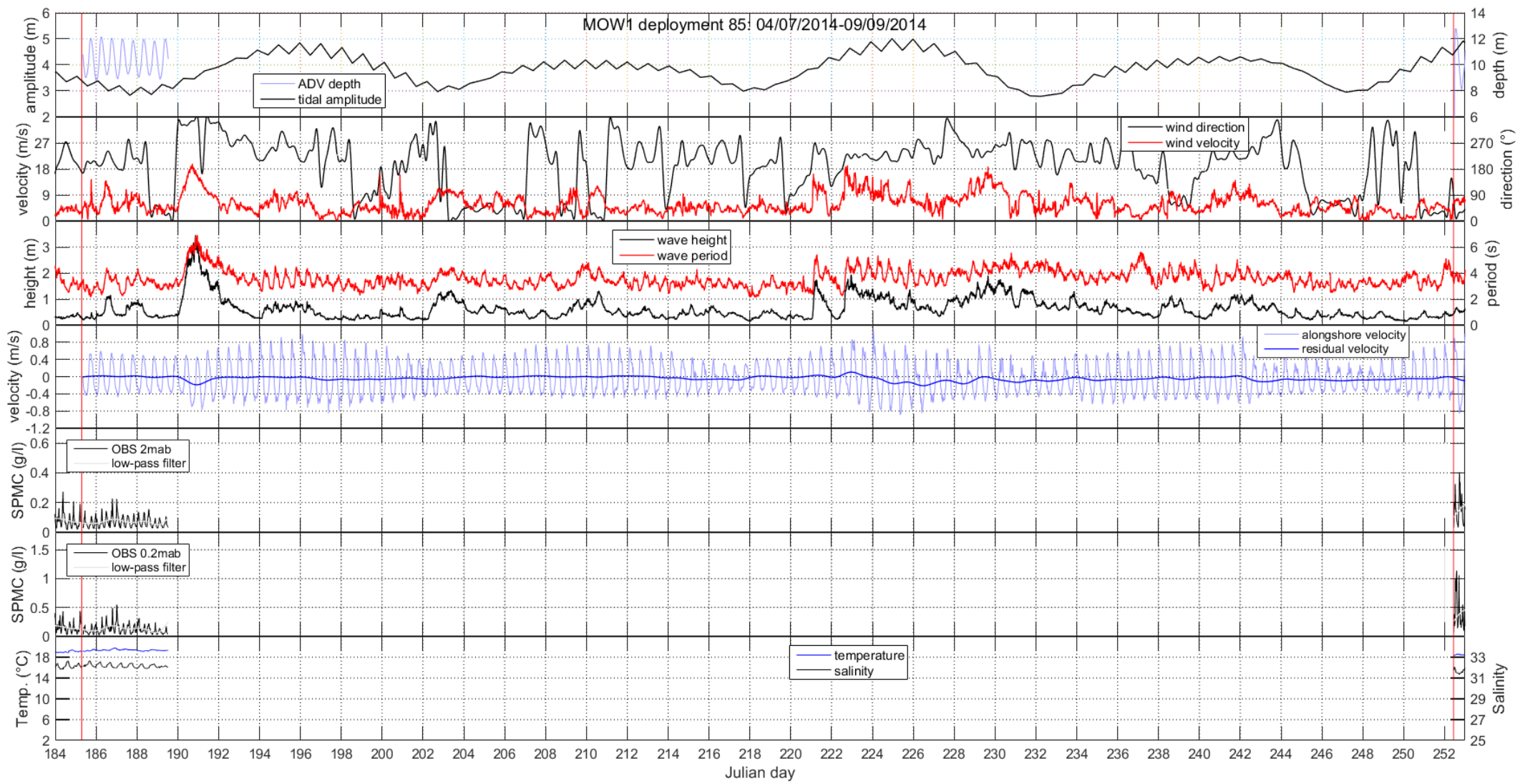
from up to down

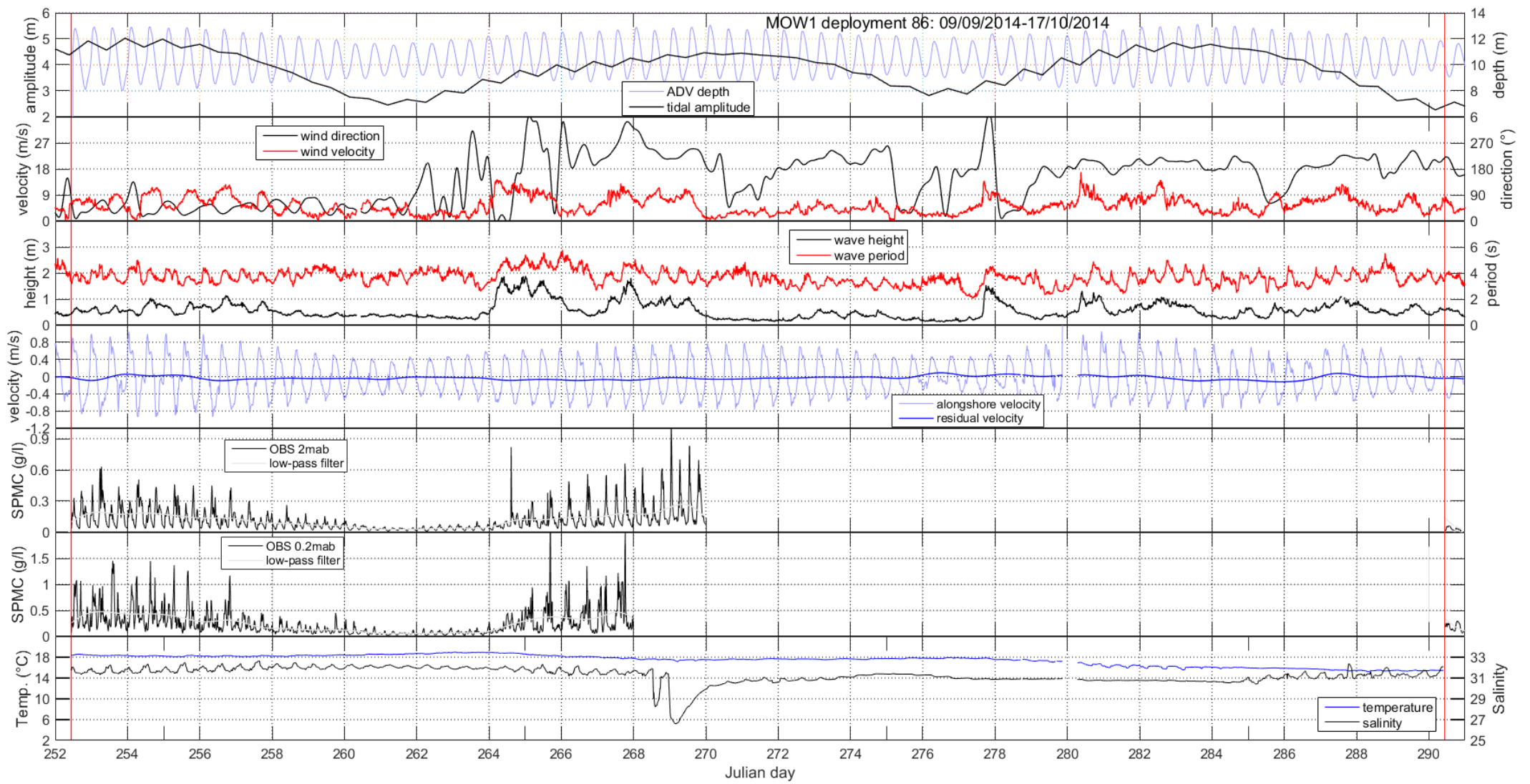
1. Harmonic tidal range at Zeebrugge and depth recorded by the ADV
2. Wind direction and velocity at Wandelaar (Meetnet Vlaamse Banken)
3. Wave height and period at A2-buoy (Meetnet Vlaamse Banken)
4. Alongshore current velocity at 1.8 mab recorded by the ADP and the residual velocity
5. OBS-derived SPM concentration at 2 mab
6. OBS-derived SPM concentration at 0.2 mab
7. Salinity and temperature

