THESIS FOR THE DEGREE OF LICENTIATE OF PHILOSOPHY

Turbulent ship wakes and their spatiotemporal extent

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A ship and its turbulent wake. Illustration by Amanda T. Nylund.

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ABSTRACT

Shipping activities occur in almost every part of the global oceans and in intensely trafficked shipping lanes there can be up to one ship passage every ten minutes. All these ships impact the marine environment in different ways through pollution or physical disturbance. This thesis is focused on the turbulent ship wake, a physical disturbance from ships and previously overlooked as an environmental impact.

When a ship moves through water, the turbulence induced by the propeller and hull, will create a turbulent wake which remains and expands after the ship passage. The turbulence in the wake will govern the spread of contaminants and affect gas exchange in the wake water, physically perturb plankton, and potentially impact local biogeochemistry through increased vertical mixing.

To be able to assess the environmental impact of ship induced turbulence in areas with intense ship traffic, knowledge of the spatiotemporal extent and development of the turbulent wake is necessary. The aim of this thesis is to increase that knowledge, by conducting *in situ* observations of turbulent ship wakes, which can be used to estimate the spatiotemporal extent of the turbulent wake.

By using a collection of methods, the thesis work has resulted in a first estimate of the spatiotemporal extent of the turbulent ship wake, based on more than 200 field observations of different real-size ships in natural conditions. The observed turbulent wakes showed large variation in their spatiotemporal extent, and further studies are needed to fully disentangle how environmental conditions and vessel specifications affect the intensity and extent of the turbulent wake.

The results and experiences gained from the *in situ* observations, give an indication of the complexity entailed in characterising the development of the turbulent wake, and provide valuable input regarding the relevant parameters and spatiotemporal scales to include in future studies. The work of this thesis constitutes the first step in addressing the knowledge gap regarding the environmental impact from ship-induced turbulence and can be used as a road map for further studies within the field.

Keywords: ship wake, turbulence, environmental impact, shipping

SVENSK SAMMANFATTNING

Idag finns det fartygstrafik i nästan alla delar av världshaven och i de mest intensivt trafikerade farlederna kan det passera ett fartyg upp till var tionde minut. Alla dessa fartyg påverkar den marina miljön på olika sätt genom föroreningar eller fysisk påverkan. Den här avhandlingen är fokuserad på fartygets turbulenta vak (kölvatten), en fysisk påverkan från fartyg vars inverkan på den marina miljön inte har beaktats tidigare.

När ett fartyg rör sig genom vatten skapar propellern och skrovet turbulens som ger upphov till en turbulent vak, vilken lever kvar och expanderar efter det att fartyget har passerat. Vakens turbulens kommer att styra hur föroreningar sprider sig i vaken, påverka gasutbytet i vakvattnet, fysiskt störa plankton och potentiellt påverka lokal biogeokemi genom ökad vertikal omblandning.

För att kunna bedöma miljöpåverkan från fartygsinducerad turbulens i områden med intensiv fartygstrafik, så krävs kunskap om den turbulenta vakens utbredning i tid och rum. Syftet med denna avhandling är att öka den kunskapen genom *in situ* observationer av turbulenta fartygsvakar och använda dem för att uppskatta den turbulenta vakens spatiotemporala utbredning.

Genom att använda en kombination av olika metoder, har arbetet med denna avhandling resulterat i en uppskattning av den spatiotemporala utbredningen av turbulenta fartygsvakar. Denna uppskattning baseras på mer än 200 fältobservationer av olika typer av fartyg i verklig storlek, från mätningar under naturliga förhållanden. De observerade vakarna visade stor variation i rumslig och tidslig utbredning, och vidare studier behövs för att reda ut hur olika miljöförhållanden och fartygsspecifikationer påverkar den turbulenta vakens intensitet och utbredning.

Resultaten ifrån *in situ* observationerna ger en indikation på hur komplext det är att karaktärisera utbredningen av den turbulenta vaken, och ger även värdefull information om vilka parametrar som är relevanta att inkludera i framtida studier. Denna avhandling är det första steget i att adressera kunskapsluckan gällande miljöpåverkan från fartygsinducerad turbulens och kan användas för att vägleda utformningen av framtida studier inom fältet.