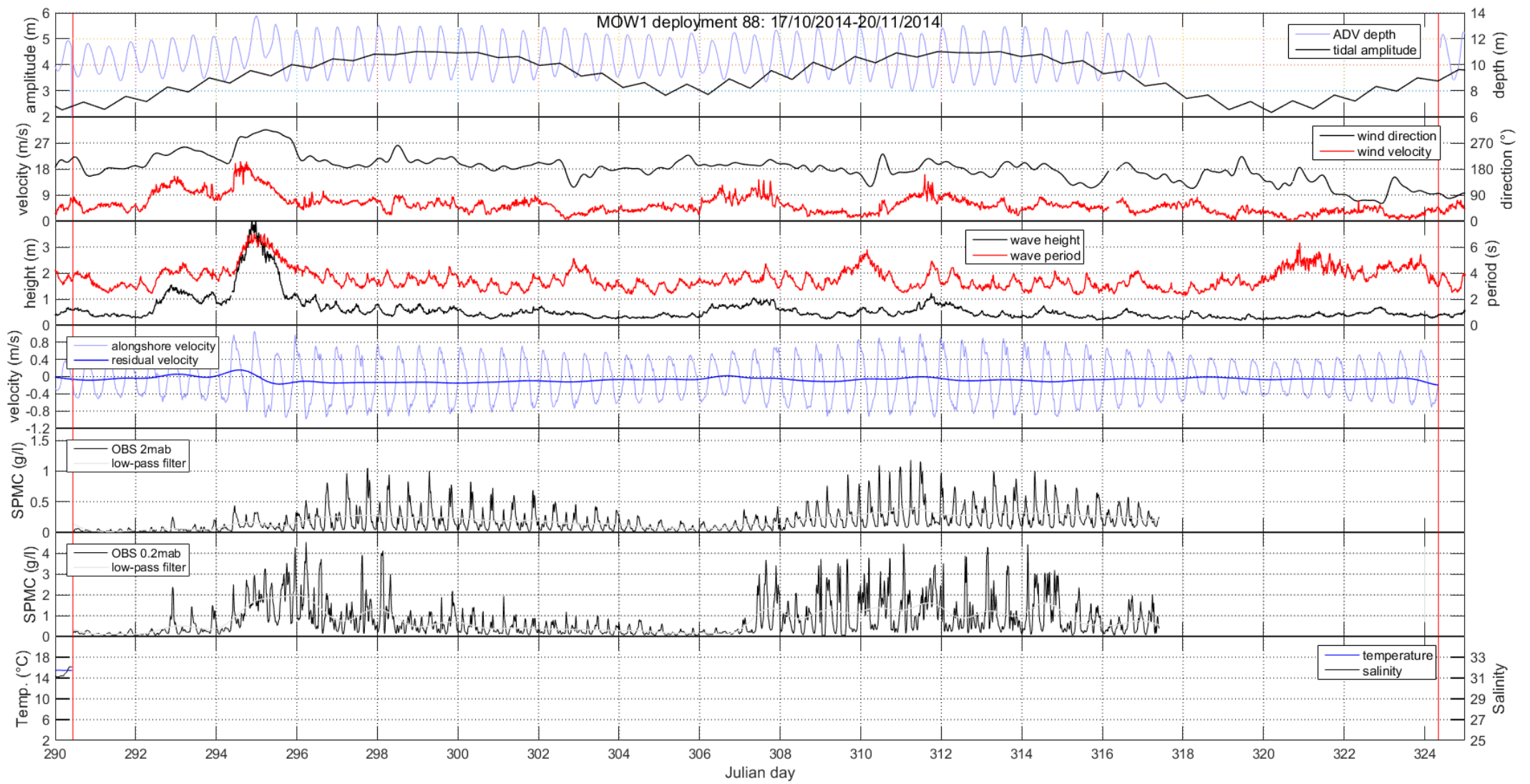


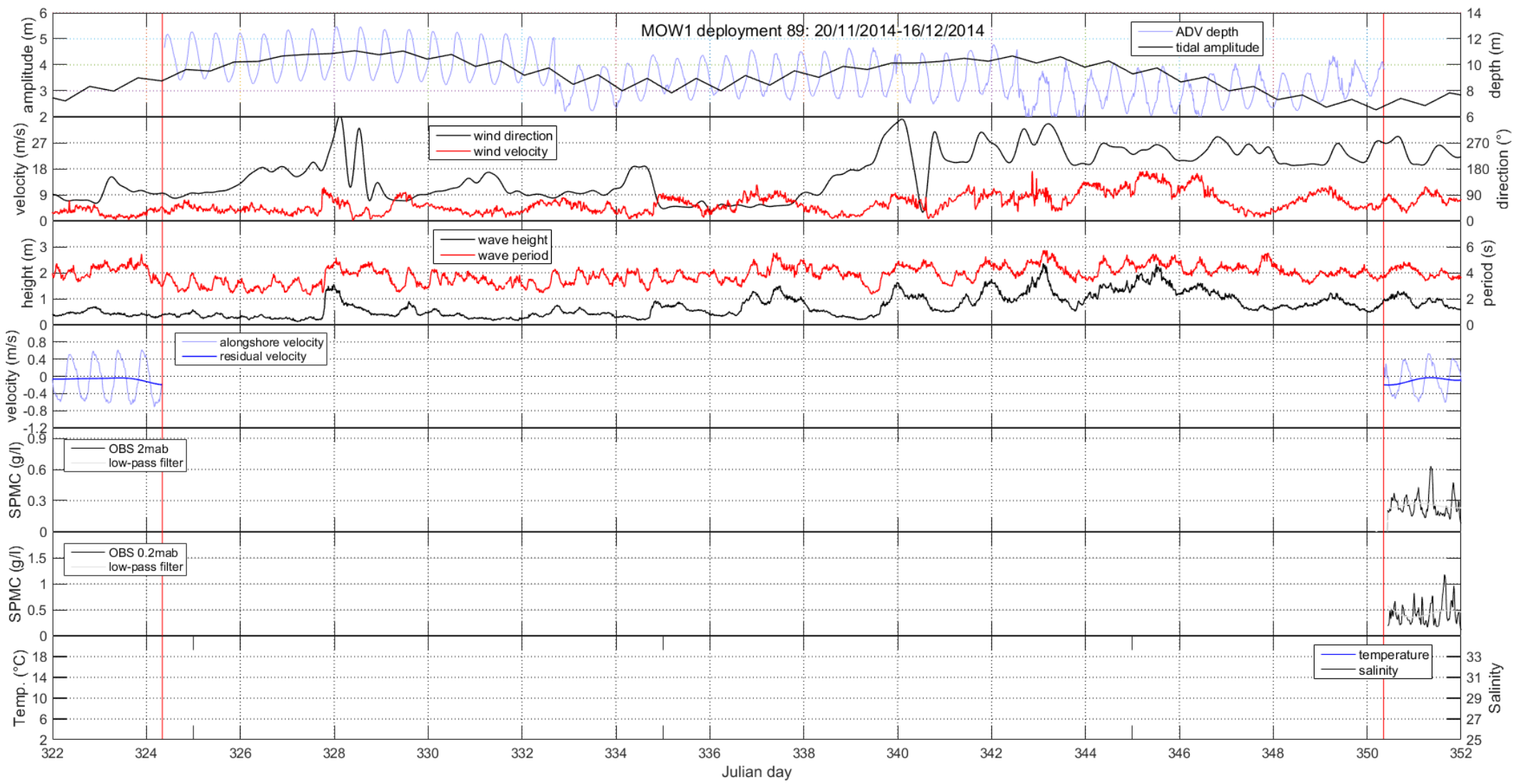


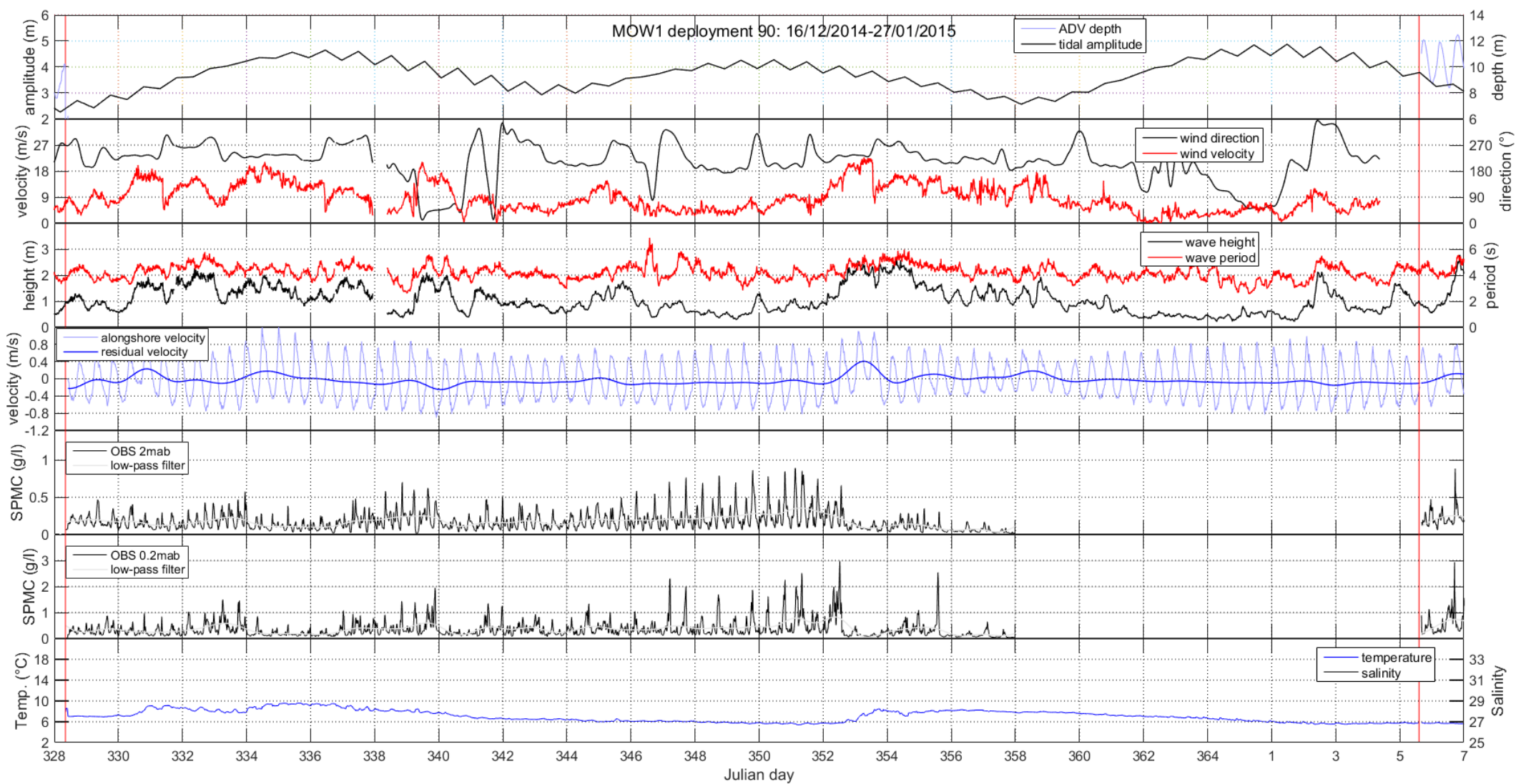


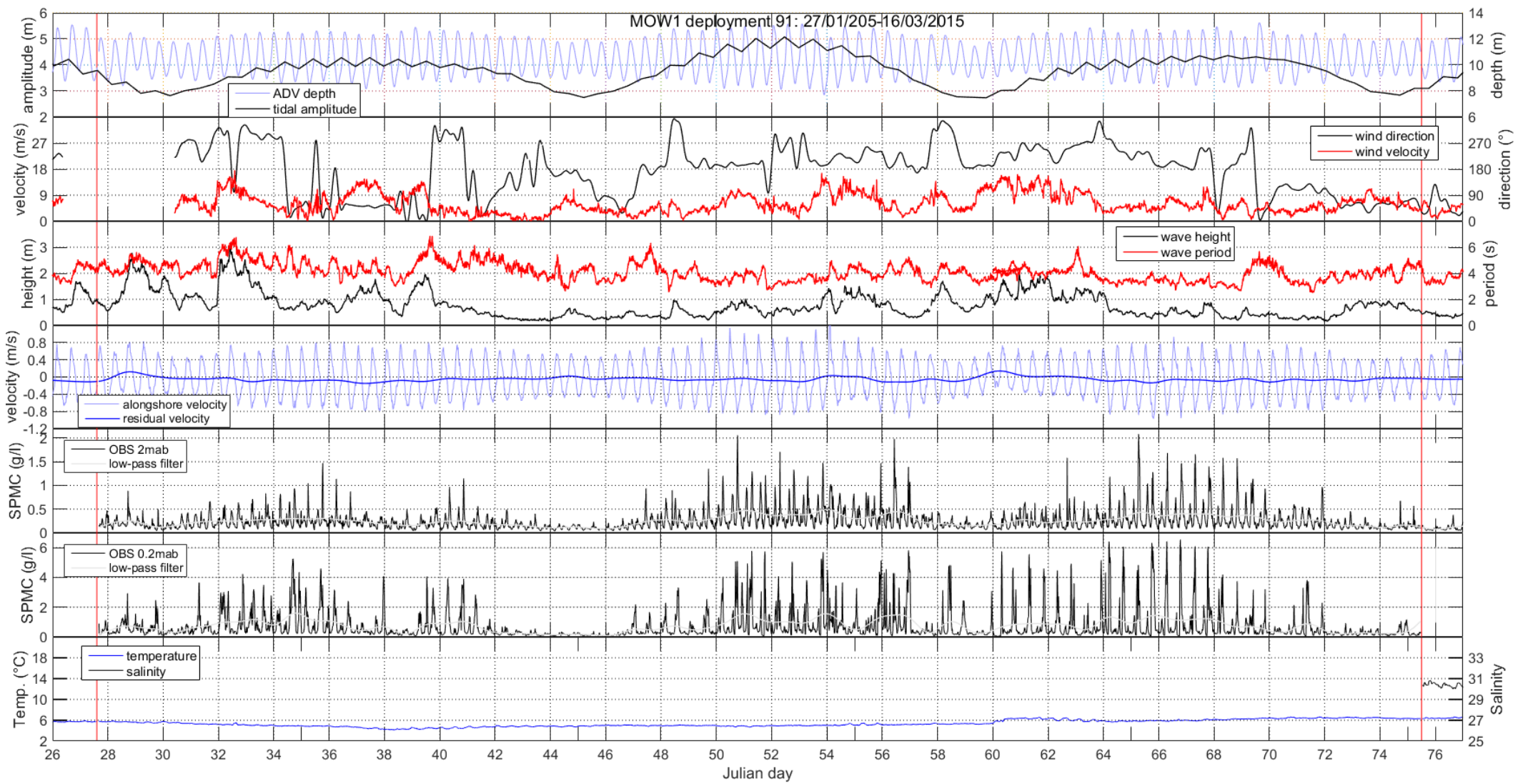


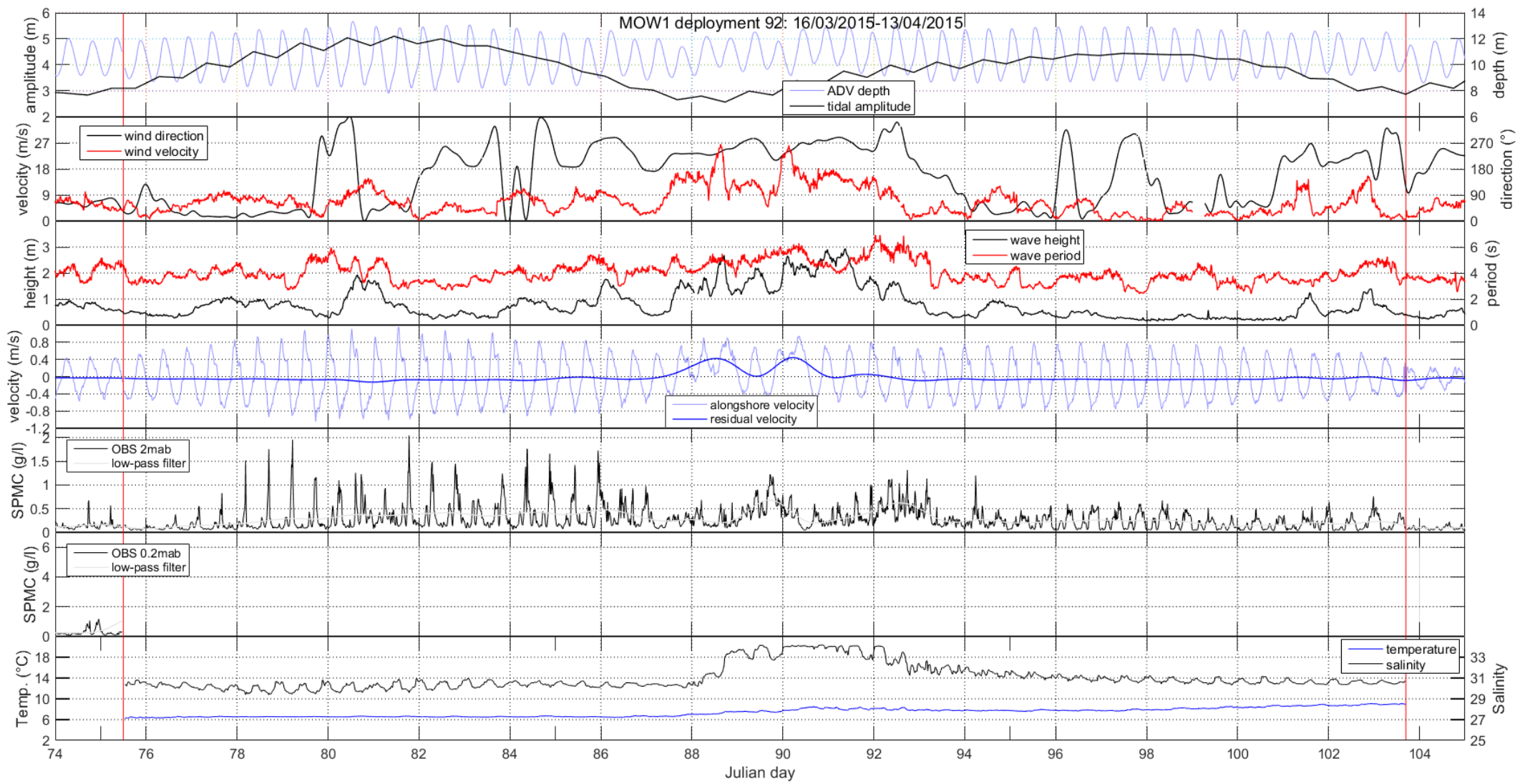


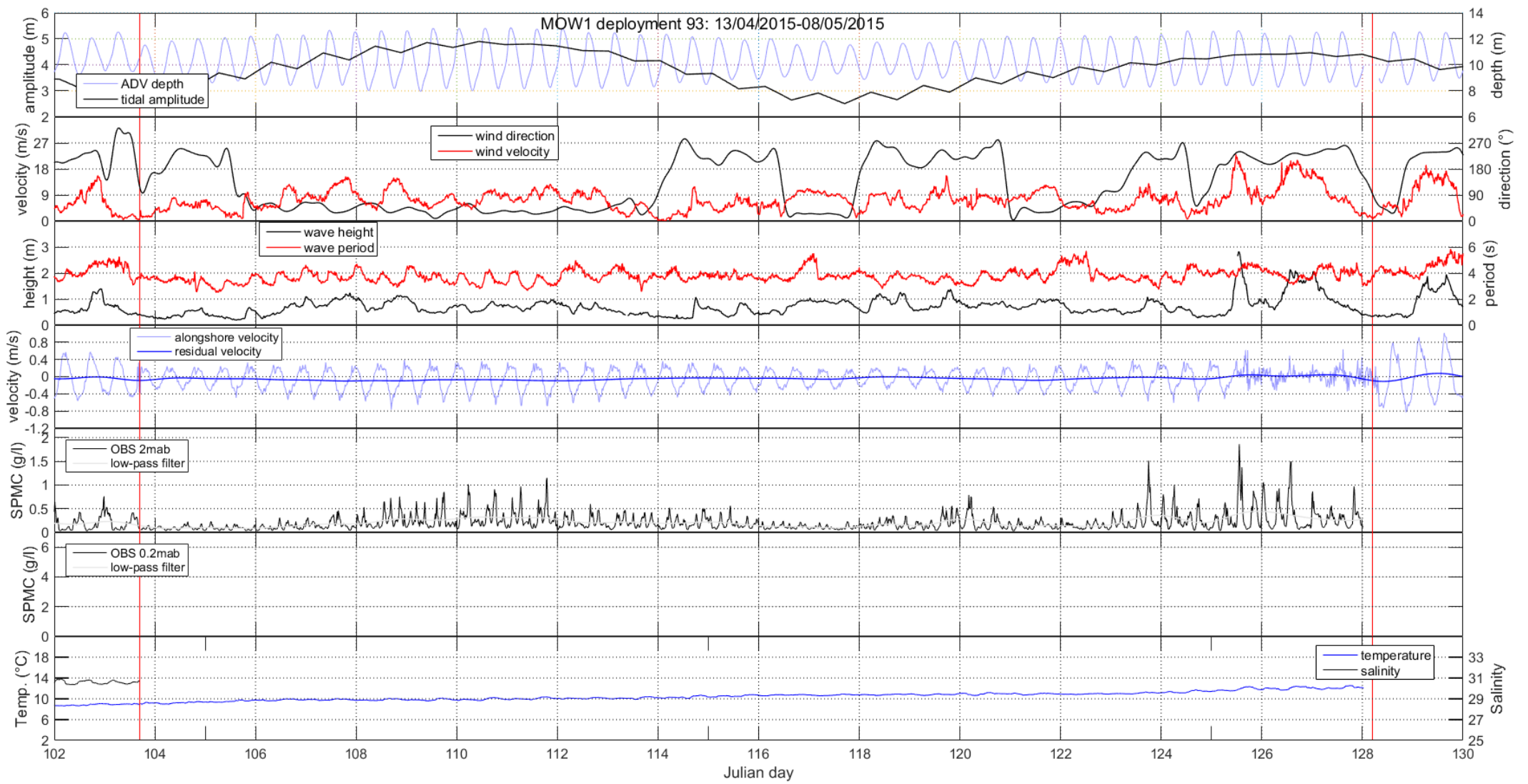


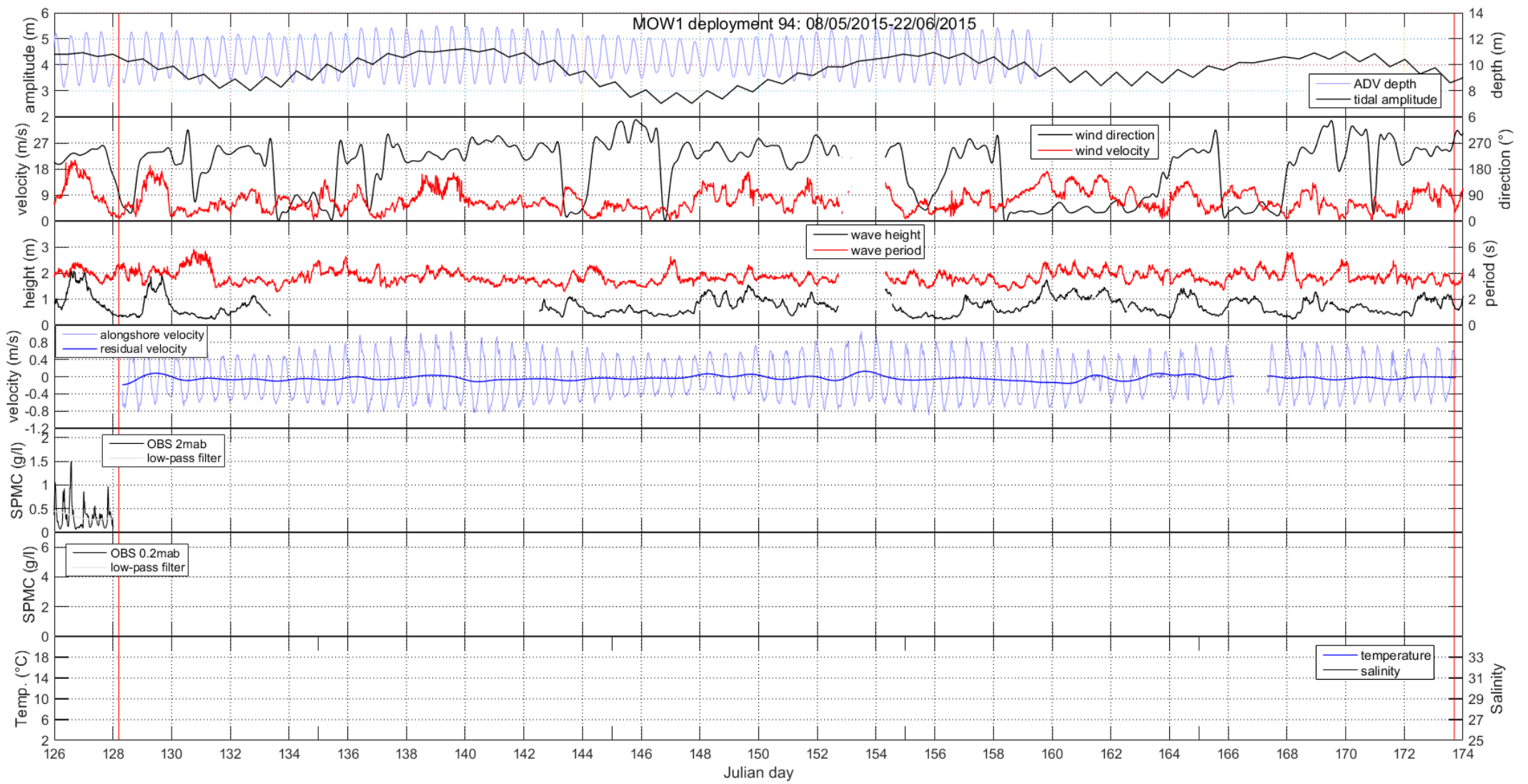


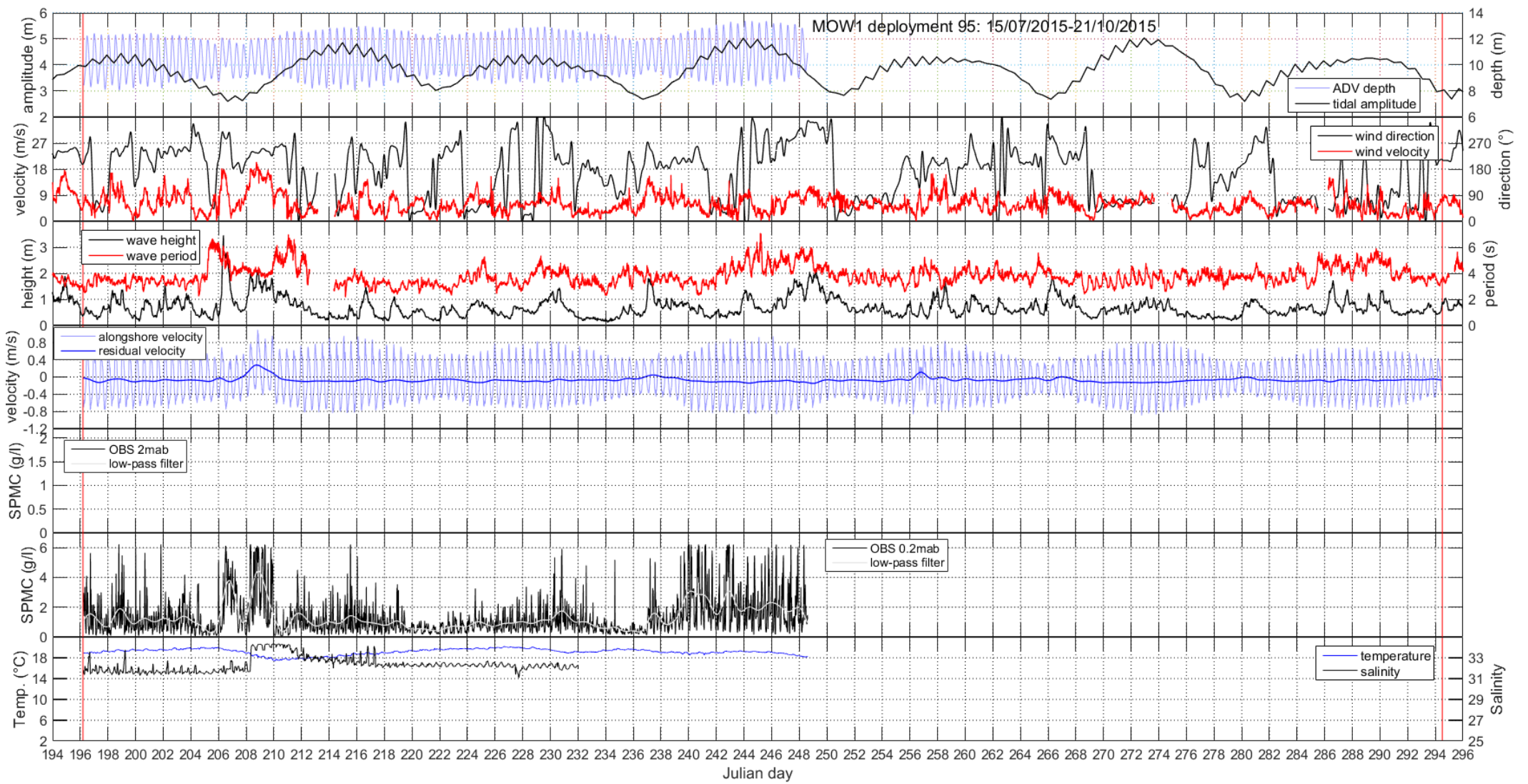


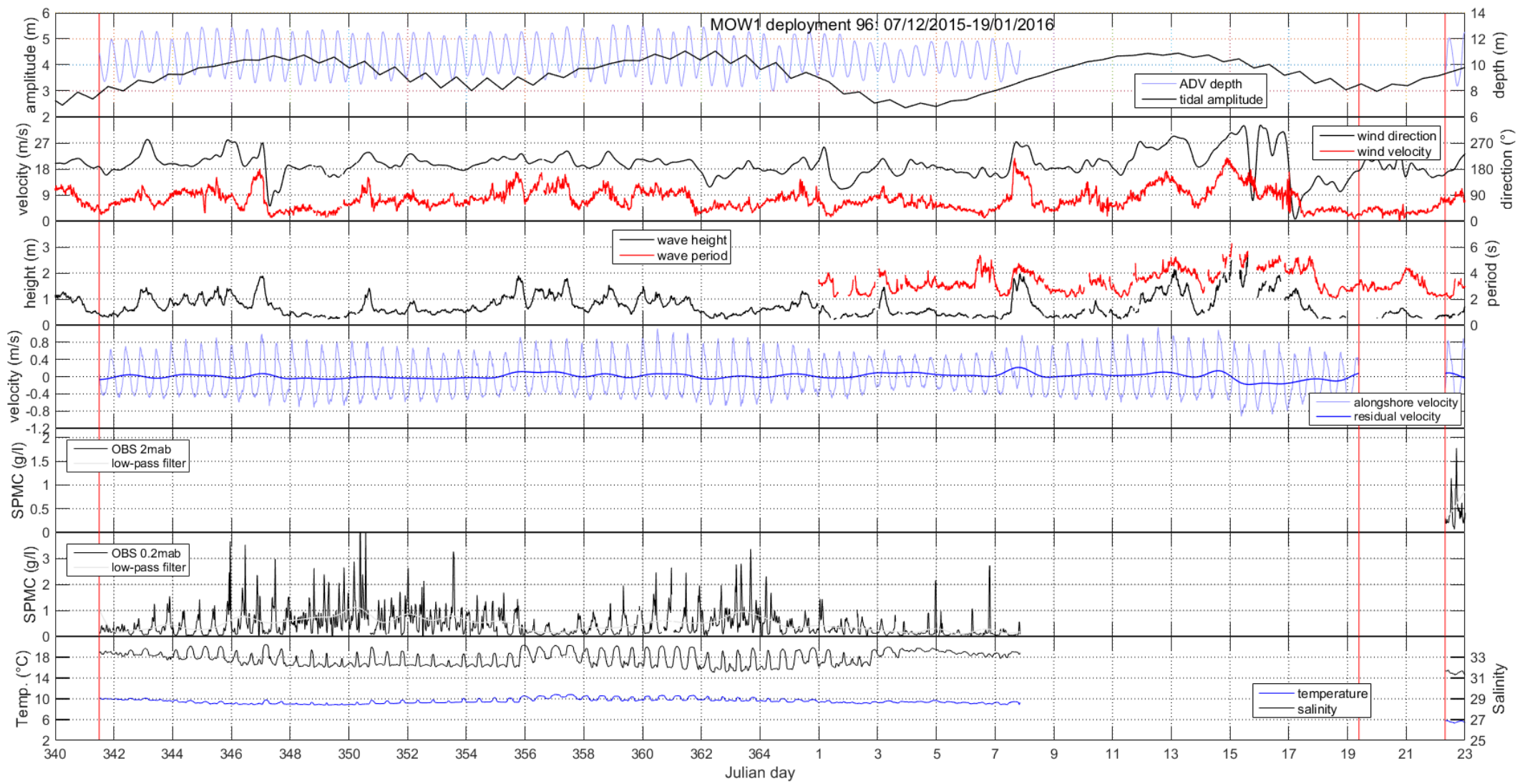










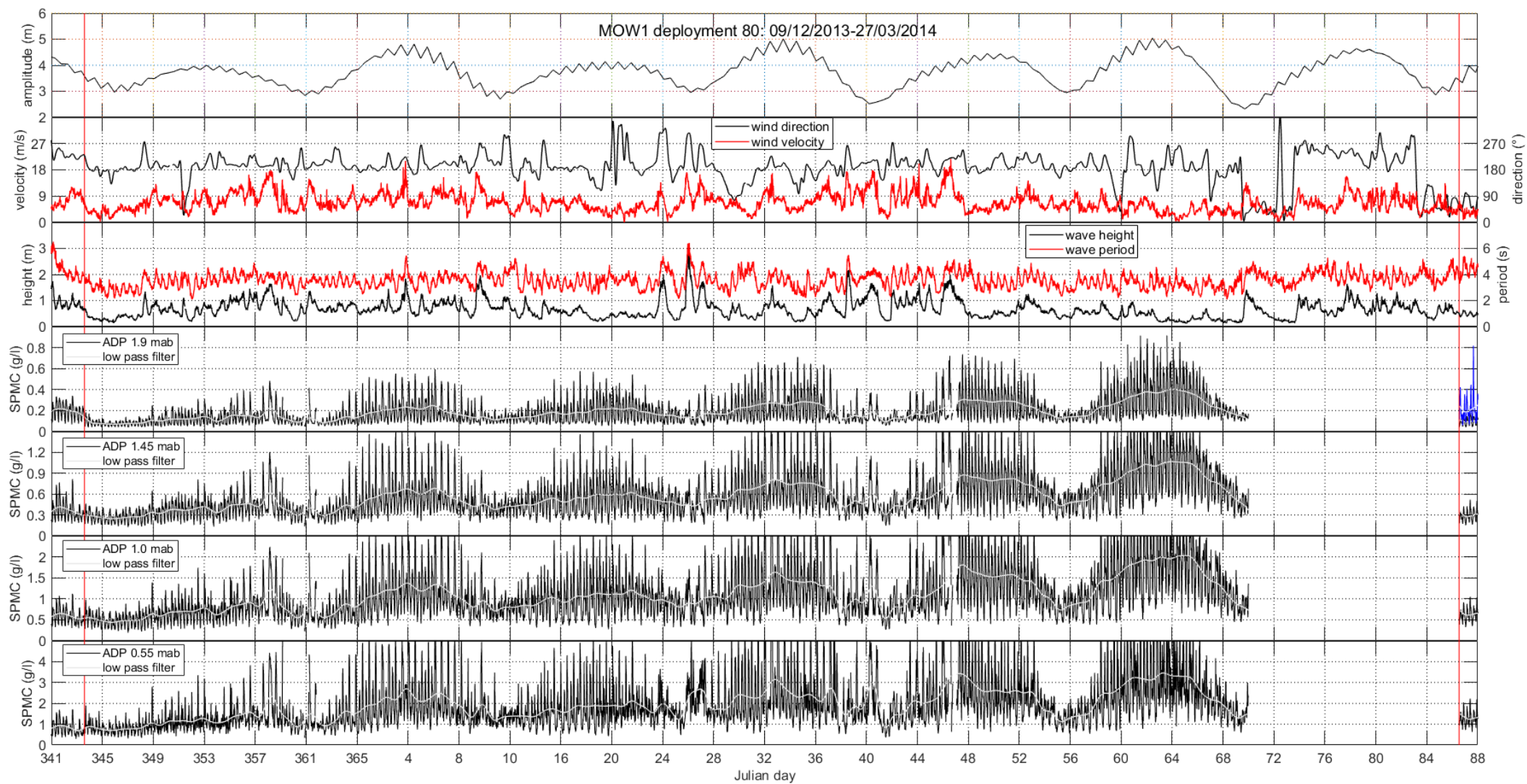


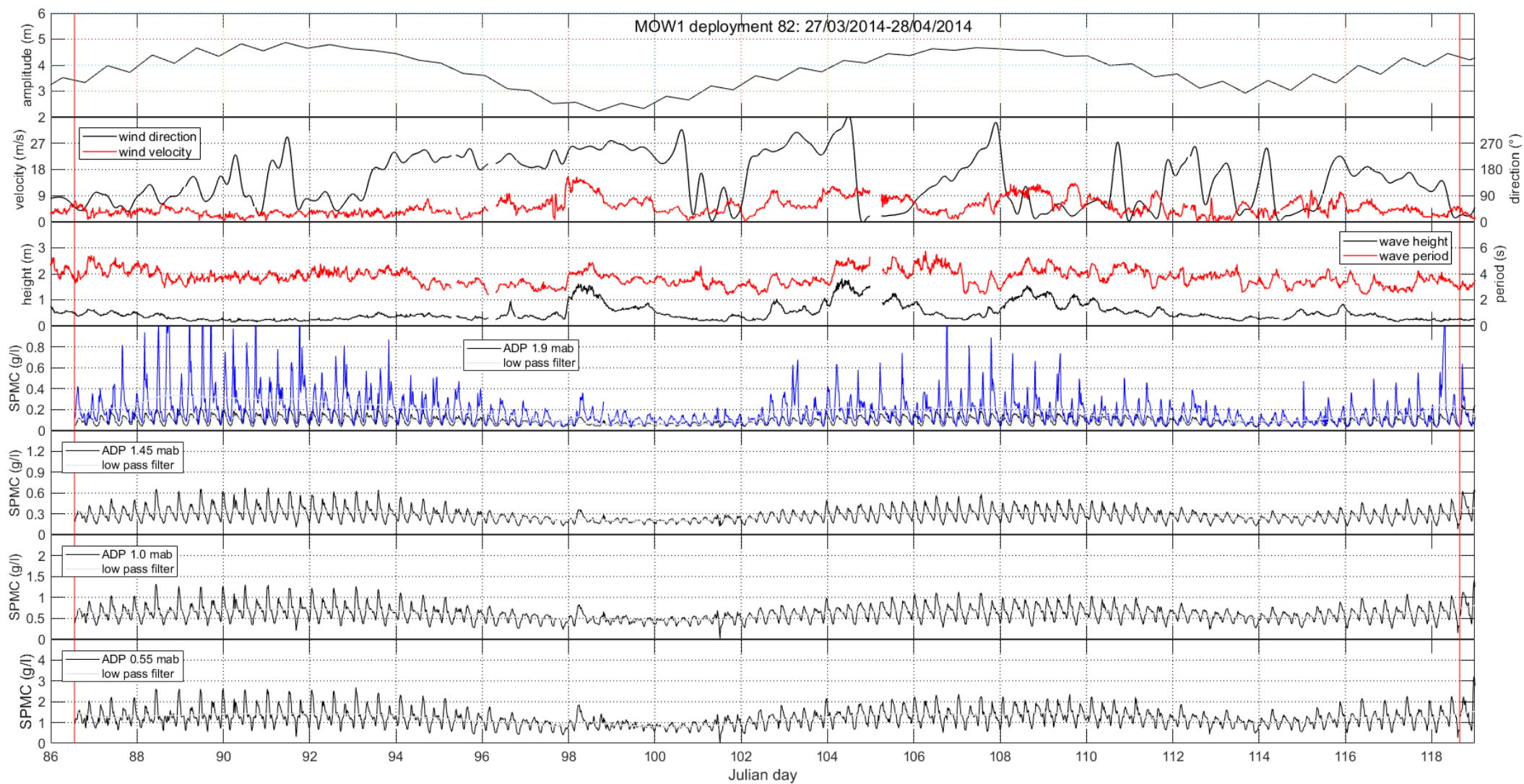
APPENDIX 2

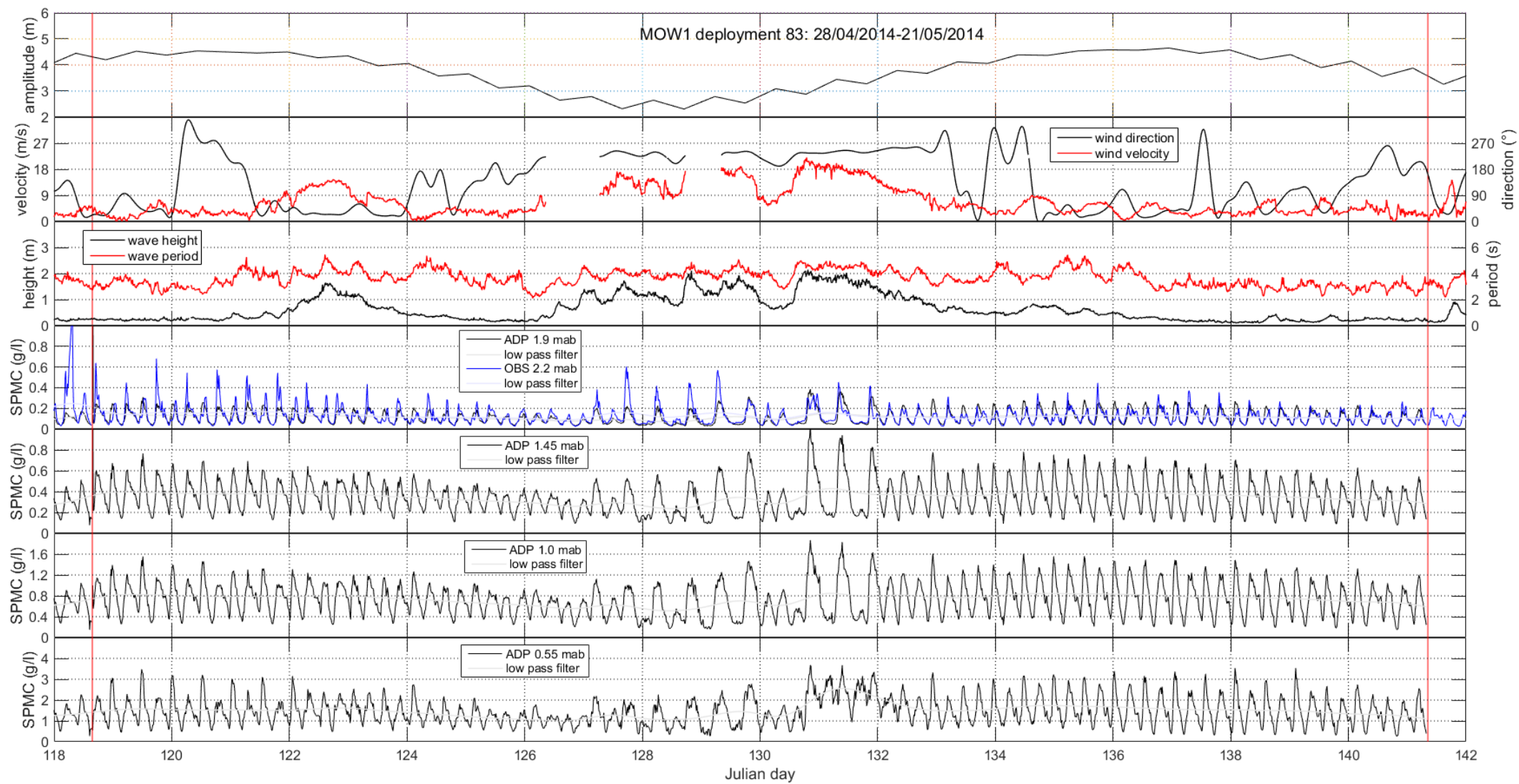
Time-series 2014-2015 MOW1 ADP-SPM concentration

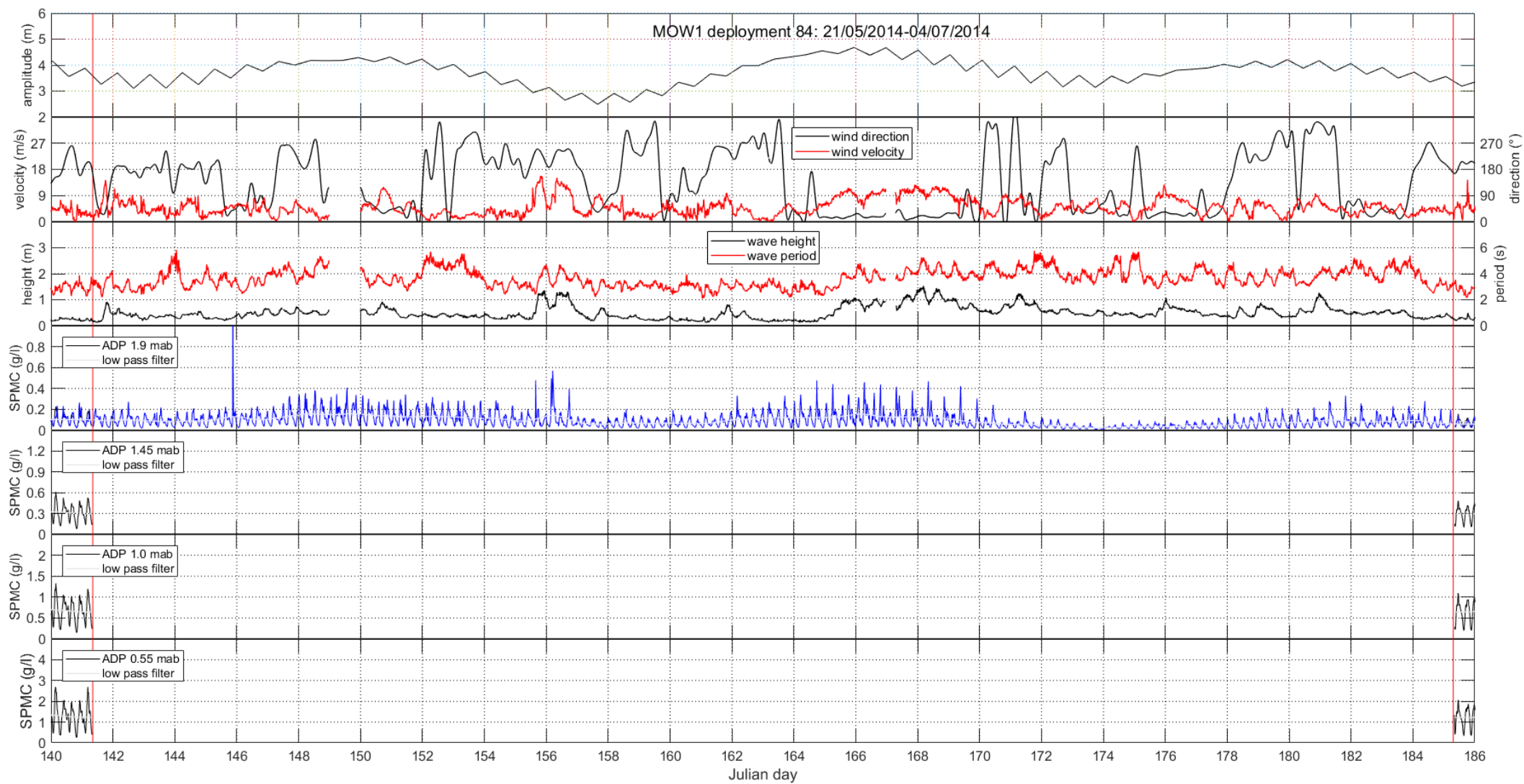
from up to down

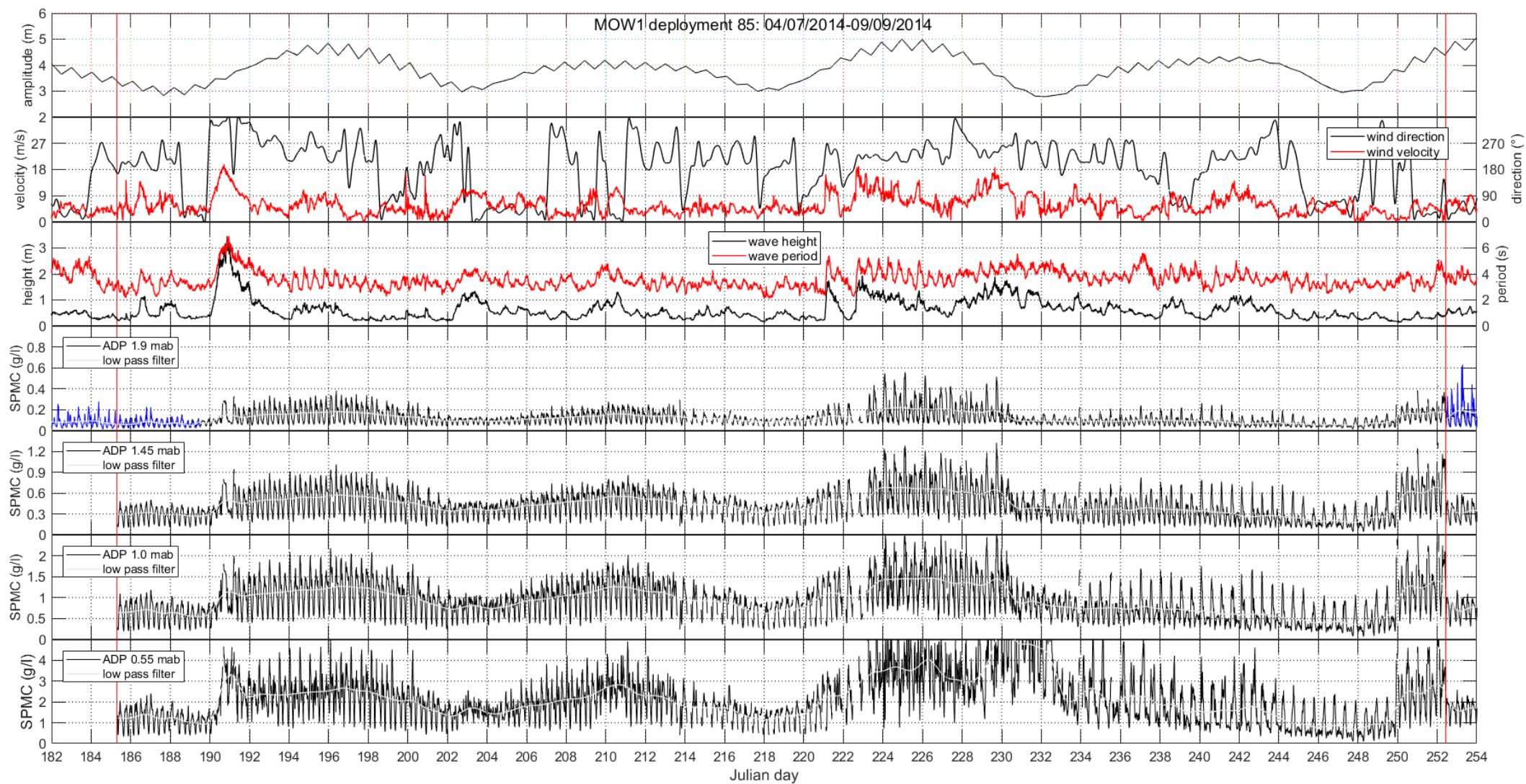
1. Harmonic tidal range at Zeebrugge
2. Wind direction and velocity at Wandelaar (Meetnet Vlaamse Banken)
3. Wave height and period at A2-buoy (Meetnet Vlaamse Banken)
4. SPM concentration at 1.95 mab (ADP and OBS)
5. SPM concentration at 1.45 mab
6. SPM concentration at 1.0 mab
7. SPM concentration at 0.55 mab

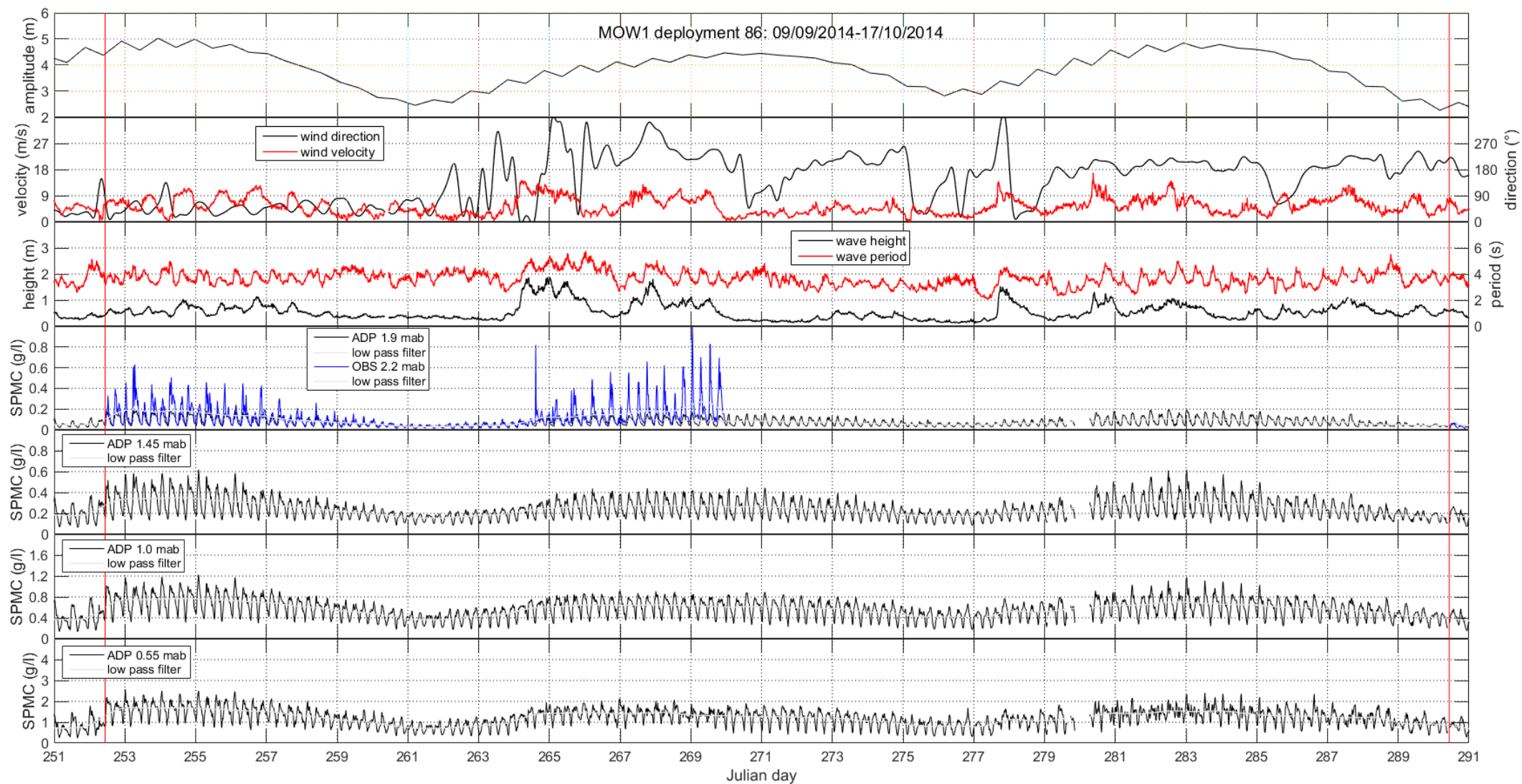


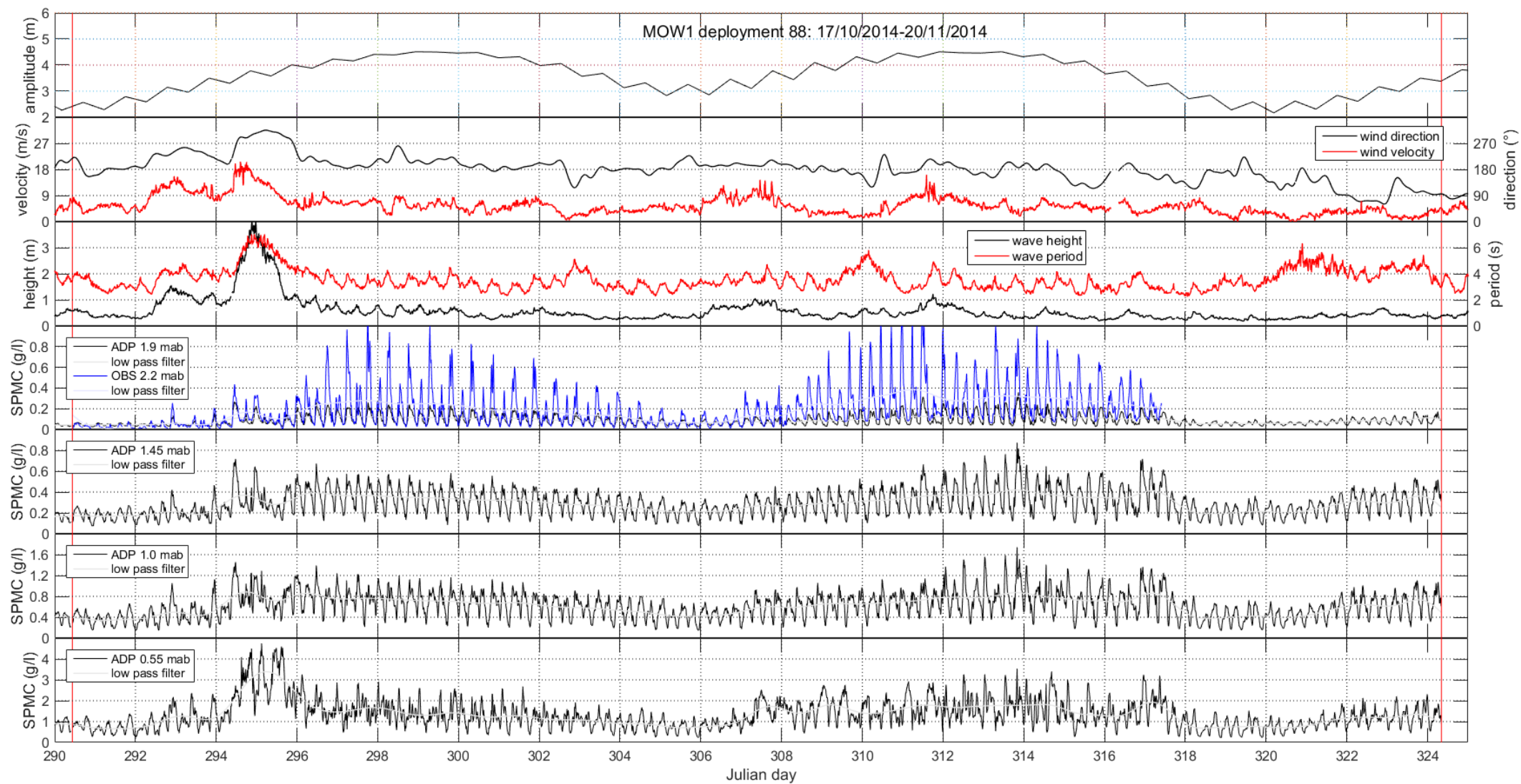


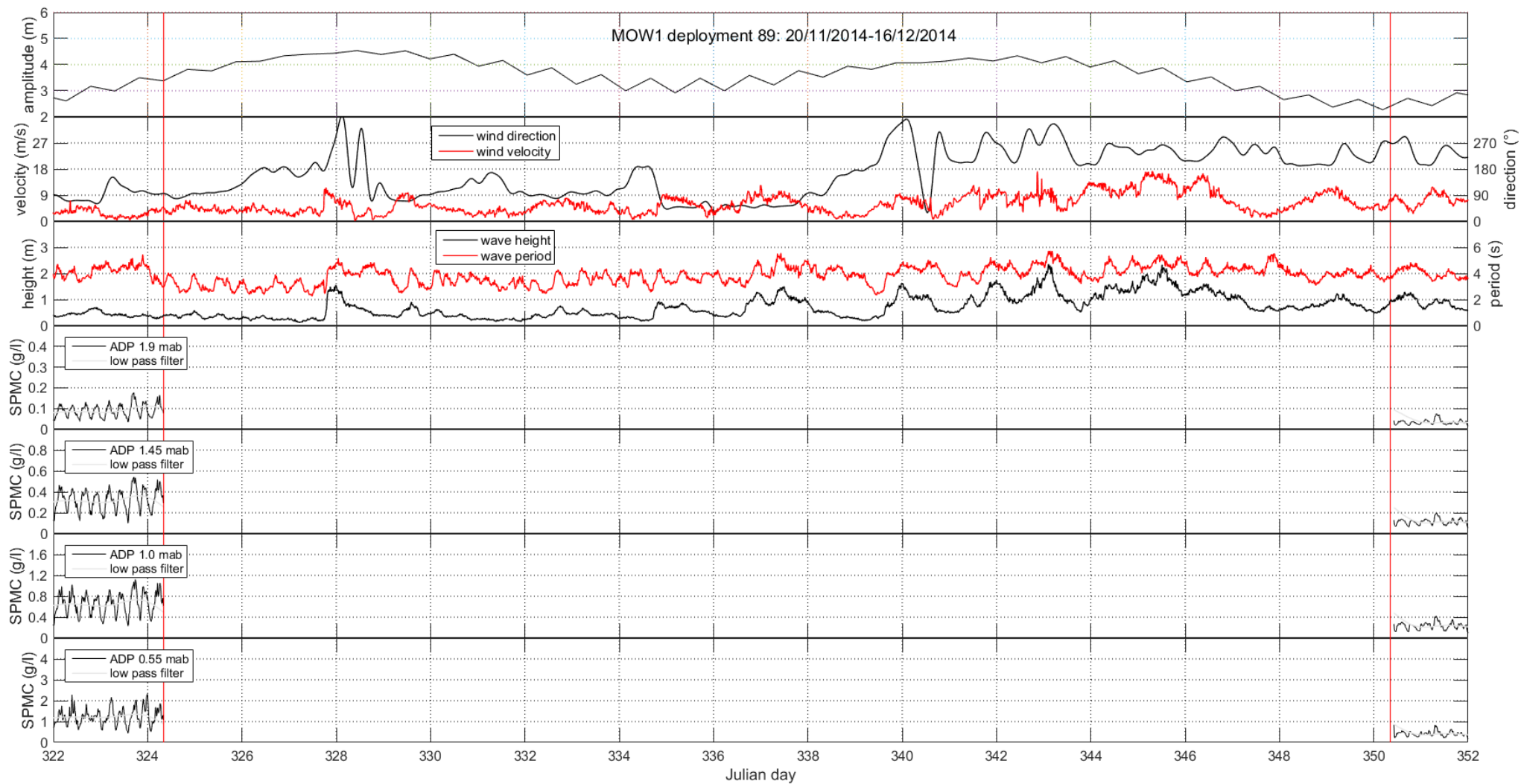


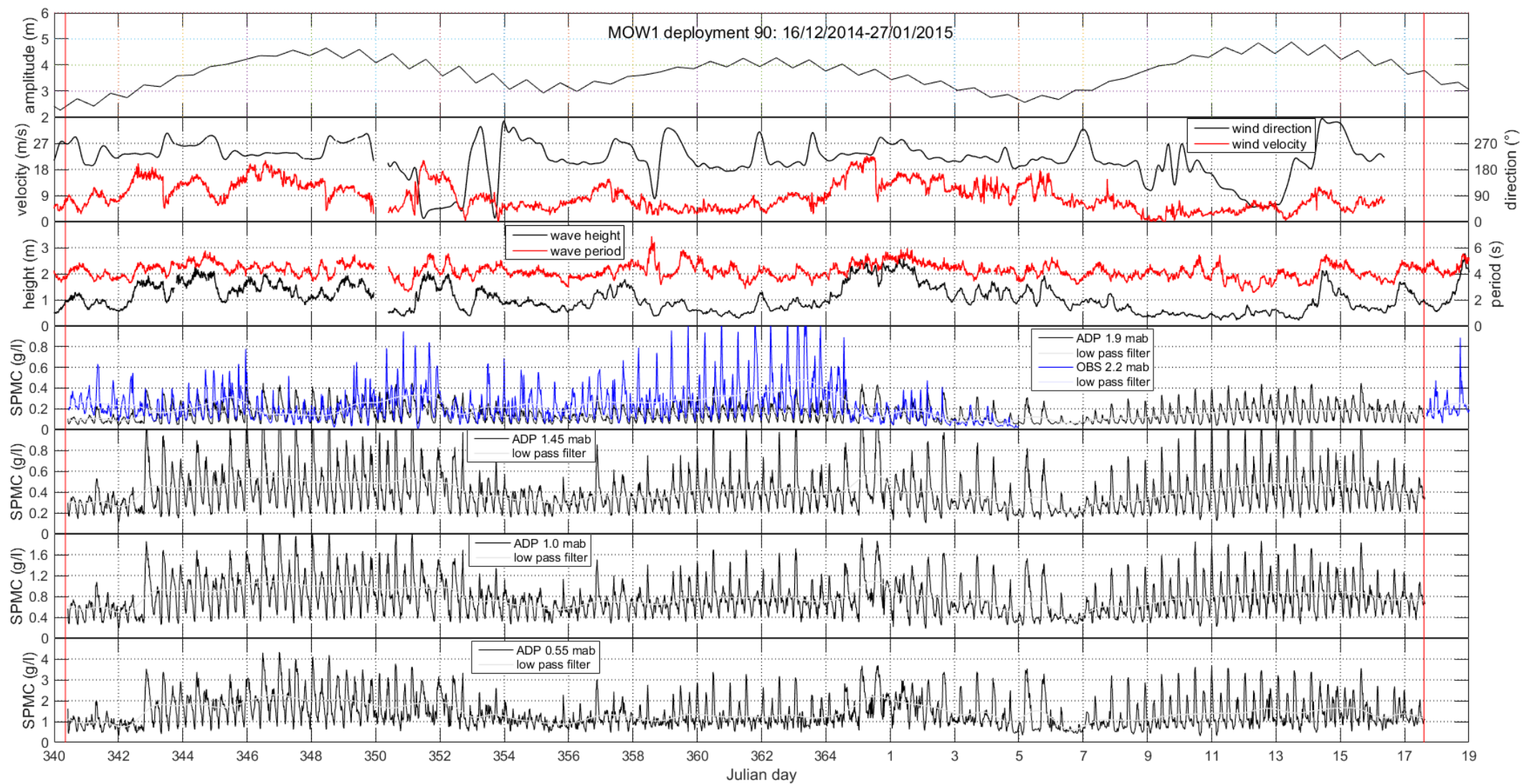


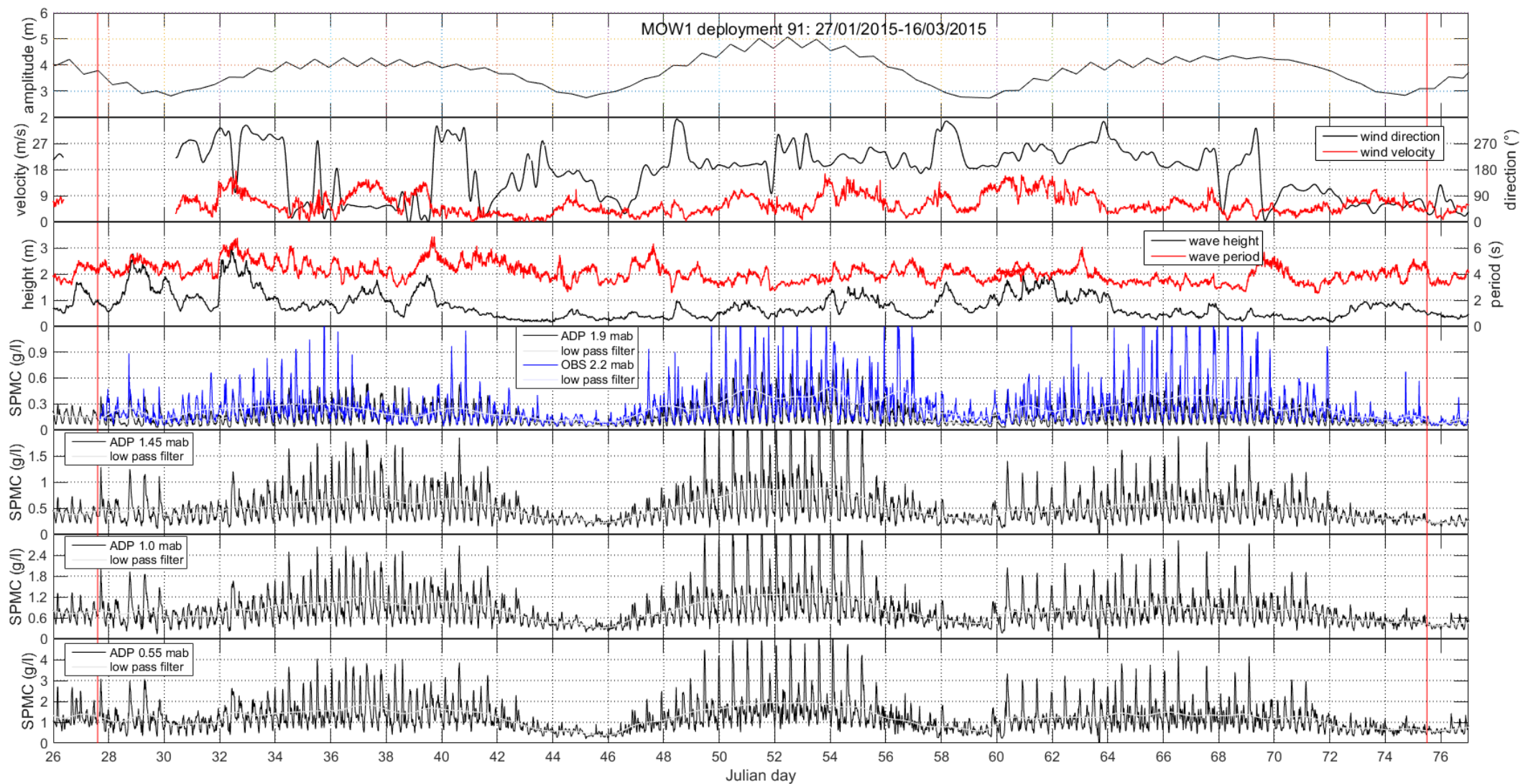


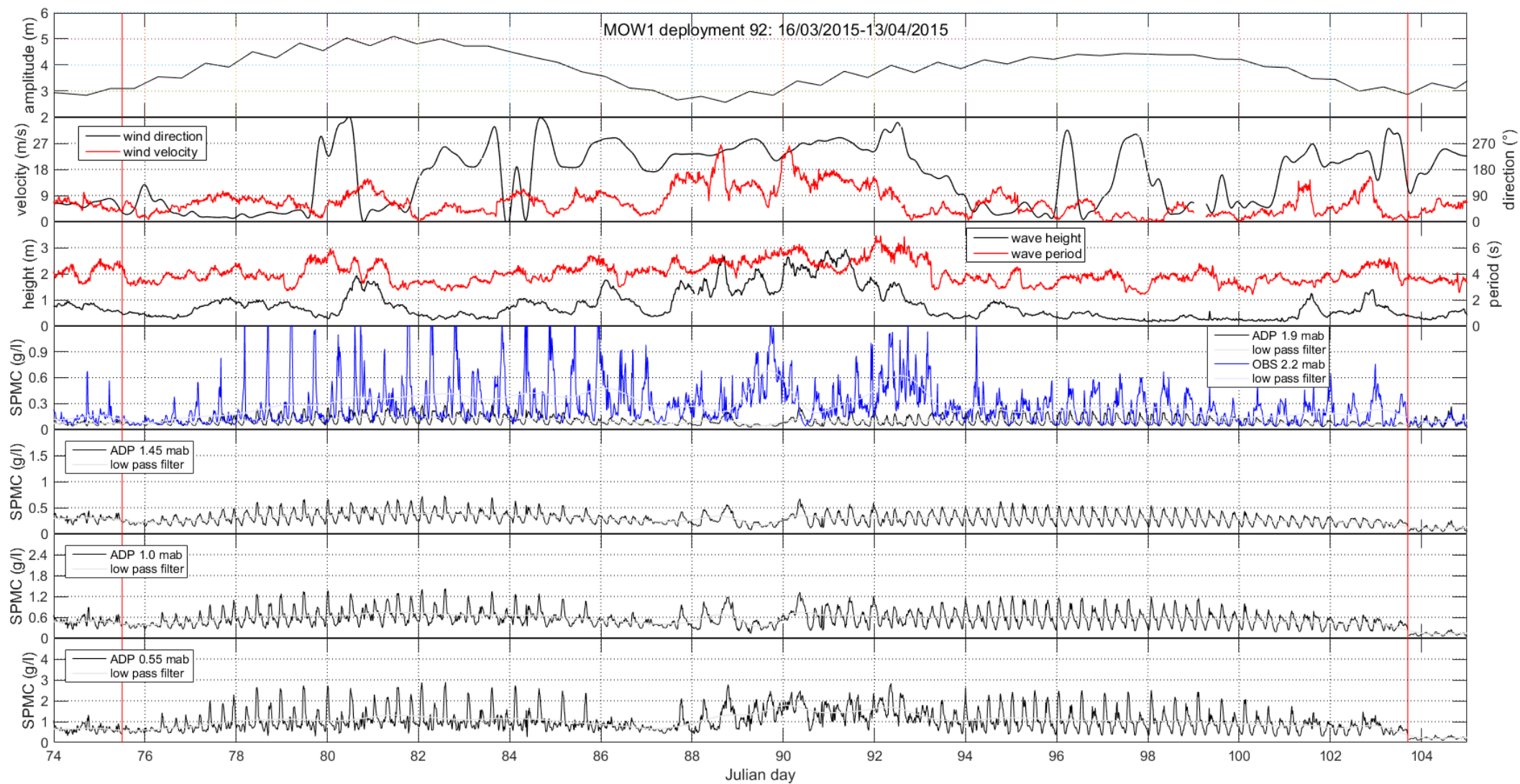


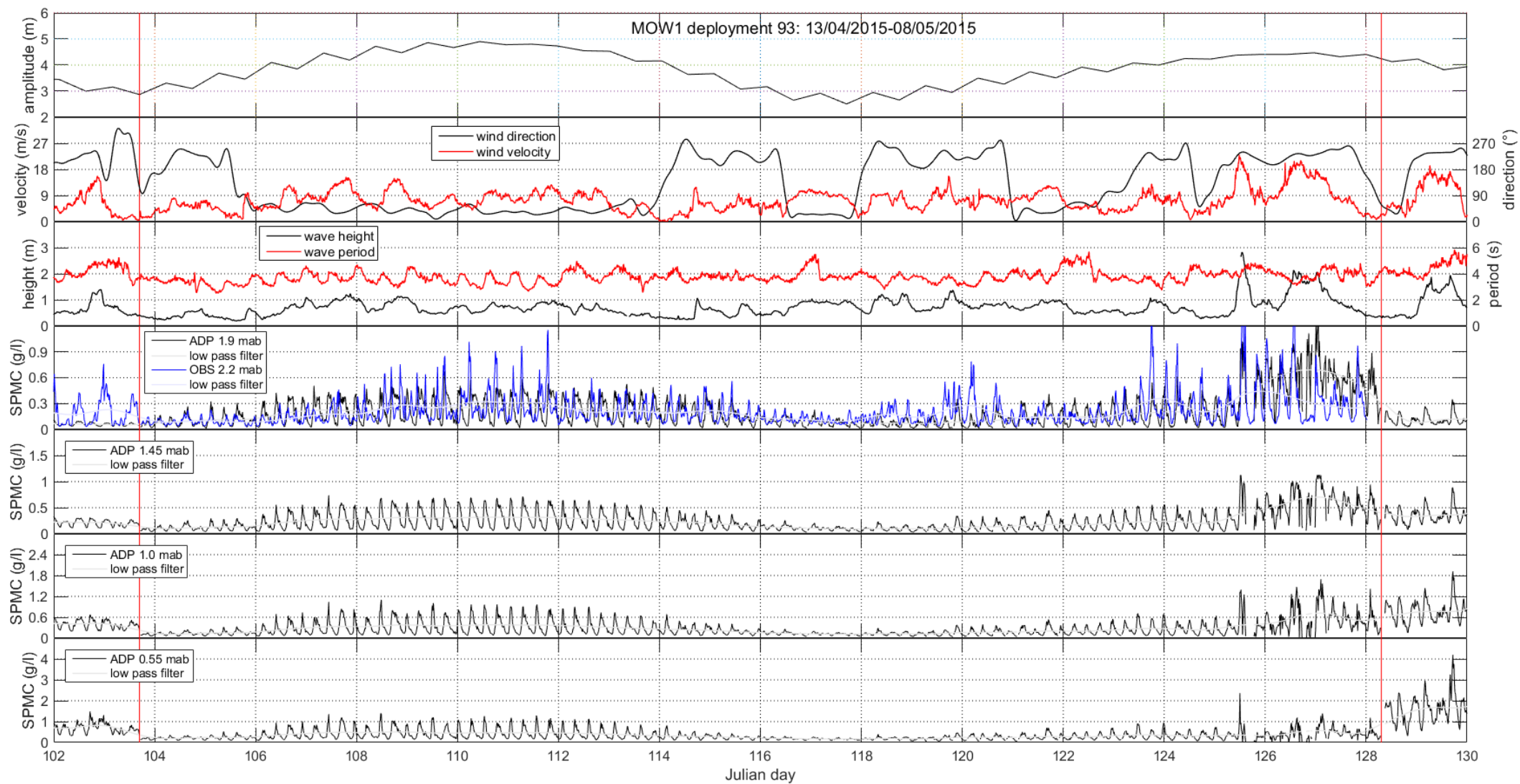


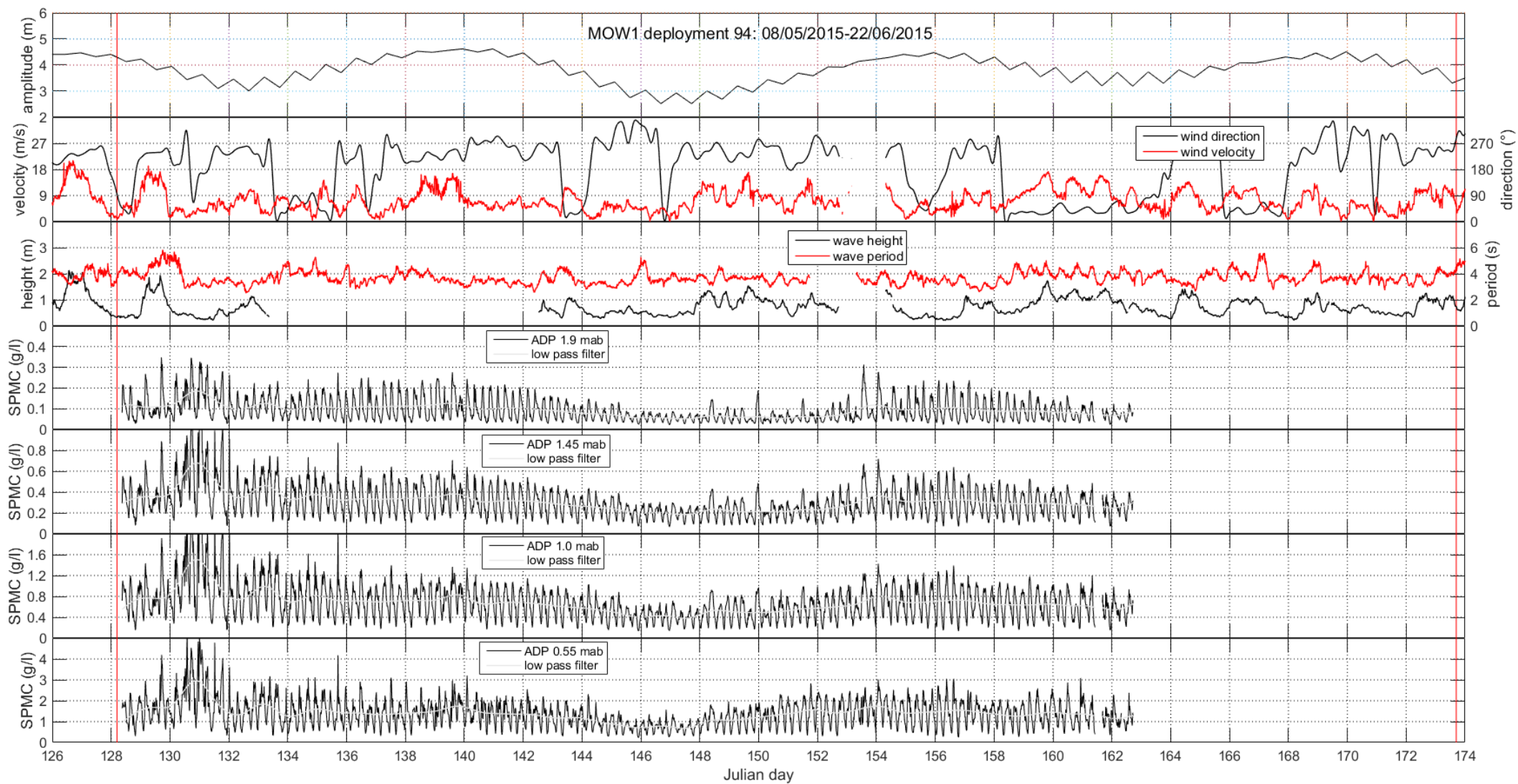


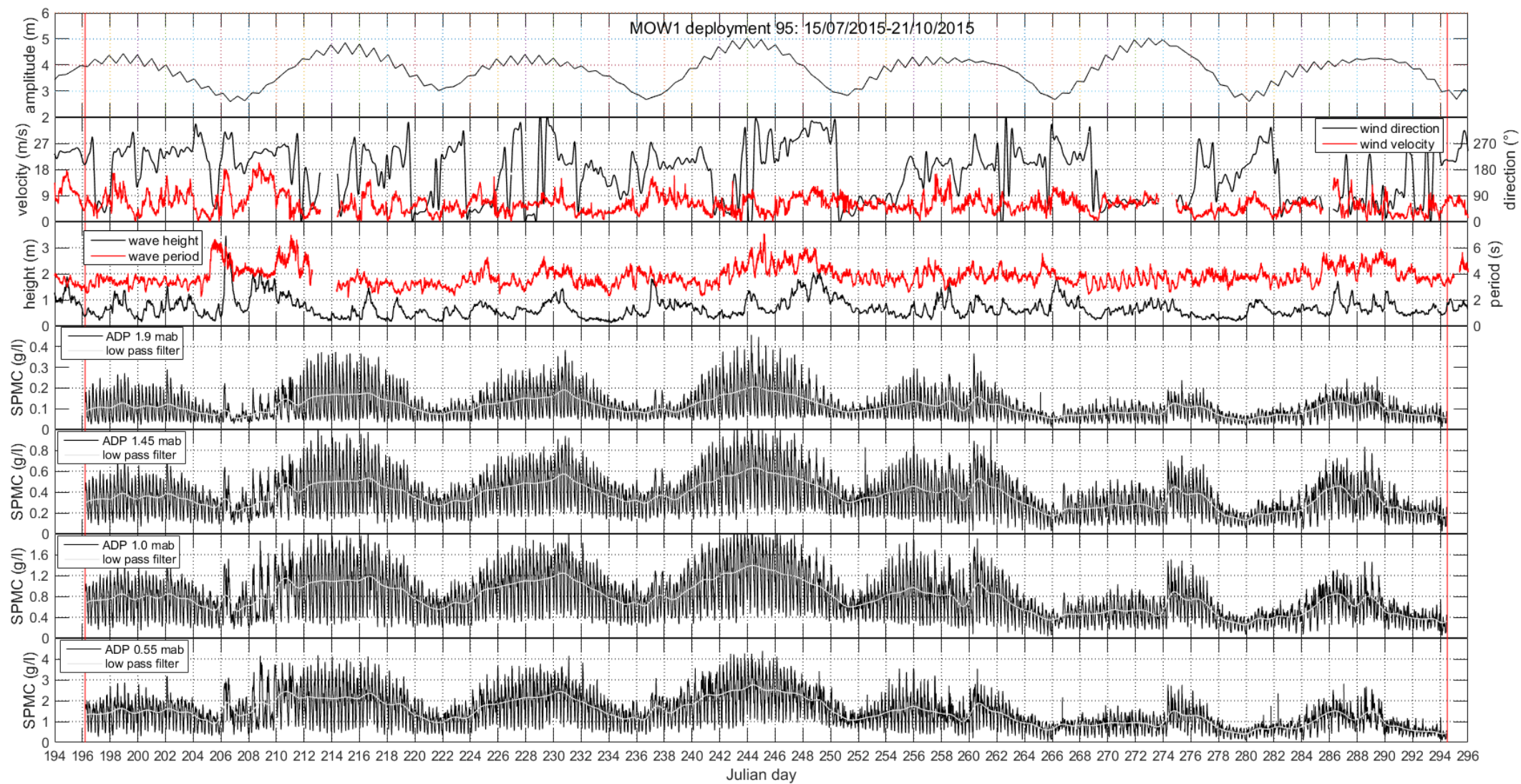


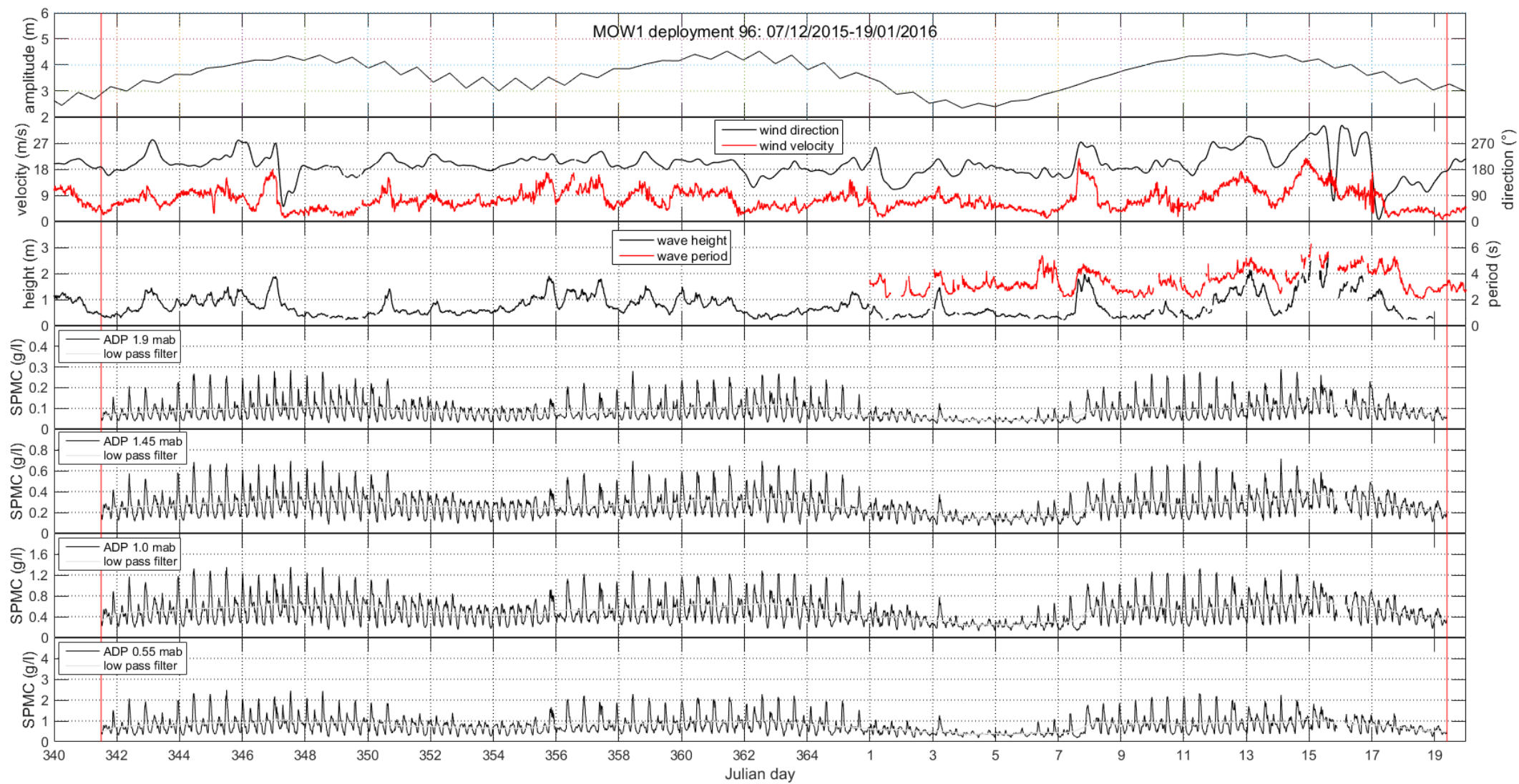












APPENDIX 3

Bijdragen (abstract, poster)

ECSA Conference 'Coastal system in transition: from a natural to an anthropogenically modified state', 4-7 September 2016, Bremen (Germany)

Remote sensing of suspended particulate matter concentration, inter-comparison with surface buoy and tripod lander data

M Baeye¹, F Francken¹, M Fettweis¹

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The dynamics of suspended particulate matter (SPM) control processes such as sediment transport, deposition, resuspension, primary production and benthic communities. Automated tripods allow recording of continuous time series of SPM concentration (SPMC) near the bottom at specific sites and are the only method to detect the effects of storms at sea on the SPM dynamics. On the other hand, large synoptic scenes of surface SPM concentrations may be retrieved from satellites. Time series of in situ SPM concentration and satellite imagery (MODIS Aqua and Landsat 8 OLI) are valuable data sources for the analysis of suspended sediment transport in coastal areas. Still, shortcomings remain, with satellite imagery suffering from a low temporal resolution and only related to surface data, whilst in situ measurements have a limited spatial resolution. Both data can be combined when the vertical variation and the temporal SPM concentration heterogeneity are known. SPM concentration is measured near the seabed (tripods) and at the surface (remotely). The missing link is the in situ concentration at the surface that was tackled by using a sensor buoy measuring SPMC. This configuration increased the number of match-ups (satellite picture at the same time as in situ measurements), and allowed to establish a relation between surface SPMCs, measured in situ (buoy) and remotely (satellite) on one hand, and between the in situ measured SPMCs at the surface (buoy) and near the bottom (tripod) on the other hand. The overall conclusion of the first trials is that an optical backscatter sensor instrumented on a surface buoy is a valuable tool towards better understanding the temporal (and also the spatial) SPM dynamics in the high-turbidity area in front of the Belgian coast.

Remote sensing of suspended particulate matter concentration (SPMC) - inter-comparison with surface buoy and tripod lander data

Matthias Baeye, F. Francken, M. Fettweis

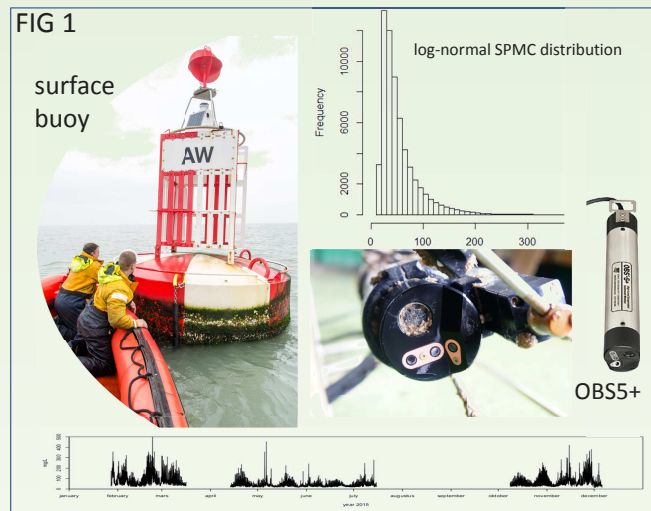
From in-situ measurements (both tripod lander and surface buoy) SPM dynamics reveal a well-known semi-diurnal signal of higher and lower SPMC during increased and decreased current speeds resp. (FIG 2). This cycle is superimposed on the overall spring (higher SPMC background) – neap (lower SPMC background) lunar cycle (see FIG 1, bottom graph). The seasonal changes in the surface SPMC are likely due to the organic matter content that is higher in spring-summer causing SPM flocs to grow (macroflocs) and deposit massively (Fettweis et al. 2014).

In this study, we wanted to investigate

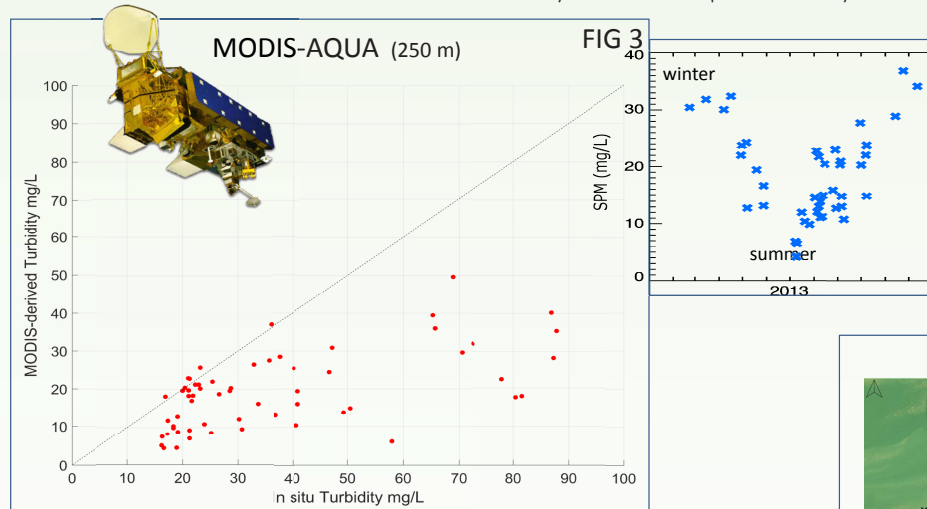
- 1) the accuracy of the match-ups between in-situ and satellite data,
- 2) how well satellite derived SPMC data compare with in-situ SPMC and
- 3) the spatial variability in SPMC in satellite images vs. the temporal buoy SPMC variability.

Surface buoy measurements with a OBS5+ turbidity meter were realised at about 6 km off the Belgian coast (FIG 2). The sensor is Campbell Sc. OBS5+ with laser wavelength of 780 nm, scattering angles between 105 and 165° and a necessary anti-fouling wiper. Collected data were quality checked and published at PANGAEA.

Just south of the buoy, a **tripod lander** was deployed for measuring the daily fine sediment dynamics. As a result of the waterdepth between 10 and 14 m, surface SPMC peaks occur 2 hours later compared to the SPMC peaks near the bed.



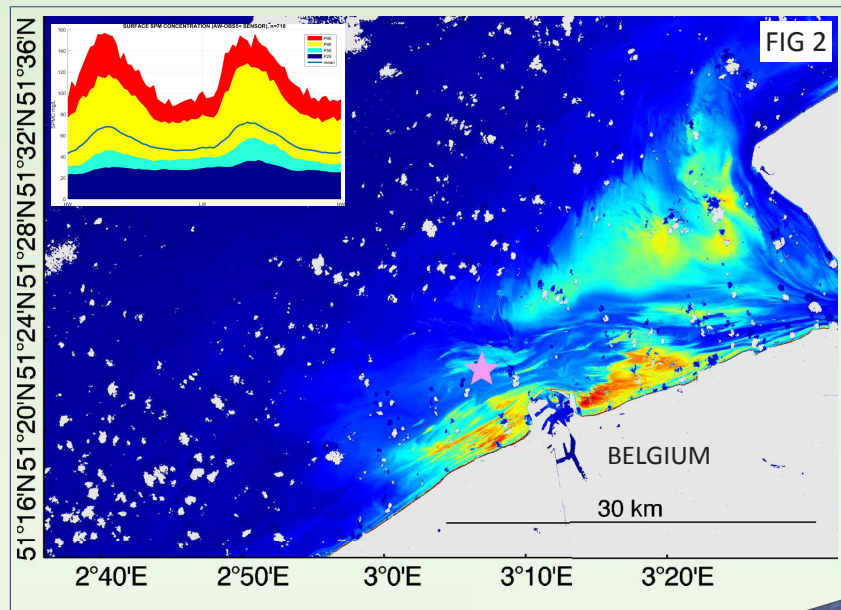
For both **MODIS-AQUA** (FIG 3) and **LANDSAT 8 OLI** (FIG 4), there is a significant amount of match-up points lying under the 1:1 line implying OBS5+ derived SPMC being higher (2 to 4 times) than the satellite derived SPMC. For the lower LANDSAT 8 OLI SPMC values (i.e. 50% of the match-ups), a good fit was found as a result of the much better spatial resolution. Due to the high spatial variability (see FIG 2) and the increased spatial resolution of nowadays satellite sensors, the precise location of the in-situ surface SPMC measurements therefore is a real MUST. In this study an ARDUINO GPS kept track of the buoy's location.



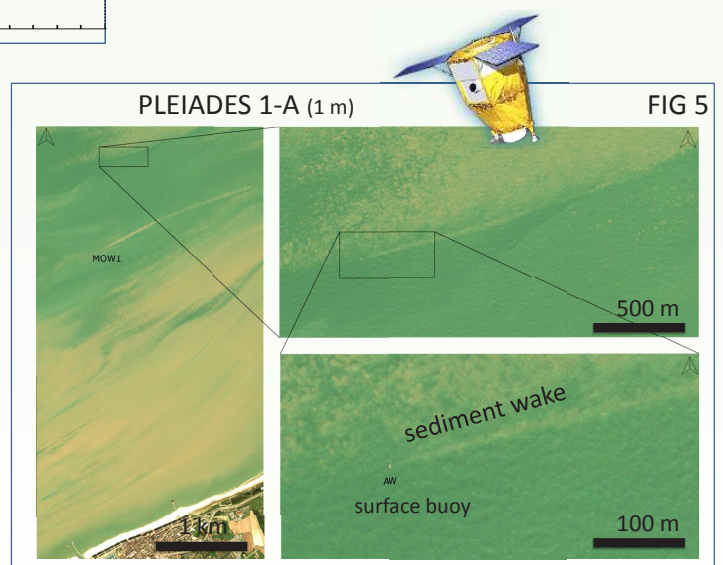
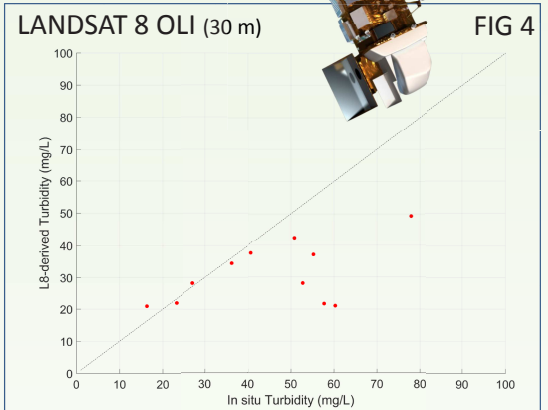
A likely explanation for the bad fit between the different data sources is the often increased SPMC at the location of buoy. The so-called **sediment wake** that typically aligns to the current downstream during full current. The origin of these wakes is likely to be the buoy anchorage concrete blocks and chain. This immediately raises the question if the surface buoy and the attached OBS5+ sensor are directly present in this wake effect? (see FIG 5)

This phenomenon of sediment wakes has already been observed associated to offshore wind turbines (Baeye and Fettweis 2015, Vanhellemont and Ruddick 2014), measuring piles, oil rigs, and even submerged shipwrecks (Baeye and Fettweis 2016). It explains why sometimes - under full current speeds - the match between SPMC from the OBS5+ and the LANDSAT 8 OLI is bad, especially for the higher range SPM concentrations. Both MODIS-AQUA and LANDSAT 8 OLI are not able to capture this small-scale process, and consequently these sediment plumes will be averaged out in the associated MODIS-AQUA and LANDSAT 8 OLI pixels. SPMC maps derived from PLEIADES is work in progress but first results already correspond with sediment wake concentrations of about 4 times the surrounding concentrations (pers. comm. Q. Vanhellemont), confirming the above-mentioned findings.

Baeye and Fettweis 2015. In situ observations of suspended particulate matter plumes at an offshore wind farm, southern North Sea. *Geo-Marine Letters* 35(4): 247-255.
Baeye and Fettweis 2016. Detection of shipwrecks in ocean colour satellite imagery. *Journal of Archaeological Science* 66: 1-6.
Fettweis, Baeye, Van der Zande, Van den Eynde and Lee 2014. Seasonality of flocc strength in the southern North Sea. *Journal of Geophysical Research* 119(3): 1911-1926.
Vanhellemont and Ruddick 2015. Turbid wakes associated with offshore wind turbines observed with Landsat 8. *Remote Sensing of Environment* 145: 105-115.



From space, images and corresponding SPMC maps show that the spatial variability is large, with a decreasing SPMC gradient offshore. The high-turbidity area along the BE coast is a consequence of the local hydrodynamics, the presence of the W-Scheldt river, the erosion of outcropping clay layers, ...



SPM concentration measurements in low and high turbulent conditions

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In nearshore areas turbulence and suspended particulate matter (SPM) concentration vary considerably during a tide. During low turbulence aggregation dominates over floc break-up, resulting in larger flocs and rapid settling of the SPM. During high turbulence, the flocs are breaking-up and the resuspended fine-grained material is mixed throughout the water column. These tidal variations are associated with changes in SPM composition from more organic rich during low to more mineral rich during high turbulence regimes. These changes in composition of the SPM may induce uncertainties when converting the observed optical and acoustical backscatter signals to SPM concentration.

In order to investigate how optical and acoustical sensors react to variations in composition measurements inside and outside the port of Zeebrugge have been carried out. Tidal harbors situated in dynamic and turbid coastal zones have gradients in turbulence ranging from high outside to very low conditions inside the port. They are thus a field laboratory to study the effect of turbulence on SPM concentration. The measurements consisted of ADCP transect from outside towards inside the port and of vertical profiling using CTD, OBS and a LISST 100X at 2 stations inside and one outside the port. Water samples have been taken in the profiling stations to determine SPM, POC and Chl-A concentration. The SPM that enters the harbor is quickly settling within the first hundreds of meters, resulting in a rapid decrease of the SPM concentration inside the harbor. The SPM inside the harbor consist of the slow settling particles and flocs that affects the acoustic and optic backscatter signals.

On best-practice for long-term observations of total suspended particulate matter

Rolf Riethmüller¹, Michael Fettweis² and Romaric Verney³

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Measurement of suspended particulate matter concentration (SPMC) spanning long time and large geographical scales became a matter of growing importance in the last two decades. Worldwide numerous observation platforms were installed to capture temporal and spatial variability from turbulent regimes to decades, from local scales to whole basins. Direct (samples) or indirect (optical and acoustic sensors) measurements of SPMC are inherently associated with a number of uncertainties along the whole operation chain from laboratory work over mostly unsupervised long-term deployments to final conversion of the observed continuous optical and acoustical proxy values to SPMC. When observation comprises systems of numerous sensors, minimisation of methodological inconsistencies and control of uncertainties in each step become a critical issue to achieve unambiguous statistical significance to detect events and trends in long-term data or to separate anthropogenic impact from natural variations. Despite several years of practical experience in a number of institutions with systems operating in highly dynamic and productive coastal ocean environments, proper comprehensive and agreed operational guidelines have not been formulated so far. To collect knowledge on potentials and limitations of present practice, more than 20 experts from science to management institutions of four West-European countries gathered for a two-day workshop in February this year. As an outcome a number of recommendations were formulated that shall be published as a basis to acquire best quality-assured SPMC data sets obeying procedures put forward by the expert group. On the basis of examples we will illustrate main sources of uncertainties, e.g. variabilities in optical or acoustical properties of the suspended particles, biofouling in connection with limited accessibility to the observational sites, or different regression models. Further we will present means to quantify and reduce their ranges and a set of recommendations for suitable protocols.

APPENDIX 4

Bijdrage (abstract, poster)

ICES Annual Science Conference, 19-23 September 2016, Riga (Latvia)

ICES CM 2016 / Session O: “When is enough, enough?” Methods for optimising, evaluating, and prioritising of marine data collection

Rolf Riethmüller, Michael Fettweis and Romaric Verney

Best-practice for long-term observations of total suspended particulate matter in coastal marine environments

Total suspended matter concentration (SPMC) is a key parameter to assess the status of and impacts to marine environments. To capture its high variabilities over long time periods numerous observation platforms were being installed worldwide to identify and predict changes induced by e.g. human activities. They combine direct (samples) with indirect (optical and acoustic sensors) measurements of SPMC. The long-term operations are inherently associated with uncertainties along the whole operation chain from in situ calibration of the sensors, laboratory work, mostly unsupervised long-term deployments to final sensor output conversion. Knowledge of these uncertainties are needed to obtain validated time series that can be used for direct (e.g. trend lines, moving averages) or indirect predictions (e.g. validated numerical models) of the environmental status. Despite several years of practical experience with systems operating in highly dynamic and productive coastal ocean environments, proper comprehensive and agreed operational guidelines have not been formulated so far. International guidelines exist only for water sample data but not for the usage of indirect systems. To collect knowledge on potentials and limitations of present practice, more than 20 international experts gathered for a two-day workshop in February this year. As an outcome a number of recommendations were formulated that shall be published as a basis to acquire best quality-assured SPMC data sets obeying procedures put forward by the expert group. On the basis of examples we will illustrate main sources of uncertainties, present means to quantify and reduce their ranges, and a set of recommendations for suitable protocols.

Keywords: monitoring methodology, suspended particulate matter, turbidity, long-term time series

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On best-practice for long-term observations of total suspended particulate matter (SPMC)

Rolf Riethmüller¹, M. Fettweis², R. Verney³, J. Backers, M. Baeye, M. Becker, M. Chapalain, S. Claeys, J. Claus, D. Depreitere, J. Deloffre, G. Flöser, S. Grünler, F. Jourdin, R. Lafitte, J. Nauw, B. Nechad, R. Röttgers, A. Sottolichio, W. Vanhaverbeke, T. van Hoestenberge, H. Vereecken

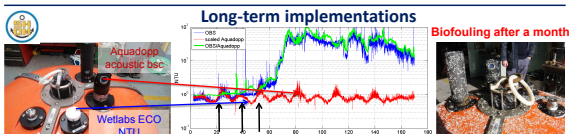


Challenges with long-term and large-scale SPMC observations

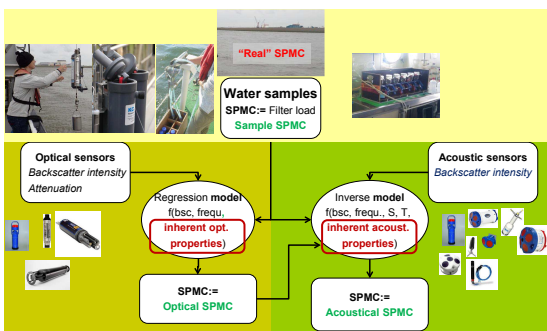
- Involvement of numerous platforms, sensors, procedures
- Preservation of data homogeneity and accuracy under harsh and variable environmental conditions.

Integrated Coastal Ocean Observing Systems

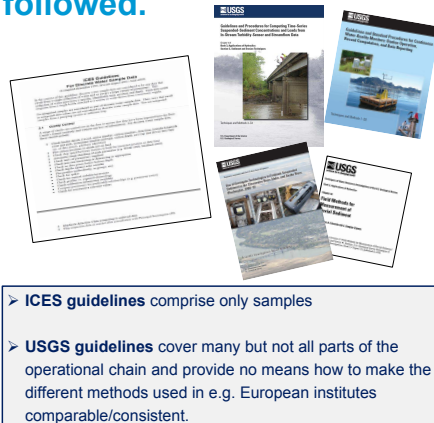
Example: COSYNA



Integration of several SPMC surrogates



Existing guidelines are incomplete & not commonly followed.



- ICES guidelines comprise only samples
- USGS guidelines cover many but not all parts of the operational chain and provide no means how to make the different methods used in e.g. European institutes comparable/consistent.

Expert workshop



Brussels Feb 2016

- How reliable or consistent are *in-situ* SPMC data
 - over time
 - from local to European scales?
- What do we know about errors/uncertainties: sources and magnitudes?
- What is present practice in authorities, research institutions and companies?

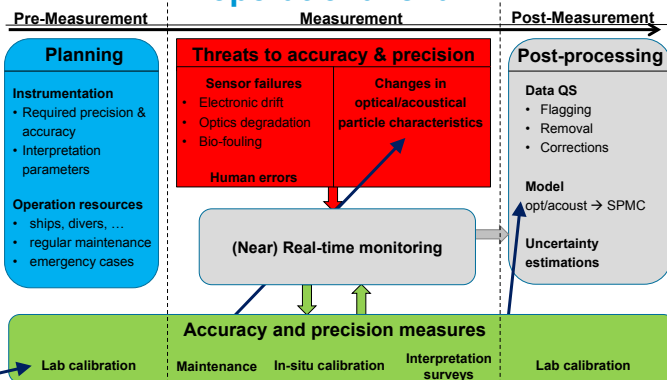
Objectives

- inform about practice, success and failures
- discuss error sources & magnitudes of all processing steps
- contribute to the development of international standards.
- lay the basis and procedures to publish data as DOI

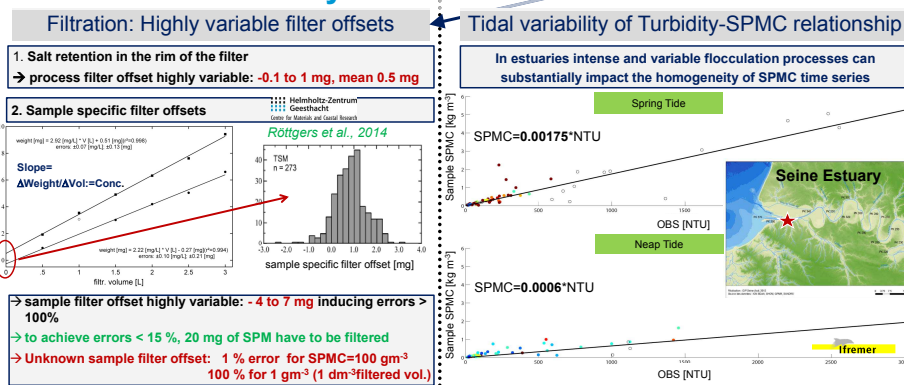
& remote operation



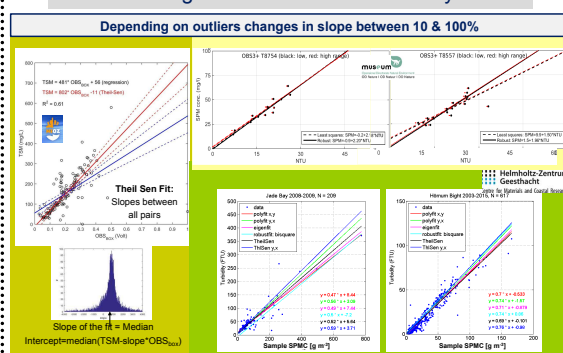
demand a complex and work-intensive operational chain



This results in hardly controllable errors & uncertainties

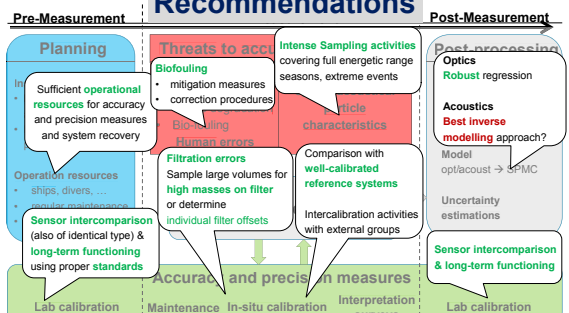


Examples



Towards best practice:

Recommendations



Joint publication

- Errors and uncertainties & Comprehensive protocol along the operation chain
- Quantification & hierarchy of errors
- Required actions towards harmonised SPMC measurements in estuarine and coastal waters

EMODnet will require consistent, quality assured and well documented data sets



SPMC as an EMODNET parameter will and has to come!

APPENDIX 5

Bijdrage (abstract)

Particles in Europe, 3-5 October 2016, Budapest (Hungary).

SPM concentration measurements in low and high turbulent conditions

Michael Fettweis and Matthias Baeye

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In nearshore areas turbulence and suspended particulate matter (SPM) concentration vary considerably during a tide. During low turbulence aggregation dominates over floc break-up, resulting in larger flocs and rapid settling of the SPM. During high turbulence, the flocs are breaking-up, the resuspended fine-grained material is mixed throughout the water column, and SPM concentration increases. These tidal variations are associated with changes in SPM composition from more organic rich during low to more mineral rich during high turbulence regimes, see Figure 1. The hypothesis is that these changes in composition of the SPM may induce different reaction of acoustic and optical backscatter sensors and thus necessitates a different calibration.

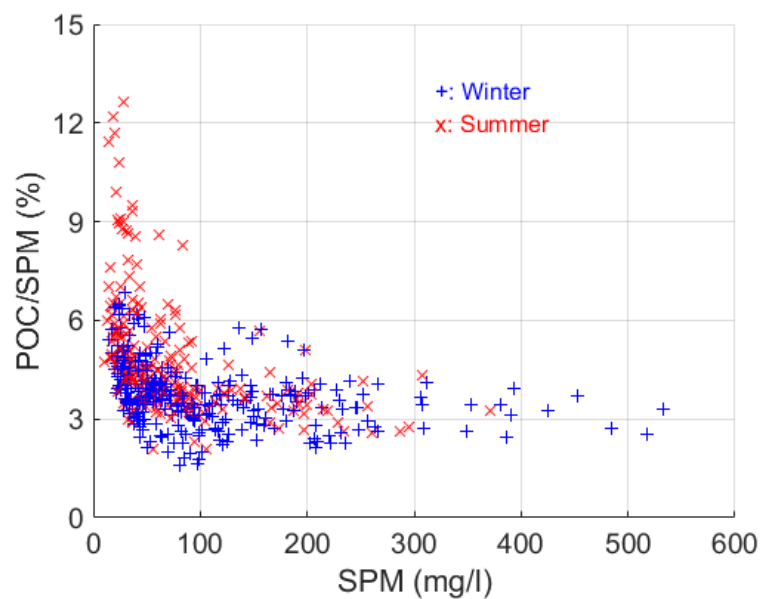


Fig. 1: Particulate Organic Carbon (POC) fraction in the SPM, Belgian nearshore area.

In order to investigate how these sensors react to variations in composition shipborne measurements inside and outside the port of Zeebrugge have been carried out, see Figure 2. Zeebrugge is a tidal harbor situated in dynamic and turbid coastal zones and has a gradient in turbulence and also SPM concentration ranging from high outside to low inside the port. The SPM that enters the harbor is quickly settling within the first hundreds of meters, resulting in a rapid decrease of the SPM concentration and as a consequence in siltation of the harbor.



Fig. 2: Aerial photo of the port of Zeebrugge with the three measuring station indicated. The water is more turbide (brownish color) outside the harbour than inside.

Tidal harbors can therefore be used as field laboratories to study the effect of turbulence and thus changes in SPM composition and size on the way OBS and acoustic backscatter sensor measure the particle concentration in the water. The measurements consisted of 300 kHz ADCP transect from outside towards inside the port and of vertical profiling using CTD, OBS and a LISST 100X at 2 stations inside and one outside the port during about 8 hours (from 2 h before LW until HW). Water samples have been taken near the bottom in the profiling stations to determine SPM, POC and Chl-A concentration. The optical instruments (OBS3+) and the ADCP backscatter were calibrated against the SPM concentration obtained from samples after filtration. A first result is shown in Figure 3, where the OBS3+ is calibrated against water samples inside and outside the port and in Figure 4 where the particle size distributions are shown in the different stations. As the number of samples is small, it is not yet possible to argue if the differences in calibration curve are due to inherent uncertainties of the procedure or to changes in composition and size of the SPM.

A similar calibration will be carried out with the ADCP backscatter. This work will be used to change or optimize the existing calibration protocols to obtain SPM concentration in mg/l from the OBS and acoustic backscatter sensors (ADP, ADV) used in our long-term stations near Zeebugee.

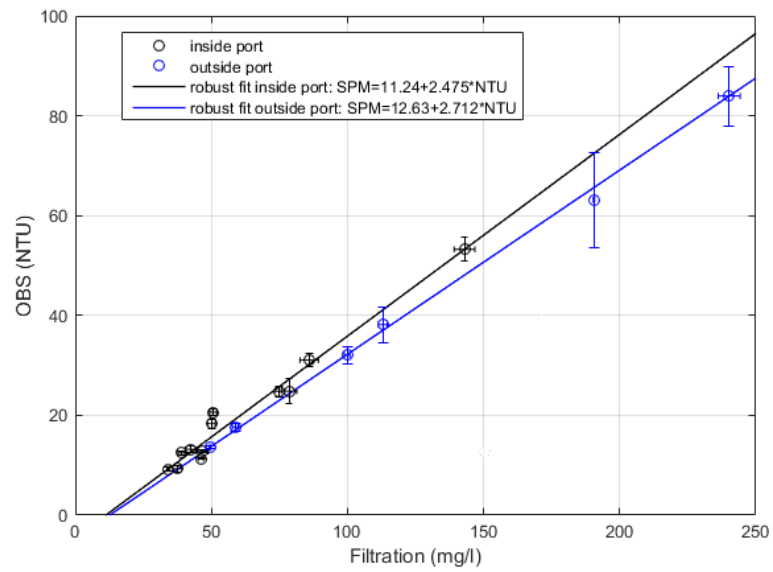


Fig. 3: Scatter plot of the OBS3+ output in NTU versus SPM concentration in mg/l obtained from water samples after filtration. The straight line fitted through the data indicates the calibration curve.

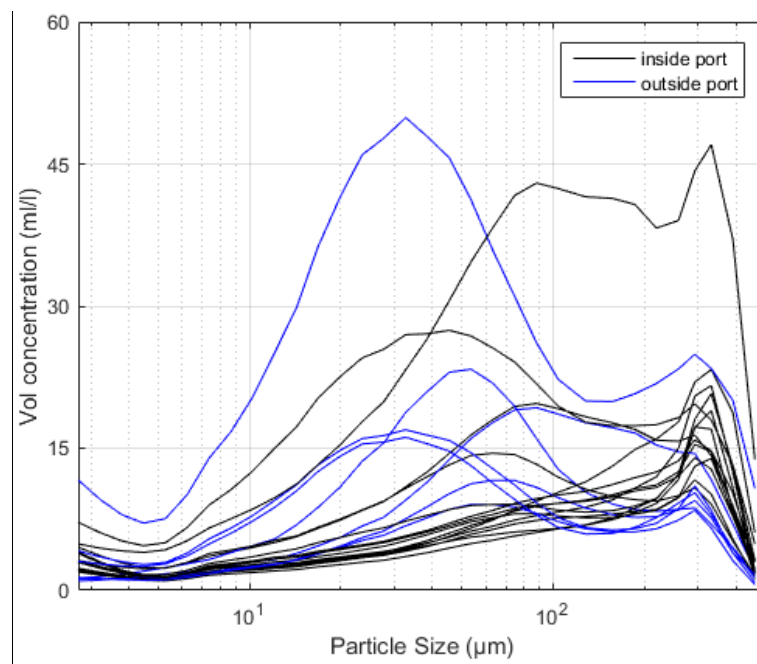


Fig. 4: Mean particle size distribution in and outside the port Zeebrugge during a vertical profile in the three measuring stations.

APPENDIX 6

Bijdrage (abstract)

North Sea Conference, 7-10 November, Ostend (Belgium)

Environmental impact assessment in line with the EU Nature Directives.

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The debate on a sustainable performance of human activities, need to be more objectively structured and scrutinized. For this, the assessment criteria developed under the EU Nature Directives (Marine Strategy Framework Directive (MSFD), Habitat Directive (HD, Water Framework Directive WFD)) can form the basis for a scientifically, more uniform environmental impact assessment (EIA). The list of criteria, funded by operational indicators allow a more objective assessment of the degree of impact on the marine ecosystem across human activities. A major obstacle is the variety of criteria between EU Directives, which is likely to be harmonized for Belgian waters. The achievability of such type of EIA is illustrated by the evaluation of the activity of disposal of dredged material at designated areas on the Belgian Part of the North Sea. Substantial dredging activities of mainly fine-grained material take place in the navigation channels and harbors throughout the year. The disposal of this dredged material has effects on the water surface, in the water column and on the seabed. These effects are followed up in a joint monitoring program and a periodical integrated assessment is made, which is now put in line with the MSFD requirements. 10 MSFD criteria/indicators out of the list of 50 used in Belgium have a clear relevance to this activity. Those relevant indicators are related to evaluation of the characteristics of the bottom fauna, chemical pollution and physical changes of the disposal areas. An integrated assessment is possible and easily visualized by means of a star diagram. Based on this information, the effect of the activity itself can be evaluated, monitoring optimized and operational limits for managing allocated. If such approach is applied to all human activities, we will have made a great step towards sustainable management of our marine ecosystem.

APPENDIX 7

Fettweis M, Baeye M, Cardoso C, Dujardin A, Lauwaerts B, Van den Eynde D, Van Hoestenbergh T, Vanlede J, Van Poucke L, Velez C, Martens C. 2016. The impact of disposal of fine grained sediments from maintenance dredging works on SPM concentration and fluid mud in and outside the harbor of Zeebrugge. *Ocean Dynamics*, 66, 1497–1516.

The impact of disposal of fine-grained sediments from maintenance dredging works on SPM concentration and fluid mud in and outside the harbor of Zeebrugge

Michael Fettweis¹ · Matthias Baeye¹ · Claudio Cardoso² · Arvid Dujardin^{2,3} ·
Brigitte Lauwaert¹ · Dries Van den Eynde¹ · Thomas Van Hoestenbergh^{2,4} ·
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Abstract The amount of sediments to be dredged and disposed depends to a large part on the suspended particulate matter (SPM) concentration. Tidal, meteorological, climatological, and seasonal forcings have an influence on the horizontal and vertical distribution of the SPM in the water column and on the bed and control the inflow of fine-grained sediments towards harbors and navigation channels. About 3 million tons (dry matter) per year of mainly fine-grained sediments is dredged in the port of Zeebrugge and is disposed on a nearby disposal site. The disposed sediments are quickly resuspended and transported away from the site. The hypothesis is that a significant part of the disposed sediments recirculates back to the dredging places and that a relocation of the disposal site to another location at equal distance to the dredging area would reduce this recirculation. In order to

validate the hypothesis, a 1-year field study was set up in 2013–2014. During 1 month, the dredged material was disposed at a new site. Variations in SPM concentration were related to tides, storms, seasonal changes, and human impacts. In the high-turbidity Belgian near-shore area, the natural forcings are responsible for the major variability in the SPM concentration signal, while disposal has only a smaller influence. The conclusion from the measurements is that the SPM concentration decreases after relocation of the disposal site but indicate stronger (first half of field experiment) or weaker (second half of field experiment) effects that are, however, supported by the environmental conditions. The results of the field study may have consequences on the management of disposal operations as the effectiveness of the disposal site depends on environmental conditions, which are inherently associated with chaotic behavior.

This article is part of the Topical Collection on the *13th International Conference on Cohesive Sediment Transport in Leuven, Belgium 7–11 September 2015*

Responsible Editor: Erik A. Toorman

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Keywords SPM concentration · Dredging and disposal operations · Long-term observational time series

1 Introduction

Dredging operations in coastal areas are essential in order to maintain channels and harbors navigable for large vessels. These deepened areas—often protected by breakwaters—are not in equilibrium with the hydrodynamics, and as a consequence, sediments are quickly accumulating after removal, demanding thus for almost continuous maintenance works. The amount of sediments to be dredged depends to a large part on the suspended particulate matter (SPM) concentration. SPM concentration is highly variable in coastal areas due to tidal, meteorological, climatological, and seasonal forcings (Fettweis and Baeye 2015). These forcings have an influence

on the horizontal and vertical distribution of the SPM in the water column and on the bed and control the inflow of fine-grained sediments towards harbors and navigation channels (Mehta 1991; van Ledden et al. 2004; Van Maren et al. 2009; Vanlede and Dujardin 2014; Wan et al. 2014). Further to the natural variability, dredging and disposal influence the SPM concentration in the near and far field due to the operations itself and due to dispersal, transport and buffering of the disposed fine sediments (Smith and Friedrichs 2011; Decrop et al. 2015; Van Maren et al. 2015). Massive sedimentation of fine-grained sediments in harbors and navigation channels is often related to the occurrence of fluid mud layers (Verlaan and Spanhoff 2000; Winterwerp 2005; Kirby 2011; Van Maren et al. 2009). Fluid mud may be formed by fluidization of cohesive sediment beds or by the quick settling of larger SPM flocs during slack water resulting in an increase of the near-bed SPM concentration and the formation of lutoclines (Mehta 1991; van Kessel and Kranenburg 1998; Li and Mehta 2000; Becker et al. 2013). The particle-turbulence interactions and the stratification-induced turbulence damping contribute to the formation and stability of these layers (Le Hir et al. 2000; Toorman 2002; Winterwerp 2006).

The potential effects of the disposal of fine-grained sediments are relatively well described with respect to environmental issues, such as alteration of benthic and pelagic communities, decrease of water clarity, dispersion of pollutants and nutrients, and changing bathymetry and hydrodynamic processes (Smith and Rule 2001; Stronkhorst et al. 2003; Orpin et al. 2004; Simonini et al. 2005; Bolam et al. 2006; Du Four and Van Lancker 2008; Okada et al. 2009; Stockmann et al. 2009; Fettweis et al. 2011; Agunwamba et al. 2012; Bolam 2012; van Maren et al. 2015). Relatively less attention has been paid to the effect of disposal of fine-grained material on the dredging works itself (e.g., Kapsimalis et al. 2013). Depending on the location of the disposal site, significant amounts of the disposed matter may recirculate in suspension or as high concentrated benthic layers back to the dredging areas, increasing thus the volume to be dredged and disposed. A smart relocation of the disposal site that does not induce recirculation is a straight-forward way to decrease dredging volumes, costs, and environmental impact. In order to evaluate the impact of a relocation of disposal site in highly dynamic and turbid areas, continuous measuring stations are mandatory. With increasing implementation of long-term monitoring stations, an understanding of variations and short-term impacts became possible (e.g., Badewien et al. 2009; Garel and Ferreira 2011; Fettweis et al. 2011; Henson 2014; Jalón-Rojas et al. 2015).

The harbor of Zeebrugge, situated in the coastal turbidity maximum area along the Belgian coast (southern North Sea), is subject to high siltation rates and, as a result, huge maintenance dredging and disposal works are mandatory (Fettweis et al. 2011). The focus of the present study emerged from

numerical model results that have indicated that part of the disposed sediments quickly returned back to the dredging areas and that the mass to be dredged could be decreased by relocating the disposal site (Van den Eynde and Fettweis 2006). In the framework of studies conducted by the Flemish Ministry of Public Works and Mobility to reduce dredging costs, a 1-year field study was set up to validate the model results with in situ data. The field study consisted of 11 months “business as usual,” i.e., disposing of the dredged material on the existing disposal site and of a 1-month period where an alternative disposal site without recirculation was used. An extensive monitoring campaign was set up during the field study which consisted of measurements in and outside the harbor of Zeebrugge of various oceanographic, meteorological, and sediment parameters (SPM concentration, current velocity, waves, salinity, temperature, tides, wind, bathymetry, density of mud layers) in order to estimate the impact of the relocation of the disposal site on the SPM concentration and on the fluid mud dynamics in and outside the harbor of Zeebrugge. A key element in the analysis is the use of environmental parameters that allowed establishing a representative baseline encompassing the major actors (tides, wind, waves) responsible for variabilities in SPM concentration and fluid mud thickness, as well as human activities such as ship maneuvering and dredging/disposal works.

2 The study site

The harbor of Zeebrugge is situated in the Southern Bight of the North Sea at the marine limit of influence of the Westerscheldt estuary (see Fig. 1). The relatively well-protected Southern Bight is mainly tidally dominated as compared with other shallow areas in the North Sea where wave influences are more pronounced (Fettweis et al. 2012b). The tides are semidiurnal and the mean tidal amplitude is about 3.6 m. The nearshore tidal current ellipses are elongated and vary on average between 0.2 and 0.8 m/s during spring tide and 0.2 and 0.5 m/s during neap tide at 2 m above the bed. The strong tidal currents and the low freshwater discharges result in a well-mixed water column. Slack water occurs around 3 h before and 3 h after high water (HW). Ebb (about 3 h after HW until about 3 h before HW) is directed towards the southwest (SW) and flood towards the northeast (NE). Maximum currents occur during flood around 1 h before HW; the peak currents during ebb are slightly lower and occur around LW. Southwesterly winds dominate the overall wind climate, followed by winds from the NE sector. Maximum wind speeds coincide with southwesterly winds; nevertheless, the highest waves are generated under northwesterly winds, due to a longer fetch. The waves have generally a period of about 4 s, lower frequency swell waves with a period of about 6 s are less abundant. The median significant wave height is 0.6 m

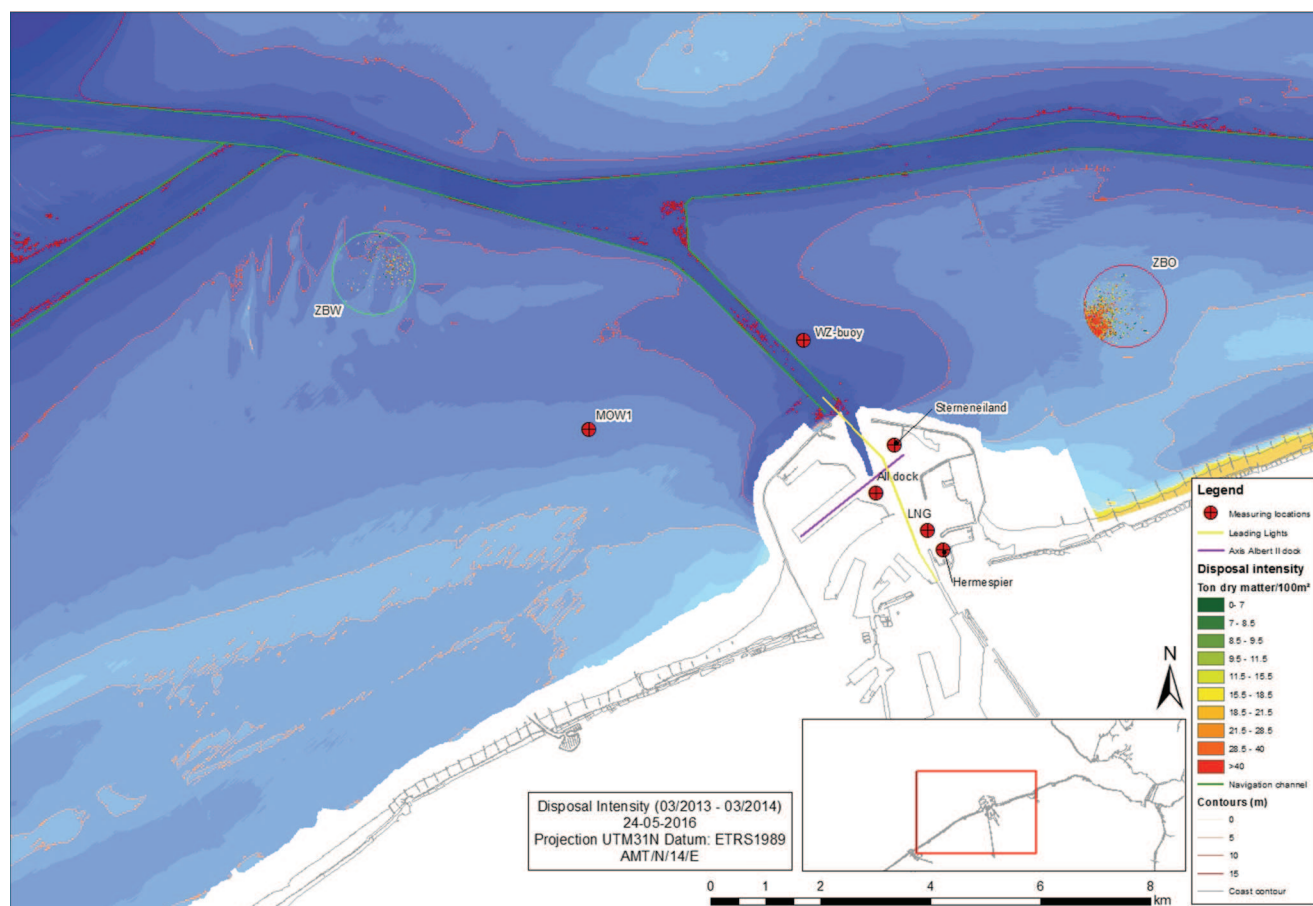


Fig. 1 Map of the Belgian coastal area (southern North Sea) showing the measurement stations outside (*MOW1*; *WZ buoy*) and inside the port of Zeebrugge (*Hermespier*, *LNG*, *Albert II dock* (*AIJ dock*), and

Sterneneiland), the regular disposal site *ZBO* and the disposal site *ZBW* used during the field experiment. The background consists of bathymetry and of the dredging and disposal intensity during 2013

and the P90 percentile 1.2 m. The salinity is generally between 28 and 34, and changes in salinity are caused by the advection of marine and Scheldt water masses (Arndt et al. 2011; Fettweis and Baeye 2015). The residual alongshore currents at *MOW1* (*WZ buoy*) (see the location of these stations in Fig. 1) are in 80 % (64 %) of the time directed towards the SW (i.e., in ebb direction) and salinity is then around 30. During the prevailing SW wind, salinity may increase up to 34 and marine water with generally lower SPM concentration enters the area; the residual alongshore current is then directed towards the NE. SW-NE direction corresponds with the alignment of the coastline.

The harbor is situated in a coastal turbidity maximum area with SPM concentrations between 0.02 and more than 0.1 g/l at the surface and between 0.1 and more than 3 g/l near the bed; lower values (<0.01 g/l) occur offshore (Baeye et al. 2011; Fettweis et al. 2012b). The SPM concentration, floc size, and settling velocity have a distinct seasonal signal (Fettweis and Baeye 2015). An acoustic detection method using ADV and ADP altimetry revealed bed boundary level changes of up to 0.2 m in the nearshore area during tidal and spring-neap cycles, suggesting the occurrence of lutoclines

and possibly of fluid mud layers (Baeye et al. 2012). The occurrence of brownish-colored fluffy layers on top of consolidated black and anoxic mud deposits of Holocene age, intercalated with thin sandy layers, have frequently been observed in Van Veen grab and box core samples taken in the vicinity of the harbor.

The outer port of Zeebrugge is reclaimed from the sea and is protected from it by two breakwaters, each about 4 km in length (Vanlede and Dujardin 2014). The harbor mouth is in open connection to the sea. The open water surface is $6 \times 10^6 \text{ m}^2$, which gives a tidal volume of $24 \times 10^6 \text{ m}^3$. The cross-sectional surface between the harbor and sea is about 12,000 m^2 . The sediment exchange between the harbor and the sea is caused mainly by horizontal and to a lesser extent vertical exchange at the harbor mouth (Vanlede and Dujardin 2014). Most horizontal sediment exchange occurs from 2 h before high water to high water. Around that time, the flood flow in the North Sea (directed northeastward along the Belgian coast) drives a primary gyre in the harbor. The high SPM concentrations result in an average siltation rate of 3.6×10^6 tons dry matter (TDM) per year, which is dredged and disposed on the authorized disposal site *ZBO* (Fig. 1)

(Lauwaert et al. 2009). Because of the high sediment retention in the harbor, the sediment concentration in the outflowing water is lower than that in the inflowing water.

3 Methodology

The field study lasted for 1 year (between January 2013 and March 2014) and consisted of 11-month disposing of the dredged material on the existing disposal site ZBO, which induces recirculation of the disposed material back to the dredging sites and of a 1-month period (further called field experiment) with disposal on an alternative site (ZBW) with more limited recirculation (see Fig. 1). The fine-grained dredged sediments ($D_{50} < 10 \mu\text{m}$) from the harbor of Zeebrugge consist of 20–40 % clays, 20–40 % quartz, 20–30 % carbonates, and 1–7 % organic material (Adriaens 2015). In total, about 3×10^6 TDM have been dredged and disposed during the period March 2013–March 2014. During the 1-month field experiment, 0.41 million TDM (14 % of the yearly amount) were disposed on the ZBW site. The disposal on site ZBW occurred between 21 October 2013 and 20 November 2013. The 11-month period of disposal on site ZBO (further called disposal as usual) was situated between February 2013 and March 2014. Besides the monitoring station MOW1, where data are available since 2005 (Fettweis and Baeye 2015), a second station (WZ buoy) outside the harbor and four inside the harbor were installed during the field study.

3.1 Monitoring stations for SPM concentration outside and inside the port

Current velocity, salinity, SPM concentration, and altimetry were collected with tripods at MOW1, located about 5 km offshore, and at WZ buoy located at about 2 km from the harbor entrance (Fig. 1). Both measuring stations are situated in the influence zone from dispersion of dredged material disposal at ZBO (Van den Eynde and Fettweis 2006). The instrumentation suite consisted of a point velocimeter (5 MHz ADVOcean velocimeter), a downward looking ADP profiler (MOW1, 3 MHz SonTek Acoustic Doppler Profiler; WZ buoy, 2 MHz Aquadopp current profiler), two D&A optical backscatter point sensors (OBS3+), a Sequoia LISST-100X, and a Sea-bird SBE37 CT. The data were collected in bursts every 10 or 15 min for the OBS, LISST, and ADV, while the ADP was set to record a profile every 1 min; later on, averaging was performed to a 15-min interval to match the sampling interval of the other sensors. The OBSs were mounted at 0.2 and 2 m above bed (mab). The tripods were moored between 3 and 6 weeks and then replaced with similar tripod systems to ensure continuous time series.

Inside the port current velocity, salinity and SPM concentration were measured at four locations (Sterneneiland, Albert II dock, LNG and Hermespier, see Fig. 1) at two points in the water column, respectively about 2 m below MLLWS and about 2 mab. The instrumentation suite consisted of a point velocimeter (Aquadopp), an OBS3+, and a CT probe (Valeport 620). At Hermespier, the instrumentation was mounted on a fixed cable, attached to the gangway of the pier and a concrete anchor at the bottom. The other three measuring locations were equipped with two concrete anchors connected by a 50-m steel cable; the measurement devices were attached to the first, 300 kg anchor, a localization buoy to the second, 1000 kg anchor. The instruments were kept at the desired depth by an underwater buoy, positioned just below MLLWS, and a second flotation buoy at the water surface. The data were collected every 10 min (average value of 60 s bursts). To reduce data gaps to a minimum, the measurement devices were retrieved and cleaned every 3 weeks. After some functionality checks, the measuring suite was then lowered again.

3.2 Top sediment layer outside and inside the port

Recently, applications in fine-grained sediment environments have been documented where the ADV altimeter was used to elucidate the high concentrated mud suspension (HCMS) or fluid mud layer dynamics (see Baeye et al. (2011)). The acoustic signal of the ADV records the distance between the measuring volume and the sea floor at both stations outside the port. This distance varies as a function of settling of the tripod, variation in bathymetry (erosion/deposition) and the presence of lutoclines or sharp gradients in the SPM concentration that act as reflector for the acoustic signal. The variation in altimetry can thus be used as a proxy for the dynamics of HCMS or fluid mud layer.

The thickness of the top mud layer inside the harbor was measured with a dual-frequency echo sounder on a regular basis. Besides the two weekly measurements along the central axis of the outer harbor (leading lights line in Fig. 1), a daily survey of the axis of the Albert II dock (axis Albert II in Fig. 1) was conducted during the field study. The 210-kHz reflector is considered to be the top of the mud layer, while the 33-kHz reflector is interpreted to be the hard sandy bottom.

3.3 SPM concentration from optic and acoustic sensors

The SPM concentration was derived from optical (OBS and LISST) and acoustical instruments (ADP). The OBS voltage readings were converted into NTU using Amco clear and then into SPM mass concentration (g/l) by calibration against filtered water samples collected during one (WZ buoy, inside the harbor points) and four tidal cycles (MOW1). A linear regression was used to fit a straight line between the OBS signal (in

NTU) and the filtered SPM concentration (g/l; see Fig. 2). The stability of the OBS was further controlled by calibrating them against Amco clear solution before and after the field study. The measuring range was set to 1.5 or 3 g/l depending on the sensor. During high-energy conditions, near-bed SPM concentrations at MOW1 and WZ buoy were regularly higher than 1.5 or 3 g/l. Under these circumstances, the OBS saturated and underestimated the actual SPM concentration. The OBS at 0.2 mab was in saturated state during about 2.3 % of the time at MOW1 and 3.2 % of the time at WZ buoy. Although this represents a relatively short period of time, it may significantly affect the mean SPM concentration, e.g., an underestimation of the peak SPM concentration during saturation by 2 g/l results in an underestimation of the mean SPM concentration in summer by 60 mg/l and in winter by 30 mg/l (Fettweis and Baeye 2015).

The LISST 100X uses laser diffraction technology to measure particle size and volume concentration in 32 logarithmically spaced size groups over the range of 2.5–500 μm (Agrawal and Pottsmith 2000). The volume concentration of each size group is estimated with an empirical volume calibration constant, which is obtained under a presumed sphericity of particles. The total SPM volume concentration (units: ml/l) is the sum of the 32 volume concentrations per size class and has been used in the study. As cohesive sediments occur as flocs in suspension, the SPM volume concentration is not equal to the SPM mass concentration. The uncertainty of the instrument is related to the characteristics of the particles occurring in nature (particles smaller and larger than the size range; non-spherical particles), which affects the estimated size and volume distribution (Mikkelsen et al. 2006; Andrews et al. 2010).

The ADP profilers at both locations were attached at 2.3 mab and down-looking, measuring current and acoustic intensity profiles with a bin resolution of 0.25 m starting at 1.8 mab. The backscattered acoustic signal strength, from

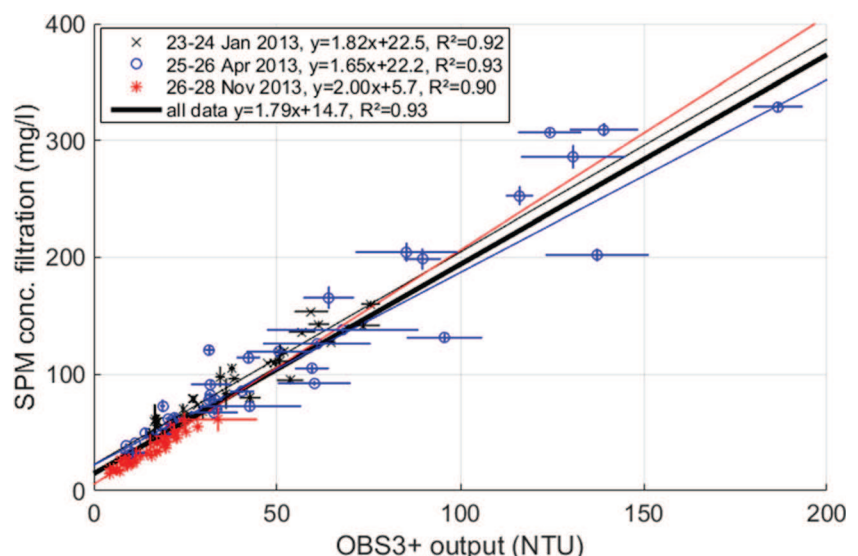
ADP, was used to estimate SPM concentrations. After conversion to decibels, the signal strength was corrected for geometric spreading and water and sediment attenuation (Thorne and Hanes 2002). The upper OBS-derived SPM concentration estimates were used to calibrate the ADP's first bin. The different sensitivity of acoustic and optic sensors to changes in the SPM particle size and characteristic is reflected in the correlation coefficient between the ADP backscatter (dB) and the OBS-derived SPM concentration of $R^2 = 0.53$. The R^2 is better for the lower SPM concentrations and the regression model thus accounts for less variance for the higher SPM concentrations.

3.4 Data classification, ensemble averaging

The number of data at WZ buoy comprises 254 (OBS), 310 (Aquadopp), and 320 LISST tidal cycles, and at MOW1, about 1390 (LISST) and 2430 (ADP, OBS) tidal cycles were collected during different seasonal, tidal, and meteorological conditions. To every tidal cycle classification, parameters were assigned that take into account seasons, tidal range, alongshore current, and the significant wave height. Each tidal cycle starts at high water (HW) and finishes at the following HW and was resampled to obtain 50 data points per cycle (i.e., every 15 min). The tidal cycles of each class were then ensemble averaged, and the standard error was calculated. The standard error estimates how far the sample mean is likely to be from the population mean and will decrease with increasing sample size.

The tidal range was calculated from the harmonic tidal signal and then grouped according to the P66 (3.95 m) and P33 (3.31 m) percentiles into a spring tide (SP; $>P66$), mean tide (MT; $P66$ – $P33$), and neap tide (NT; $<P33$). The influence of weather systems on SPM concentration was investigated by grouping the tidal cycles according to the residual alongshore

Fig. 2 Calibration of OBS output (NTU) versus filtered water samples (MOW1) during four tidal cycles (one in January and April and two in November). The errorbars indicate the standard deviation of three replica filtrations (y-axis) and 30 s of OBS measurements prior to the closure of the Niskin bottles (x-axis)



flow and the significant wave height. For each tidal cycle, the residual alongshore flow (U_a) was calculated using the ADP current velocity data at 2 mab. Subsequently, the tidal cycles were classified in terms of the direction and strength of this residual alongshore current into a SW-ward directed ($U_a < -0.09$ m/s) and a NE-ward directed ($U_a > 0$ m/s); SW-NE direction corresponds with the alignment of the coastline. The P50 percentile of residual alongshore currents is $U_a = -0.06$ m/s; a $U_a < -0.09$ m/s corresponds with the P33 percentile and a $U_a > 0$ m/s with the P80 percentile of all values. The influence of wave systems was looked at by grouping the data into tidal cycles with significant wave heights (H_s) < 0.60 m ($<P50$) and $H_s > 1.2$ m ($>P90$).

4 Results

4.1 SPM concentration outside and inside the port

The 2013 time series at MOW1 and WZ buoy of SPM concentration derived from OBS, LISST, and ADP and some additional parameters (H_s , U_a , salinity, and altimetry) are shown in Figs. 3 and 4. Less data are available at the WZ buoy location due to frequent failure of the instrumentation and collision of ships with the frame. The influence of neap-spring cycle is more pronounced in the SPM concentration derived from the ADP than the OBS. At 2 mab, the peak in the low-passed filtered SPM concentration from both the ADP

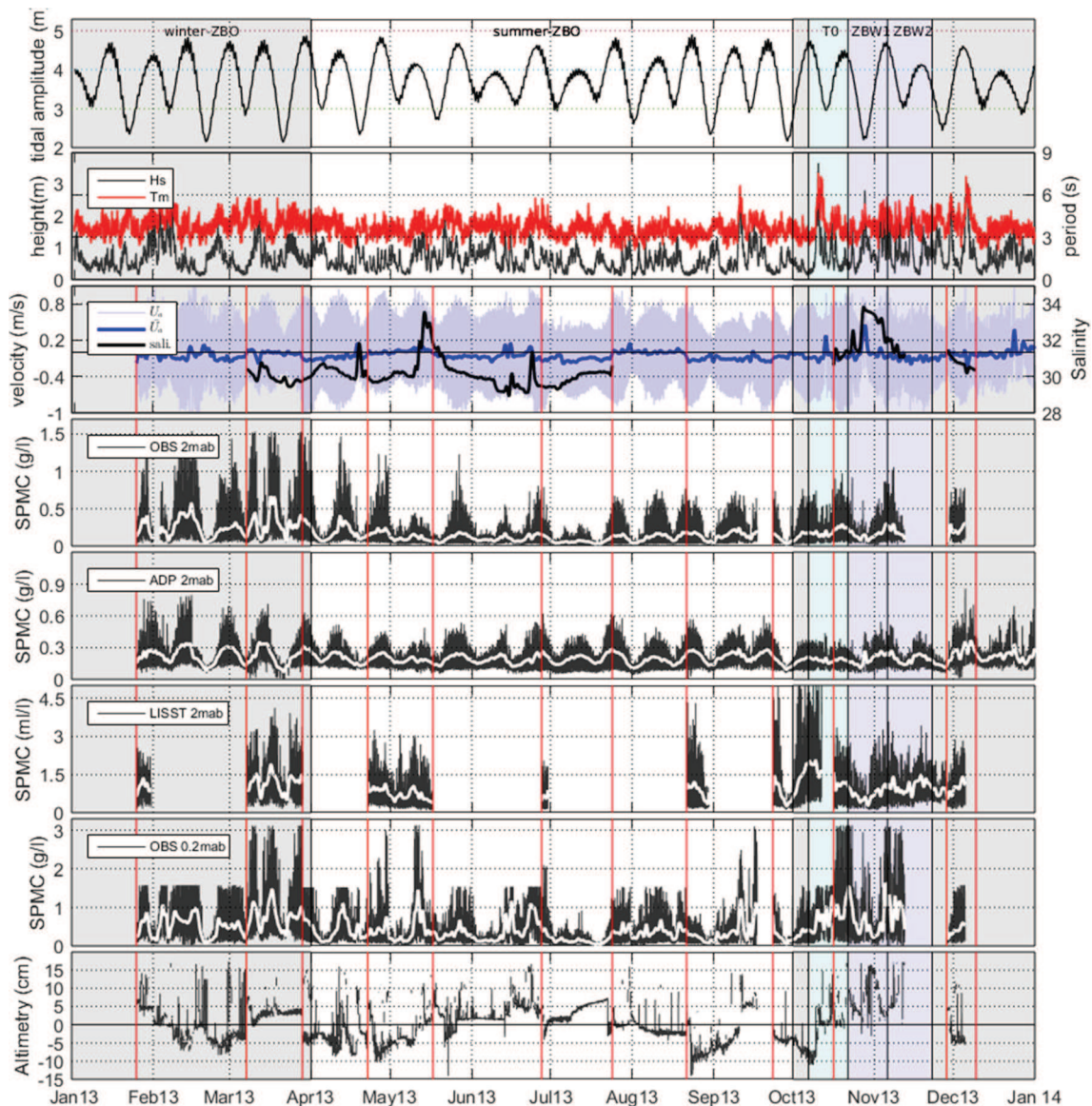


Fig. 3 MOW1 location, 1 January 2013–31 December 2013 time series of tidal amplitude, significant wave height (H_s) and mean wave period (T_m), alongshore currents (U_a), residual alongshore currents (positive is towards the NE, negative towards the SW), and salinity; SPM mass and

volume concentration at 2 and 0.2 mab (SPMC) for ADP and OBS, and altimetry (decrease: erosion, increase: accretion). Red lines indicate the start/end of a tripod deployment

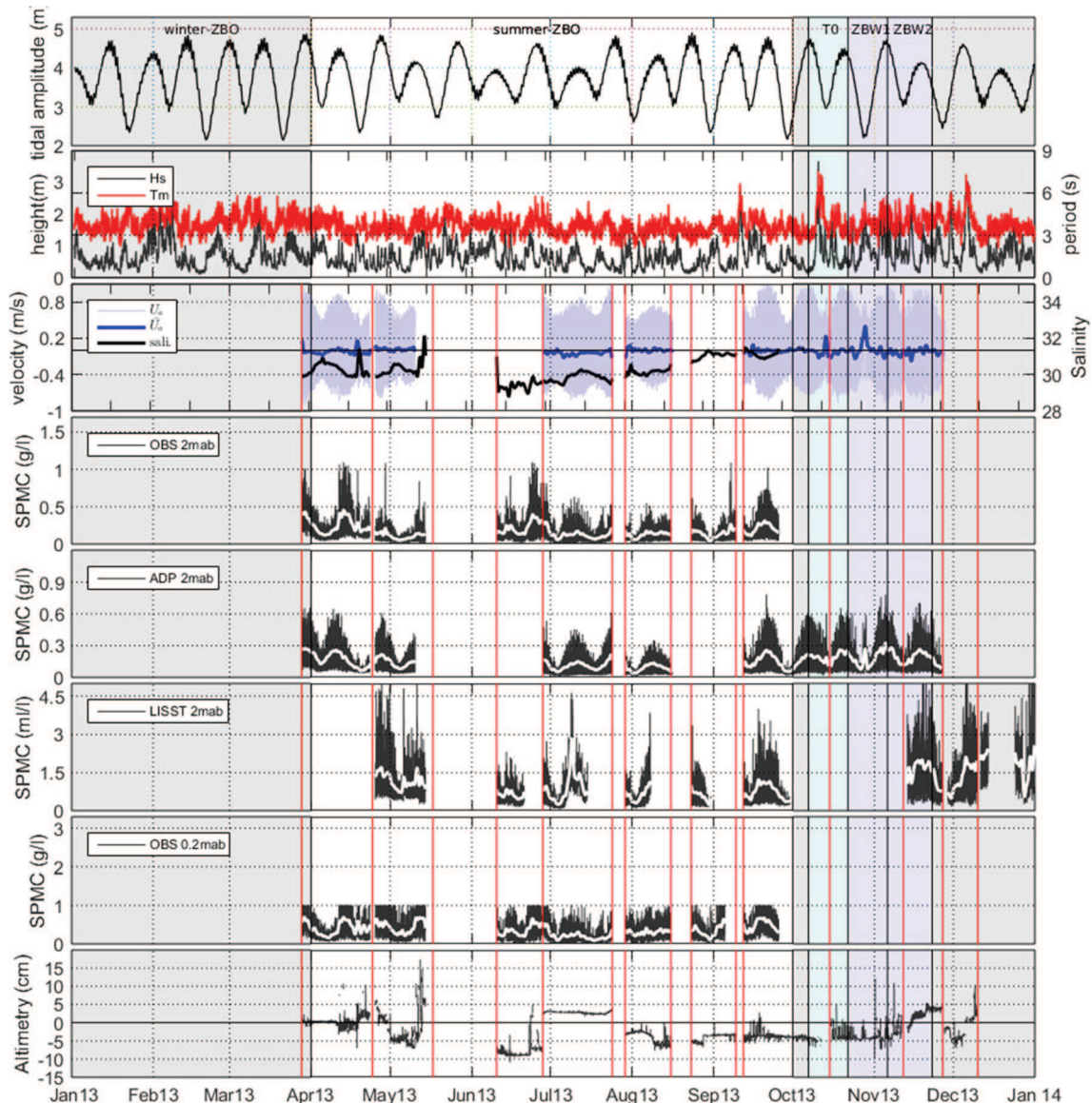


Fig. 4 Same as Fig. 3, but for WZ buoy

and the OBS corresponds generally well with the peak in tidal amplitude, which is not the case closer to the bed where the SPM concentration is more influenced by near-bed SPM dynamics, such as wave induced resuspension, or formation of HCMS. The quality of the correlation of low-pass filtered OBS-derived SPM concentrations with tidal amplitude is low for several periods at MOW1. This is the case around days 33, 45, 60, 72, 293, and 312, which have a lower low-passed filtered SPM concentration than expected from tidal amplitude. This can be explained by the direction of the residual alongshore currents, by an apparent low SPM concentration due to the fact that waves disturbed the signal, by saturation of the OBS at 0.2 mab, and by possible changes in sediment composition or the formation of fluid mud layers and a reduction of the vertical mixing.

The effect of tidal amplitude, seasons, waves and residual alongshore current on the OBS-derived SPM concentration during a tide at MOW1 is shown in Fig. 5 and Table 1. The tidal ensembles indicate that the mean SPM concentration at 0.2 mab during summer (winter) is about 13 % lower (higher) than the mean SPM concentration during the whole year. The seasonal difference is more pronounced at 2 mab where the difference with the mean during the whole year is ± 25 %. The tidal-averaged SPM concentration at 0.2 and 2 mab during winter spring (neap) tide increases (decreases) by about 25 % with respect to the tidal-averaged SPM concentration during all tides in winter. During a NE-ward-directed residual alongshore current (P10) in winter, the tidal-averaged SPM concentration decreases by 20 % at 0.2 mab and 13 % at 2 mab, with respect to the tidal-averaged SPM concentration

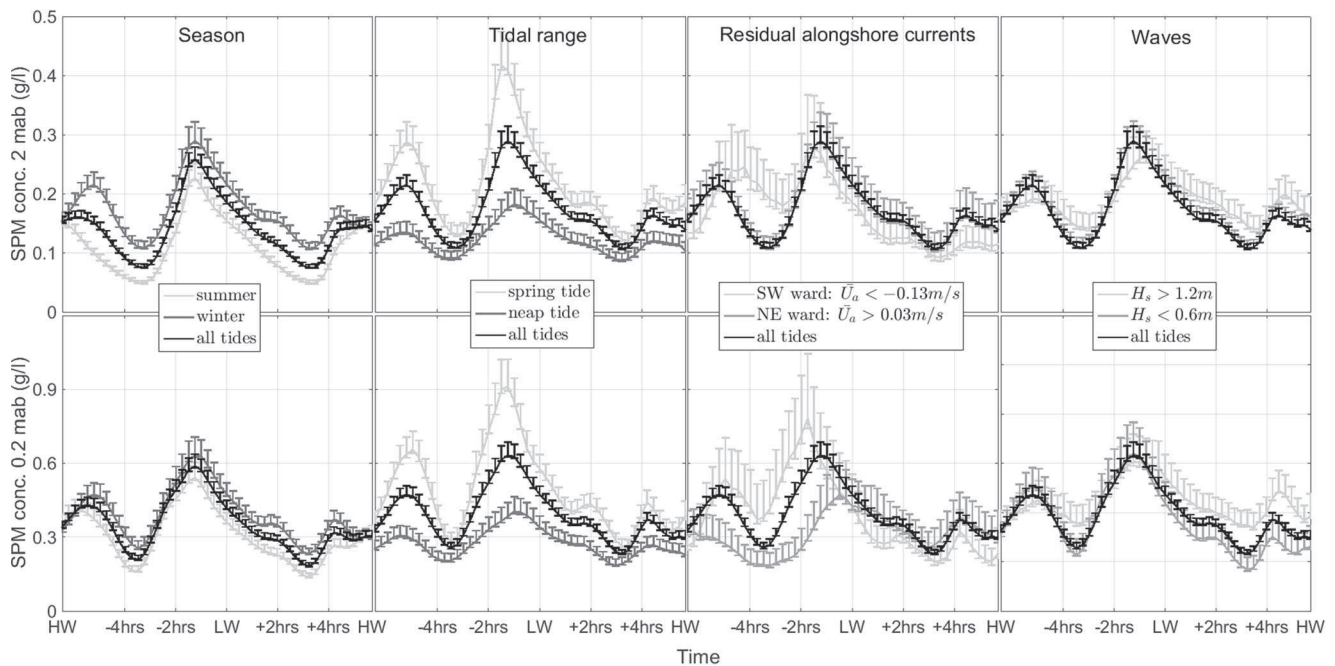


Fig. 5 MOW1 (2005–2013), ensemble-averaged OBS-derived SPM concentration at 2 and 0.2 mab during a tidal cycle as a function of season, tidal amplitude, direction of the residual alongshore current, and significant wave heights. The data grouped according to tidal amplitude,

residual alongshore current, and significant wave heights are for winter period. The error bars are the standard errors. Slack water occurs around 4 to 3 h before and 3 h after LW

in winter. During SW-ward-directed residual alongshore current (P90), the values are almost equal to the tidal-averaged SPM concentration in winter. Low (high) wave conditions result in a decrease (increase) of the tidal-averaged SPM concentration by 9 % (16 %) at 0.2 mab and by 8 % (11 %) at 2 mab. The results show that high waves and negative residual alongshore flow direction induce the highest variations near the bed (0.2 mab), whereas seasonal effects are more pronounced higher up in the water column. The effect of tidal

range is similar near the bed and in the water column. The results indicate that SPM concentration is mainly tidally dominated, but the occurrence of storms will impact the shallow regions through resuspension and by advection. Figure 5 shows the effect of one parameter separately and gives a result that incorporates the average for the other parameters. The relatively low effect of high waves is thus hidden in the average over all tidal ranges. If we look at high wave condition during several tidal ranges, then the effects are more pronounced, i.e., strong increases of the SPM concentration near the bed during both neap and spring tidal condition and a decrease of wave effects at 2 mab, which is more pronounced during neap than spring tide. The effect of waves on different residual alongshore regimes is similar. Near the bed, the effects of alongshore residual current, as described above, is overprinted by the wave effects, in contrast with the situation at 2 mab, where the effect of residual alongshore current direction is more dominant than waves effect.

The SPM concentration time series inside the port are shown in Fig. 6. Data gaps are mainly caused by insufficient power supply and fouling. All stations show higher SPM concentration in the lower measurement point, except for Hermespier, where the difference in median value is not significant (Table 2). SPM concentrations are higher in winter (October–March) compared with summer (April–September), except for location Steneneiland. This is probably caused by some exceptionally deep moorings during summer, leading to approximately the same depth for the upper

Table 1 Geometric mean and multiplicative standard deviation (multiplied divided: */) of the OBS-derived SPM concentration (mg/l) at MOW1 (2005–2013) during different tidal ranges (neap tide, spring tide), residual alongshore current directions (SW-ward, NE-ward: P10 and P90 of all values) and significant wave height. The results of tidal range, residual alongshore current, and significant wave heights are for winter period

	0.2 mab	2 mab
All tide	332*/1.36	131*/1.41
Summer	288*/1.44	100*/1.57
Winter	374*/1.31	165*/1.31
Neap tide	268/1.23	120*/1.22
Spring tide	460*/1.39	203*/1.38
SW-ward	361*/1.47	159*/1.39
NE-ward	303*/1.30	127*/1.27
$H_s < 0.6$ m	341*/1.43	147*/1.40
$H_s > 1.2$ m	432*/1.18	183*/1.19

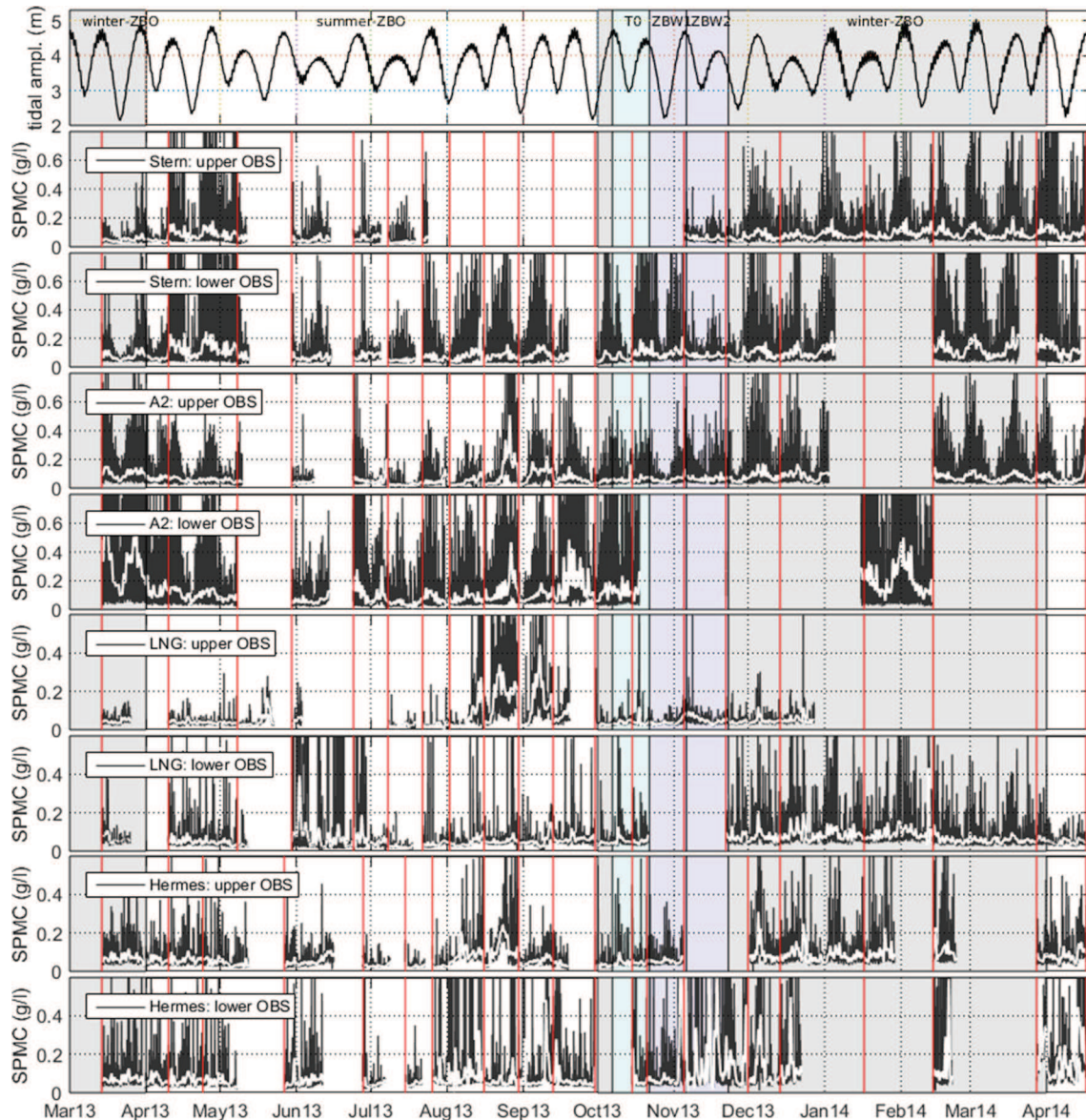


Fig. 6 1st March 2013–15th April 2014 time series of SPM concentration at two levels and in the four locations inside the harbor. Red lines indicate the start/end of a deployment

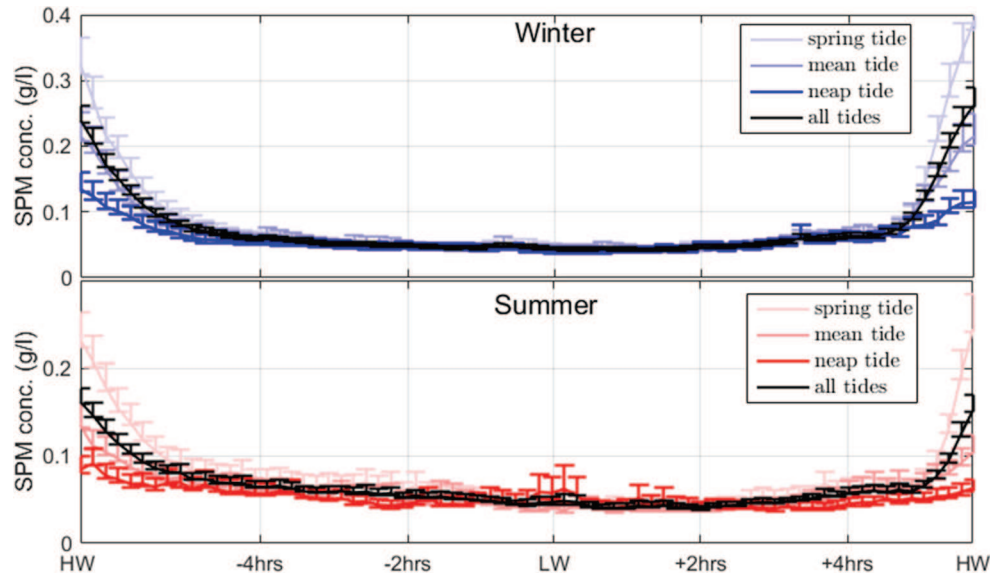
measurement point as the lower measurement point in winter. Sterneneiland and Albert II dock show significantly higher SPM concentrations during spring tide than during neap tide, in contrast to LNG and Hermespier (Table 2). The SPM concentrations at the two locations closest to the harbor mouth

(Sterneiland and Albert II dock) show a clear correlation with the tide, with highest SPM concentrations around high water (Fig. 7), indicating the period of inflow of sea water with high SPM concentration towards the harbor. At LNG this correlation is less pronounced and for location Hermespier there is no

Table 2 Median and its 95 % confidence interval of SPM concentrations (mg/l) inside the harbor: seasonal and tidal variations (spring tide–neap tide)

	Summer		Winter		Neap tide		Spring tide	
	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
Sterneneiland	66 ± 6	81 ± 6	73 ± 4	88 ± 5	66 ± 4	71 ± 4	93 ± 7	105 ± 8
All dock	54 ± 4	86 ± 8	73 ± 4	164 ± 30	51 ± 4	106 ± 14	76 ± 6	135 ± 22
LNG	38 ± 6	50 ± 3	43 ± 2	71 ± 4	40 ± 4	60 ± 5	39 ± 8	56 ± 4
Hermespier	54 ± 5	61 ± 5	68 ± 5	86 ± 14	60 ± 6	68 ± 10	62 ± 6	67 ± 7

Fig. 7 Albert II dock, ensemble-averaged OBS-derived SPM concentration at 2 m below water surface during a tidal cycle in winter (*upper*) and summer (*lower*) as a function of tidal range. The *error bars* are the standard errors. Slack water outside the harbor occurs around 4 to 3 h before and 3 h after LW



significant difference between high water and low water SPM concentrations. The SPM concentration in all locations inside the harbor correlates highly with the current velocity. Whilst the measurements outside the harbor show a peak around maximum ebb and flood flow, only the flood peak is observed in the harbor. The peak in SPM concentration during maximum flood velocity is simultaneously outside the harbor and at location Stern.

4.2 Fluid mud outside/inside the port

The 2013 time series at MOW1 and WZ buoy of the 5-MHz altimetry signal of the ADV are shown in Figs. 3 and 4. The seafloor varied between −14.8 and 17.4 cm (MOW1) and −9.2 and 17.4 cm (WZ buoy) and shows low- and high-frequent variations. In general, the low-frequent variations in altimetry are more pronounced during strong variations in residual alongshore current associated with storms. The high frequent

variations are often associated with the formation and resuspension of HCMS at slack water; these variations reach up to about 15–20 cm. The ensemble-averaged altimetry (Fig. 8) shows an increase around slack water at both locations. At MOW1, the accretion is more pronounced around the slack water after HW than that after LW. The resuspension of this material results in a peak in SPM concentration during ebb that is higher than during flood (Fig. 5). At the WZ buoy, the variations in altimetry are less pronounced and the seafloor thus more stable.

Inside the port, a mud layer up to 3.5 m thick exists, whereas at the harbor entrance (−500–0 m in Fig. 9), the thickness of the mud layer is about 0.5 to 2 m. Maximum thickness is located around the entrance of the Albert II dock; deeper in the harbor the thickness of the mud layer again decreases. However, Fig. 9 also shows that the variation of the 210 kHz altimetry is largest at the entrance and deeper in the harbor. For the whole period of the field study, the variation in

Fig. 8 Ensemble-averaged ADV altimetry signal outside the port. The altimetry is indicated with respect to the mean altimetry. The *error bars* are the standard errors. Slack water occurs between 4 and 3 h before and 3 h after LW. The variations in altimetry are a proxy for the HCMS or fluid mud dynamics

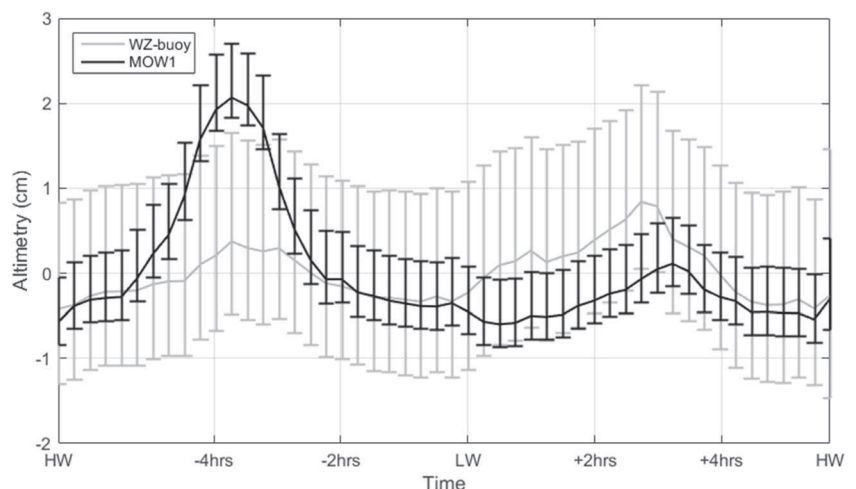
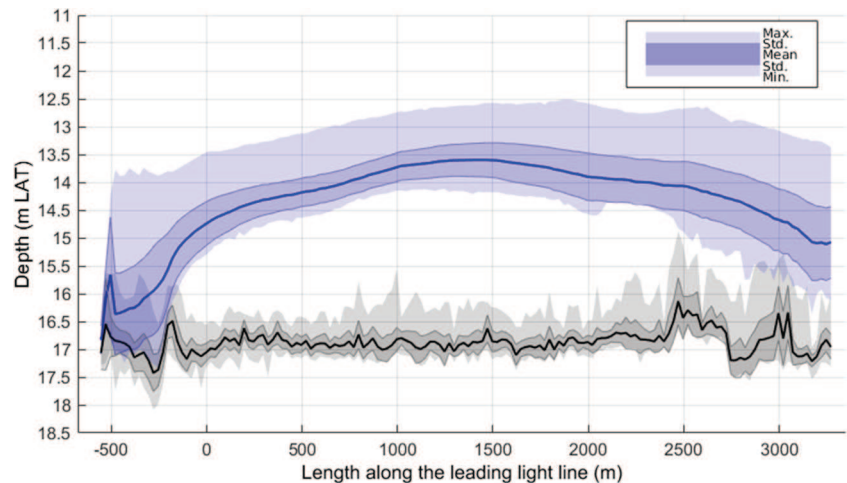


Fig. 9 Depth of the top of the mud layer (blue, mean height, standard deviation, and extremes of the 210-kHz reflector) and the “hard” sandy bottom (black, mean height, standard deviation, and extremes of the 33-kHz reflector) in m relative to Lowest Astronomical Tide (LAT) during the period March 2013–March 2014. The data are from the central part of the harbor along the leading light line (from outside towards inside, see Fig. 1.)



volume between the 210- and 33-kHz reflector has been calculated, based on both transects (leading light line and axis Albert II dock). In order to obtain a natural variability of the mud volume, the observed volume changes were corrected for the dredging works conducted during the period between two consecutive soundings (see Fig. 10). In winter, the mud volume is the largest; during spring and summer, the volume gradually decreases to reach a minimum at the beginning of autumn. This confirms what already was shown in Fig. 9 namely that the dome shape of the mud layer along the leading light line (Fig. 1) is more or less constant in time but moves up and down as a whole. Some differences in mud volume variation exist within the harbor, but all locations confirm that the thickness of the mud layer is higher in winter than in summer.

Figure 10 confirms generally that the increase of the mud volume is higher during spring tide than during neap tide, since more sediment is imported into the harbor. However, other variations (seasonal, storms) partially mask this neap-spring signal so that no statistical confirmation exist that the mud volume during or just after spring tide is higher than during neap tide.

4.3 SPM concentration during the field experiment

In order to take spring-neap cycles, seasonality and meteorology as much as possible into account, the evaluation of the field experiment was based on a 15-day period prior to the field experiment (T0: 06–20 October 2013), a 15-day period

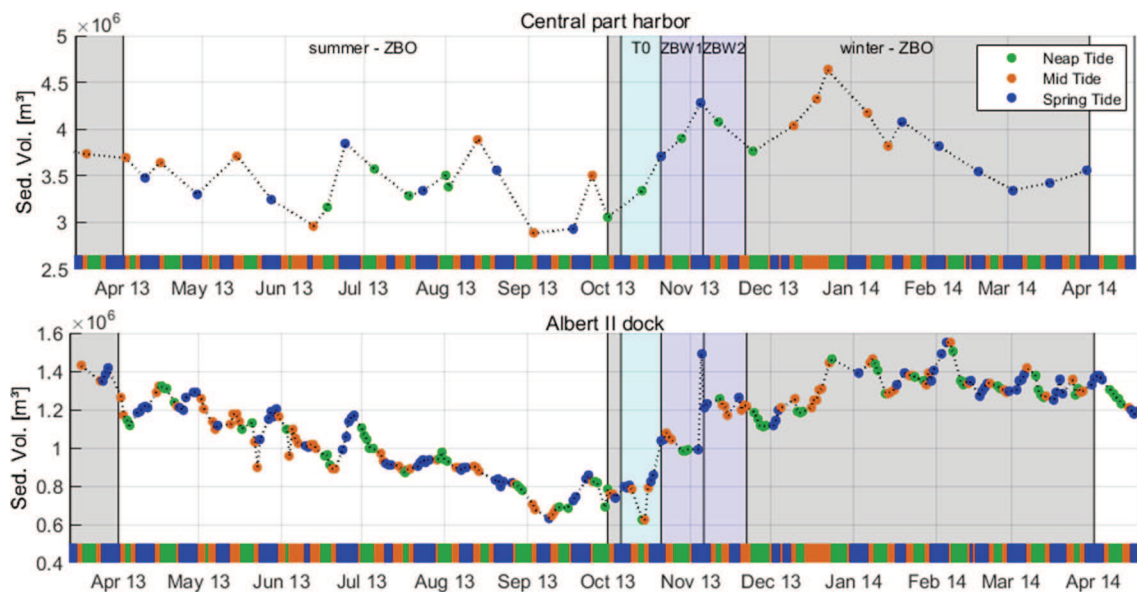


Fig. 10 Natural evolution of the mud volume in the central part of the harbor and in the Albert II dock. The volume changes are calculated from two weekly transects along the leading light line (see Fig. 1) and from

daily transects along the axis of the Albert II dock and have been corrected for the dredging works conducted during the period between two consecutive soundings

Table 3 Subperiods used for (statistical) analysis

Summer	April–September
Winter	January–March, October–December
Winter ZBO	Winter except 21 October 2013–21 November 2013
T0	6 October 2013–20 October 2013
ZBW	21 October 2013–21 November 2013
ZBW1	21 October 2013–05 November 2013
ZBW2	06 November 2013–21 November 2013
Winter 1	28 January 2013–13 February 2013
Winter 2	17 December 2013–31 December 2013
Winter 3	16 February 2014–03 March 2014
Summer 1	12–26 April 2013
Summer 2	25 June 2013–10 July 2013

during the winter 2013 (Winter 1) and the winter 2013 with disposal on ZBO (winter ZBO); the field experiment (ZBW) was divided in two 15-day period (ZBW1, ZBW2), see Figs. 3, 4, and 6 and Table 3. A comparison of the ensemble averaged SPM concentrations during these different periods as well as during winters of 2005–2012 is shown in Fig. 11 and Table 4 for the MOW1 station. Similar results have been found at the WZ buoy location for the ADP-derived SPM concentrations. The data indicate that the SPM concentration was higher during the 2013 winter with disposal on ZBO than during the previous winters. The data also show that the difference between T0 and ZBW1 is more pronounced during ebb and at the beginning of flood. The disposal site ZBO is situated in ebb direction of the measurement sites and the decrease in concentration is thus in line with expectations. Further, the ZBW2 period is more similar with the T0 than the ZBW1 period. The averaged values (Table 3) show that

variations in SPM concentrations due to waves, seasons, or disposal are more visible in the near-bed layer than higher up in the water column.

5 Discussion

The results based on time series measurements at two fixed location outside the port and 4 stations inside the port and on echo soundings and density measurements inside the port before, during and after the relocation of a disposal site did not indicate unambiguously that the relocation resulted in a decrease of the SPM concentration outside and a reduction of the siltation inside the port. The main reason for this is that the most important changes in SPM concentration at MOW1 are due to tidal range (70 % higher during spring than neap tide), waves (27 % at 0.2 mab and 24 % at 2 mab higher during high (>1.2 m) than low (<0.6 m) waves), seasons (30 % at 0.2 mab and 65 % at 2 mab higher in winter than summer) and residual alongshore flow (19 % at 0.2 mab and 25 % at 2 mab higher during SW-ward than NE-ward directed residual alongshore), see Table 1. The numerical model results suggest that after relocation of the disposal site to ZBW the tidal and vertical averaged SPM concentrations decrease from about 10 to 2 mg/l at MOW1 and from about 15 to 3 mg/l at WZ buoy (Van den Eynde and Fettweis 2014). As SPM concentration is not uniformly distributed in the water column, it is expected that the decrease at 2 mab is about a factor two larger (Fettweis and Nechad 2011). The effect of disposal at MOW1 as estimated by the model represents about 10 % of the tidal averaged SPM concentration at 2 mab and is thus lower than the variations caused by natural forcings. Due to the fact that the

Fig. 11 MOW1, ensemble-averaged OBS-derived SPM concentration at 2 and 0.2 mab during a tidal cycle for different periods in winter

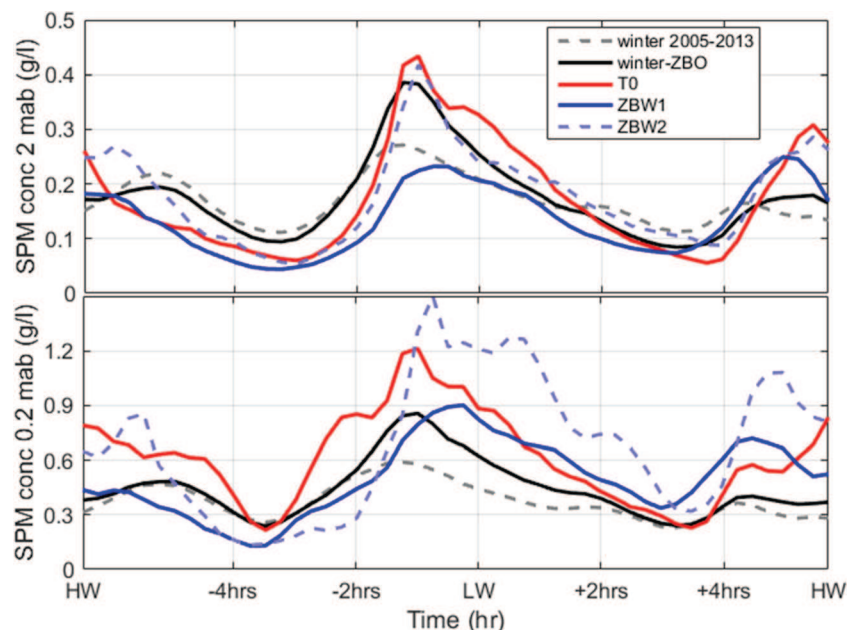


Table 4 Geometric mean and multiplicative standard deviation (multiplied divided: *) of the ADP and OBS-derived SPM concentration (mg/l) at MOW1 and of the ADP-derived one at WZ buoy at two heights above the bed and during different periods. The OBS derived SPM concentration at MOW1 is shown during low and high wave conditions

	ADP	OBS	OBS ($H_s < 0.6$ m)	OBS ($H_s > 1.2$ m)	ADP-WZ buoy
2 mab					
Summer	78*/1.71	85*/2.20	86*/2.29	102*/2.01	97*/2.13
Winter ZBO	91*/1.78	172*/2.23	176*/2.32	152*/1.93	141*/2.10
T0	74*/1.61	148*/2.09	149*/2.21	141*/1.88	150*/2.12
ZBW	70*/1.70	128*/2.08	129*/2.09	148*/1.94	149*/2.05
ZBW1	67*/1.76	117*/2.09	116*/2.00	146*/2.02	131*/2.04
ZBW2	73*/1.63	159*/1.98 [†]	172*/1.86	155*/1.77	166*/2.02
0.2 mab					
Summer	504*/1.54	217*/2.54	199*/2.47	372*/2.72	856*/1.86
Winter ZBO	469*/1.62	410*/2.43	383*/2.48	430*/2.34	1161*/1.72
T0	496*/1.41	571*/2.26	477*/2.78	700*/2.06	1246*/1.71
ZBW	504*/1.61	462*/2.89	405*/3.11	623*/2.67	1213*/1.63
ZBW1	488*/1.72	426*/2.60	404*/2.86	275*/2.41	1106*/1.65
ZBW2	518*/1.50	555*/3.50	409*/3.80	748*/3.20	1307*/1.60

model is a simplification of reality these values should be interpreted as an estimate.

In order to detect these changes, the evaluation of the field experiment was based on statistical testing together with an analysis of the environmental conditions. The null hypotheses to be tested are: (1) the SPM concentration at the measuring locations outside the harbor is the same during the field experiment (ZBW) and during disposal as usual (T0, winter ZBO) and (2) the siltation in the harbor during the field experiment (ZBW) is the same as during disposal as usual (T0, winter ZBO). The evaluation of the null hypothesis is based on Wilcoxon's and Welch's tests (Motulsky 2014). The former one tests the null hypothesis that there are no differences in the populations and can be applied for non-normal distributed data and if the variable is measured before and after an intervention. The latter one is an adaptation of the one-sided *t* test and tests the hypothesis that two populations have equal means.

5.1 Statistical analysis outside the port

The evaluation of the first null hypothesis is based on Wilcoxon's test (see Table 5). The *P* values, which are the

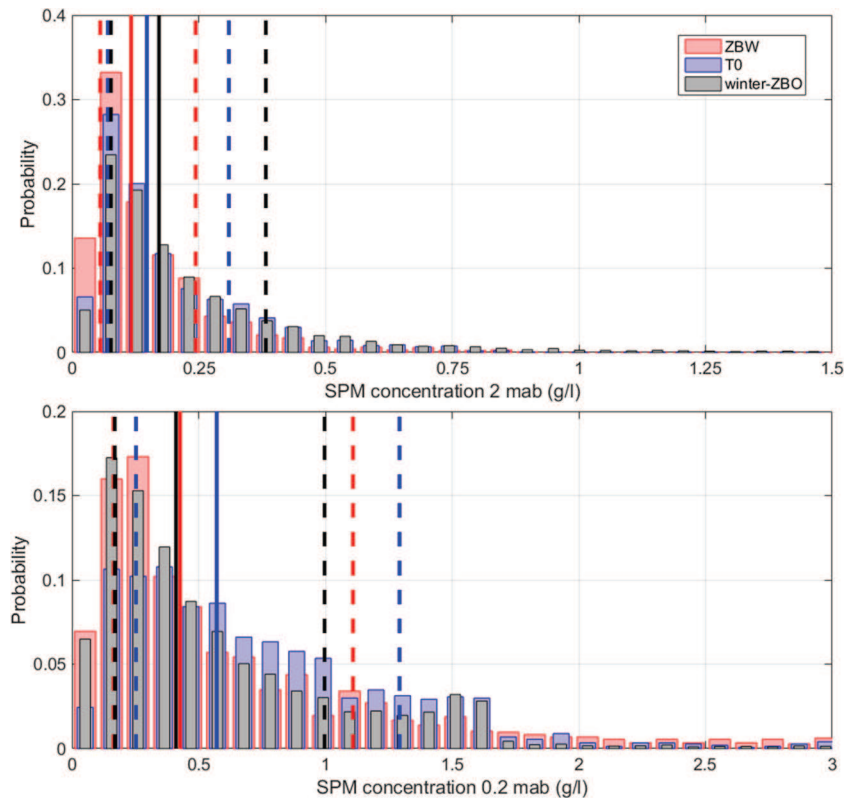
Table 5 MOW1: Wilcoxon's test statistics (*P* value) between the OBS-derived SPM concentrations at 0.2 mab (2 mab) during different periods

	Winter ZBO	T0	ZBW1	ZBW2
T0	<0.01 (<0.01)	–	–	–
ZBW1	0.21 (<0.01)	<0.01 (<0.01)	–	–
ZBW2	<0.01 (<0.01)	0.03 (0.01)	<0.01 (<0.01)	–
Winter 1	0.61 (<0.01)	<0.01 (<0.01)	0.60 (<0.01)	<0.01 (<0.01)

probability of obtaining results equal or more extreme than what was actually observed, when the null hypothesis is true, indicate that the mean SPM concentration during winter ZBO and ZBW1 and winter ZBO and ZBW2 are—depending on the height of the OBS above the bed—not always statistically different, and therefore the null hypothesis fails partially to be rejected. Further, due to the fact that various forcings change SPM concentration, 15-day periods within the winter of 2013 can be found to have statistically different means than the winter ZBO (e.g., T0) although no change in disposal has occurred. Also 15-day periods with different disposal strategies have statistically similar mean SPM concentrations (e.g., Winter 1 and ZBW1). Another way of statistically looking at the data is to calculate the probability that the SPM concentration during a certain period is higher/lower than during another period. This was done by randomly sampling the population of SPM concentration during the selected periods and to compare the values. The results indicate that the probability of having a higher OBS-derived SPM concentration during the field experiment than during T0 is 45 % (ZBW1, 41 %; ZBW2, 53 %) at 0.2 mab and 44 % (ZBW1: 35 %; ZBW2: 53 %) at 2 mab. The probability distributions of the OBS-derived SPM concentrations are shown in Fig. 12. The geometric mean SPM concentrations are within one standard deviation of each other and illustrate that the natural variability of SPM concentration is higher than the human induced one at the measuring locations.

Statistical testing is based on the assumption that the sample is representative for the whole population. The large data set available at MOW1 (2005–2013) can be seen as a representative subsample of the whole population of SPM concentration with disposal on site ZBO. However, some doubts can be formulated, given the large variability due to random and

Fig. 12 Probability distribution of SPM concentration measured at MOW1 at 2 and 0.2 mab. The *black line* shows geometric mean SPM concentration for the winter data with disposal on ZBO. The *blue* and *red lines* are geometric mean SPM concentration for the T0 period and ZBW1 period, respectively. The *dashed lines* are the mean multiplied and divided respectively by one standard deviation. The higher probability around 1.5 g/l is due to saturation of the lower OBS



natural forcings, that the 1-month period with disposal on ZBW is a representative subsample. Further, statistical testing assumes that the samples are independent if they come from unrelated populations and the samples do not affect each other. These assumptions are not guaranteed within our experiment as it is not only the forcings that influence SPM concentrations but also the sediment availability that is depending on the previous history.

5.2 Environmental analysis outside the port

Because SPM dynamics are highly variable on a multitude of time scales, establishing a baseline framework for a particular location is only possible with repeated and continuous observations, e.g., multiple years of data are required to characterize the typical range in seasonal amplitude and timing of events

Table 6 Mean and standard deviation of wind velocity (m/s), residual alongshore current at MOW1 (U_a , negative is SW-ward, positive is NE-ward) and significant wave height (H_s) during different periods in 2013. Wind velocity and wave height are given as geometric mean and multiplicative standard deviation (multiplied divided: *)

	Winter ZBO	T0	ZBW1	ZBW2
Wind (m/s)	7.8*/1.78	6.2*/2.52	11.2*/1.29	8.5*/1.63
U_a (cm/s)	-4.4 ± 7.1	-6.3 ± 8.1	$+1.4 \pm 13.4$	-9.7 ± 4.3
H_s (m)	0.64*/1.91	0.65*/1.91	0.79*/1.79	0.79*/1.70

(Henson 2014). The argument to favor that the relocation of the disposal site has had a measurable effect on SPM concentration is held in the long-term data series that allowed quantifying the variability associated with the main forcing mechanisms (see Figs. 5 and 12; Table 1).

The field experiment (ZBW) was characterized by variable wind velocities from mainly W to SW direction. The wind velocities were higher during the field experiment than during the 2013 winter with disposal on ZBO. This resulted in strongly variable residual alongshore currents and a higher frequency of strong negative and positive residual alongshore currents and also higher significant wave heights than during the 2013 winter with disposal on ZBO (see Table 6). The OBS-derived SPM concentrations at 0.2 and 2 mab were during the first 15 days of the field experiment (ZBW1) lower in both stations outside the port than during T0. The mean in situ OBS-derived SPM concentration at MOW1 was about 140 mg/l at 0.2 mab and about 30 mg/l at 2 mab lower during ZBW1 than during T0. This equals a reduction of the averaged SPM concentration by 20 % during ZBW1, which is larger than the model results. The effects during ZBW2 were lower (−15 mg/l at 0.2 mab and +30 mg/l at 2 mab), and correspond with a reduction by about 8 % (0.2 mab) and an increase by about 7 % (2 mab) as compared with T0, which is thus less than predicted by the model. The different results for ZBW1 and ZBW2 were triggered by the occurrence of two storm periods with high waves during ZBW2 and by the differences in residual

alongshore currents (ZBW1: $U_a = +1.4$ cm/s; ZBW2: $U_a = -9.7$ cm/s), see Table 6. If we consider only data measured during low wave activity ($H_s < 0.6$ m) then the 0.2 mab OBS-derived SPM concentration at MOW1 during ZBW1 (ZBW2) is about 40 % (15 %) lower than during T0 (Table 4). Same results at 2 mab are not conclusive as wave influences are mainly concentrated in the near-bed layer and thus other forcings (tidal range) dominate more the signal at 2 mab (Fettweis and Baeye 2015). The positive (NE-ward directed) residual alongshore currents during ZBW1 explain the larger decrease in SPM concentration during ZBW1 than during ZBW2, when SW-ward directed residual alongshore currents were prevailing.

The results from the LISST-derived SPM volume concentration at MOW1 during different periods support those of the OBS but are more pronounced. The mean ADP-derived SPM concentration during ZBW1 indicate a decrease of about 2 % at MOW1 and 10 % at WZ buoy as compared with the T0 period. The differences are thus less pronounced and are probably caused by the higher uncertainty in the ADP than the OBS-derived data, due to the fact that the model is a simplification of reality and that the echo intensity of the backscattered acoustic signal gives a good indication of SPM concentration variation if the particle size distribution and characteristics remain the same (Thorne and Hurther 2014; Rai and Kumar 2015). This is not the case for tidal environments where fine-grained sediments are subject to flocculation and where cohesive and non-cohesive sediments can both be in suspension (Baeye et al. 2011; Fettweis et al. 2012a; Ha et al. 2011). The different sensitivity of acoustic and optic sensors to changes in the SPM particle size and characteristic and the higher uncertainty of the acoustic-derived SPM concentration is reflected in the low correlation coefficient ($R^2 = 0.53$) between the ADP backscatter (dB) and the OBS-derived SPM concentration. The measured changes in the SPM concentration derived from solely the ADP are thus below the estimated accuracy and are hence not statistically meaningful. The results of all sensors are, however, in line with the fact that the positive (NE-ward directed) residual alongshore flow was responsible for the lower SPM concentration during ZBW1 than T0, and that the higher waves together with a stronger negative residual alongshore flow were responsible for the almost similar SPM concentration during ZBW2 and T0.

5.3 Analysis of SPM concentration and thickness of the mud layer inside the port

All measurement locations inside the harbor show increasing SPM concentrations for T0 over ZBW1 to ZBW2 (Table 7). A t test for non-normal distributions (Wilcoxon's test) was used to investigate whether these increases are statistically significant at a 95 % confidence level. The null hypothesis of this test is that the mean values of the populations are identical. In addition, a Welch test (one-sided t test) was used to calculate the confidence interval around the difference between the mean of the populations (Welsh difference) at the same confidence level as the Wilcoxon test.

Seven 15-day periods were investigated: T0, ZBW1, ZBW2, and two periods with comparable meteorological conditions as ZBW1 and ZBW2, both in summer (summer 1, summer 2) and winter (winter 2, winter 3; see Table 3). Under equal meteorological circumstances, one would expect SPM concentrations to rise from summer conditions, over T0 to winter conditions. Due to the use of an alternative disposal site, SPM concentrations during ZBW1 and ZBW2 should be lower or at least should not rise as much as between T0 and typical winter conditions. The tests show low P values results for most locations, indicating that the mean SPM values are significantly different (Table 8). In contrast to what was expected, especially when comparing the first half of the experiment, the mean of the summer population is only slightly lower or even higher (summer 1) than the mean of the T0 period. This could indicate that meteorological influences are as important as seasonal variation. For the other populations a steady increase of mean SPM concentrations can be observed for T0 over ZBW1 and ZBW2 to similar winter conditions. Only for the location LNG Upper it can be proved that the mean SPM concentration during the experiment was at least 1.7 mg/l lower than during T0 and 17.4 mg/l lower than during winter. For most other locations, the increase in mean SPM concentration from ZBW1 and ZBW2 to similar winter conditions is of the same order of magnitude as the increase from T0 to winter conditions. This gives the impression that the field experiment caused a (relative) decrease of SPM concentrations inside the harbor. However, the statistical tests are not conclusive, because of the large spread on the confidence intervals. Meteorological and seasonal differences probably have a bigger influence on the observed SPM concentrations inside the harbor than the use of an alternative disposal site.

Table 7 Geometric mean and multiplicative standard deviation (multiplied divided: */) of the SPM concentration (mg/l) at the four measurement locations inside the harbor at two heights above the bed and during different periods

	Sterneneiland		AII dock		LNG		Hermespier	
	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
T0	No data	62.0/*1.8	49.0/*1.8	80.1/*2.3	35.4/*1.4	47.1/*1.5	38.8/*1.6	54.0/*1.7
ZBW1	No data	75.4/*1.7	51.8/*1.6	No data	34.6/*1.3	No data	48.6/*1.4	68.7/*2.1
ZBW2	57.1/*1.5	77.3/*1.5	57.3/*1.7	No data	49.9/*1.6	No data	No data	104.7/*2.6

Table 8 Wilcoxon's and Welch's test statistics for SPM concentration measurements inside the harbor and for different periods (infinity (inf))

	Sterneneliland		All dock		LNG		Hermespier	
	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
Summer 1—T0								
Wilcoxon P	No data	<0.05	<0.05	0.09	<0.05	0.64	<0.05	<0.05
Welch P	No data	<0.05	<0.05	<0.05	0.07	0.35	<0.05	0.15
Welch diff (mg/l)	No data	$32.9 < \Delta x < \text{Inf}$	$-\text{Inf} < \Delta x < -0.2$	$-\text{Inf} < \Delta x < -14.6$	$-0.2 < \Delta x < \text{Inf}$	$-2.5 < \Delta x < \text{Inf}$	$16.2 < \Delta x < \text{Inf}$	$-\text{Inf} < \Delta x < 3.3$
T0—ZBW1								
Wilcoxon P	No data	<0.05	<0.05	No data	0.12	0.12	<0.05	<0.05
Welch P	No data	<0.05	0.21	no data	<0.05	0.12	<0.05	<0.05
Welch diff (mg/l)	No data	$-\text{Inf} < \Delta x < -8.5$	$-1.4 < \Delta x < \text{Inf}$	No data	$1.7 < \Delta x < \text{Inf}$	$-\text{Inf} < \Delta x < 1.2$	$-\text{Inf} < \Delta x < -7.0$	$-\text{Inf} < \Delta x < -35.7$
ZBW1—winter 2								
Wilcoxon P	No data	<0.05	<0.05	No data	<0.05	<0.05	<0.05	<0.05
Welch P	No data	0.36	<0.05	No data	<0.05	<0.05	<0.05	<0.05
Welch diff (mg/l)	No data	$-4.7 < \Delta x < \text{Inf}$	$-\text{Inf} < \Delta x < -23.0$	No data	$-\text{Inf} < \Delta x < -17.4$	$-\text{Inf} < \Delta x < -30.2$	$-\text{Inf} < \Delta x < -34.4$	$-\text{Inf} < \Delta x < -12.9$
T0—winter 2								
Wilcoxon P	No data	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Welch P	No data	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Welch diff (mg/l)	No data	$-\text{Inf} < \Delta x < -8.2$	$-\text{Inf} < \Delta x < -21.5$	$-\text{Inf} < \Delta x < -99.9$	$-\text{Inf} < \Delta x < -13.9$	$-\text{Inf} < \Delta x < -33.5$	$-\text{Inf} < \Delta x < -42.9$	$-\text{Inf} < \Delta x < -63.5$
Summer 2—T0								
Wilcoxon P	No data	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Welch P	No data	0.32	<0.05	<0.05	<0.05	0.34	<0.05	<0.05
Welch diff (mg/l)	No data	$-\text{Inf} < \Delta x < 2.9$	$-\text{Inf} < \Delta x < -3.4$	$-\text{Inf} < \Delta x < -9.9$	$-\text{Inf} < \Delta x < -18.9$	$-\text{Inf} < \Delta x < 3.7$	$-\text{Inf} < \Delta x < -9.9$	$-\text{Inf} < \Delta x < -3.5$
T0—ZBW2								
Wilcoxon P	No data	<0.05	<0.05	No data	<0.05	No data	<0.05	<0.05
Welch P	No data	0.07	<0.05	No data	<0.05	No data	<0.05	<0.05
Welch diff (mg/l)	No data	$-\text{Inf} < \Delta x < 0.5$	$-\text{Inf} < \Delta x < -5.2$	No data	$-\text{Inf} < \Delta x < -15.3$	No data	$-\text{Inf} < \Delta x < -10.4$	$-\text{Inf} < \Delta x < -110.7$
ZBW2—winter 3								
Wilcoxon P	<0.05	<0.05	<0.05	No data	No data	No data	<0.05	<0.05
Welch P	<0.05	<0.05	<0.05	No data	No data	No data	<0.05	<0.05
Welch diff (mg/l)	$-\text{Inf} < \Delta x < -36.6$	$-\text{Inf} < \Delta x < -38.6$	$-\text{Inf} < \Delta x < -8.1$	No data	No data	No data	$-\text{Inf} < \Delta x < -35.7$	$21.5 < \Delta x < \text{Inf}$
T0—winter 3								
Wilcoxon P	No data	<0.05	<0.05	No data	No data	<0.05	<0.05	<0.05
Welch P	No data	<0.05	<0.05	No data	No data	<0.05	<0.05	<0.05
Welch diff (mg/l)	No data	$-\text{Inf} < \Delta x < -42.8$	$-\text{Inf} < \Delta x < -16.5$	No data	No data	$-\text{Inf} < \Delta x < -2.2$	$-\text{Inf} < \Delta x < -50.9$	$-\text{Inf} < \Delta x < -60.5$

Fig. 13 Mud volume in the central part of the harbor and in the Albert II dock (see Fig. 1) during different periods (see Table 3). The mud volume has been calculated from the differences between the 33- and 210-kHz echo soundings

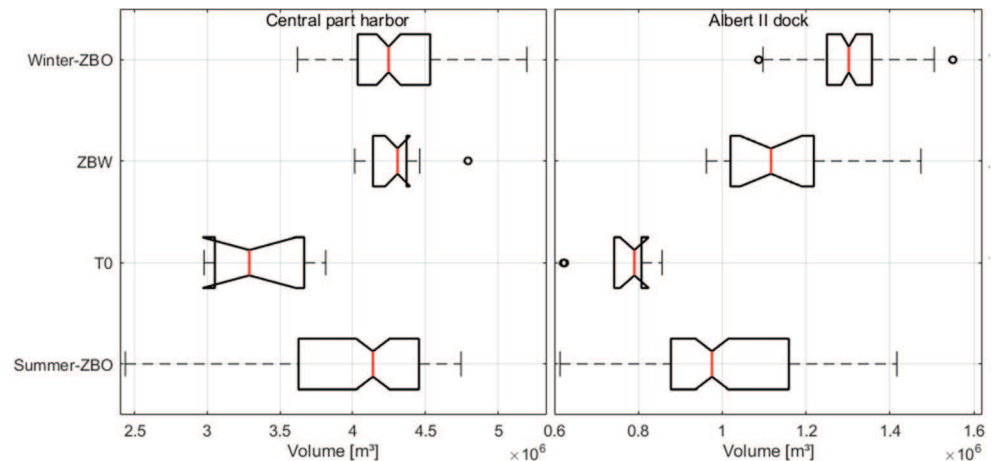


Figure 13 shows that the mud volume in the harbor (defined as the difference between the 33- and 210-kHz echo soundings) during the T0 period was exceptionally low. This could provoke higher sedimentation rates during the period thereafter (ZBW1). The distribution of the mud volume changes per day in the Albert II dock is shown in Fig. 14 for different periods with respect to the mud volumes during periods ZBW1 and ZBW2. The figure shows that no significant increase was seen in the rates of mud volume accretion during the first half of the field experiment. During the second half of the experiment (ZBW2) even a slight (although statistically not significant) decrease can be observed in the Albert II dock, which could point to a lower sedimentation in the harbor of Zeebrugge due to the relocation of the disposal site.

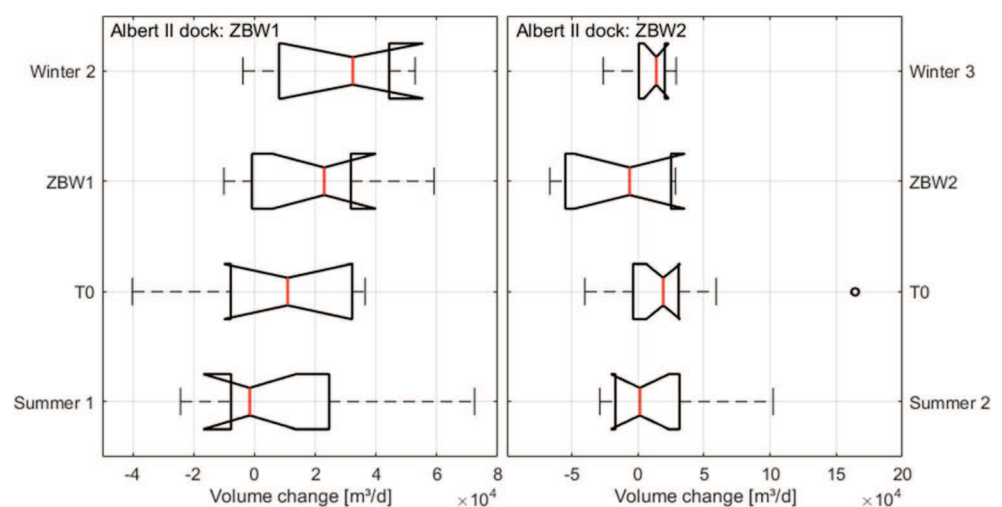
6 Conclusion

The use of optical and acoustical sensors to detect changes in SPM concentration has enhanced system understanding of the present state and helped in estimating the direction of changes

induced by the relocation of a disposal site. The use of different sensors (optical, acoustical backscatter) has also revealed the big differences in outcome that are a consequence of the fact that measurements are inherently associated with uncertainties. Positive is that the different sensors show the same trends, but the uncertainties due to the sensors itself are not fully quantified. The latter is especially relevant for the acoustic backscatter sensors, where more research is needed to develop well defined methodologies to invert backscattered signal to SPM concentration values in cohesive sediment environments (Rai and Kumar 2015).

The big issue for this and most other monitoring programs of SPM concentration and harbor siltation is to differentiate between anthropogenic impact and natural variations. The field experiment is somewhat different because the normal situation includes the human impact. The 1-month experiment, with relocation of the disposal site and reduction of the effects of disposal on the SPM concentration at the measuring locations, provides thus a glimpse on a more natural situation. Nevertheless, the method to assess the impact of the cessation of disposal or of the disposal on coastal ecosystem

Fig. 14 Mud volume changes in the Albert II dock (m^3/day) during the first (left) and second parts (right) of the field experiment as compared with other periods



and on harbor siltation is the same and is based on the understanding of the variability of the major processes that modulate the SPM concentration outside and the fluid mud layer inside the port. This can only be achieved when long-term time series exist that encompass to a certain degree also spatial variability. Quantifying the variability of SPM concentration is crucial to elucidate the processes that have an influence (tides, tidal range, alongshore flow, waves, seasons), to understand the typical range of the variability, and to identify anomalous natural or human induced events.

In the high-turbidity Belgian near-shore area, the natural forcings are responsible for the major variability in the SPM concentration signal, while disposal has only a smaller influence. The mean SPM concentrations at MOW1 is about 10 % higher when the dredged matter is disposed at ZBO site; this represents a probability of 55 % to have higher SPM concentration than using the alternative (ZBW). The results emphasize that tidal range, random events and seasons have a stronger influence on the SPM concentration signal than the relocation of the disposal site. The conclusion from the measurements is that the SPM concentration decreases after relocation of the disposal site, but indicate stronger (first half of field experiment) or weaker (second half of field experiment) effects that are, however, supported by the environmental conditions. Inside the harbor, the influence of relocation of the disposal site on SPM concentration and mud volumes is even more attenuated by seasonal and random effects. As a consequence, a statistical significant difference in SPM concentration or mud volume inside the harbor could not be found. The statistical tests also revealed that the duration of the field experiment was too short (1 month) to separate the effect of the relocation of the disposal site from the data with clear statistical significance.

Decision-makers should be aware that typical monitoring programs that follow the classical time-limited “before/after and during” approach, with a relatively short “during” period, will very often not provide unambiguous conclusions, but rather conclusions that indicate a probability of the (environmental) impact. In other words our results indicate that on the long run and with the assumptions that the forcings as well as the geometry and bathymetry of the port will not change, a reduction of the dredging volumes is to be expected when disposal site ZBW will be in use. The results of the field study may have consequences on the management of disposal operations as the effectiveness of the disposal site depends on environmental conditions, which are inherently associated with chaotic behavior. Changes in hydrodynamics, e.g., that are induced by changes in weather types, influence the direction of the residual currents and thus also of the residual SPM transport. A disposal site that is efficient during most of the time may induce recirculation of the disposed matter back to the dredging places during other weather types. Disposal

strategies should therefore allocate sites in a flexible way based on short-term predictions of environmental conditions and sediment dynamics. Developments in line with a flexible disposal strategy should encompass the recalibration and validation of the numerical model in order to obtain results over long periods of time that show the optimal use of disposal sites for forecasted weather conditions.

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