ACKNOWLEDGEMENTS

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LIST OF PUBLICATIONS

PAPER I

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Author contribution:
I-M. Hassellöv, **A. T. Nylund**, L. Arneborg and A. Tengberg conceptualised and conducted the in situ field measurements and consecutive analysis and visualisation. **A. T. Nylund** developed the code used in the analysis, with contribution from L. Arneborg. U. Mallast conducted the data curation and formal analysis of the satellite images, with contribution from **A. T. Nylund**. The manuscript was prepared by **A. T. Nylund** with contributions from all co-authors.

PAPER II

Ryazanov, I., **Nylund, A. T**., Basu, D., Hassellöv, I.-M. & Schliep, A. 2021. Deep Learning for Deep Waters: An Expert-in-the-Loop Machine Learning Framework for Marine Sciences. *Journal of Marine Science and Engineering,* 9**,** 169.

Author contribution:
I.R. and **A.T.N.** contributed equally to this work. A.S. and I.-M.H. conceived and supervised the study. All authors contributed to the design of the study. **A.T.N**. and I.-M.H. acquired the acoustic data, and **A.T.N**. performed the data annotation. I.R. and D.B. developed the method, the testing procedure and performed data analysis; the method was implemented by I.R. under supervision by D.B. The initial draft was written by I.R. and **A.T.N**. All authors discussed, read, edited and approved the article. All authors have read and agreed to the published version of the manuscript.

OTHER RELEVANT PUBLICATIONS, NOT INCLUDED IN THE THESIS

Ytreberg, E., Hassellöv, I.-M., **Nylund, A. T.**, Hedblom, M., Al-Handal, A. Y. & Wulff, A. 2019. Effects of scrubber washwater discharge on microplankton in the Baltic Sea. *Marine Pollution Bulletin,* 145**,** 316-324.

ABBREVIATIONS

ADCP	Acoustic Doppler Current Profiler
AIS	Automatic Identification System, a tracking system for ships.
CFD model	In this thesis, CFD model refers to a high resolution computational fluid dynamic (CFD) model used for optimising the ship hull and propeller design, which models the turbulent wake up to a few ship lengths behind the ship.
CNN	Convolutional Neural Network
CTD	An instrument used to measure Conductivity, Temperature and Depth
EU	European Union
FNR	False Negative Rate
GMM	Gaussian Mixture Model
GT	Gross Tonnage, a measure of a ships overall internal volume
HELCOM	Baltic Marine Environment Protection Commission, also the Helsinki Commission
IMO	International Maritime Organisation
IR	Infrared
PCA	Principal Component Analysis
RoPax	A roll-on/roll-off and passenger vessel, transporting vessels, cargo, and passengers.
SOLAS	International Convention for the Safety of Life at Sea
SST	Sea Surface Temperature

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1 INTRODUCTION

The shipping industry is an essential part of today's society and almost all areas of the global oceans are affected by shipping activities (Figure 1). One of the most heavily trafficked areas in the world is the Baltic Sea, where the major shipping lanes have more than 40 000 passages per year (HELCOM, 2010, Swedish Maritime Administration, 2015). That corresponds to almost one passage every ten minutes, around the clock, all year round. All these passing ships give rise to different types of pollution and physical disturbance, which in turn often leads to negative impacts on the marine environment (Moldanová et al., 2018).

This thesis is focused on a physical disturbance related to shipping, which has previously been overlooked as an environmental impact, namely the turbulent wake created behind the ship. When a ship moves through water, the hull and propeller induce turbulence, which forms a turbulent and bubbly wake (NDRC, 1946, Trevorrow et al., 1994, Soloviev et al., 2010, Voropayev et al., 2012, Francisco et al., 2017). The turbulent wake will govern how pollutants discharged from the ship will spread (Katz et al., 2003, Loehr et al., 2006, Golbraikh and Beegle-Krause, 2020), affect gas exchange in the wake water (Weber et al., 2005, Emerson and Bushinsky, 2016), cause physical disturbance to the plankton community (Bickel et al., 2011, Garrison and Tang, 2014), and potentially change the nutrient availability in the upper surface layer due to increased vertical mixing (Paper I). However, to assess the effects of these different environmental impacts from the turbulent wake, a description of the spatial and temporal extent of the turbulent wake is needed.

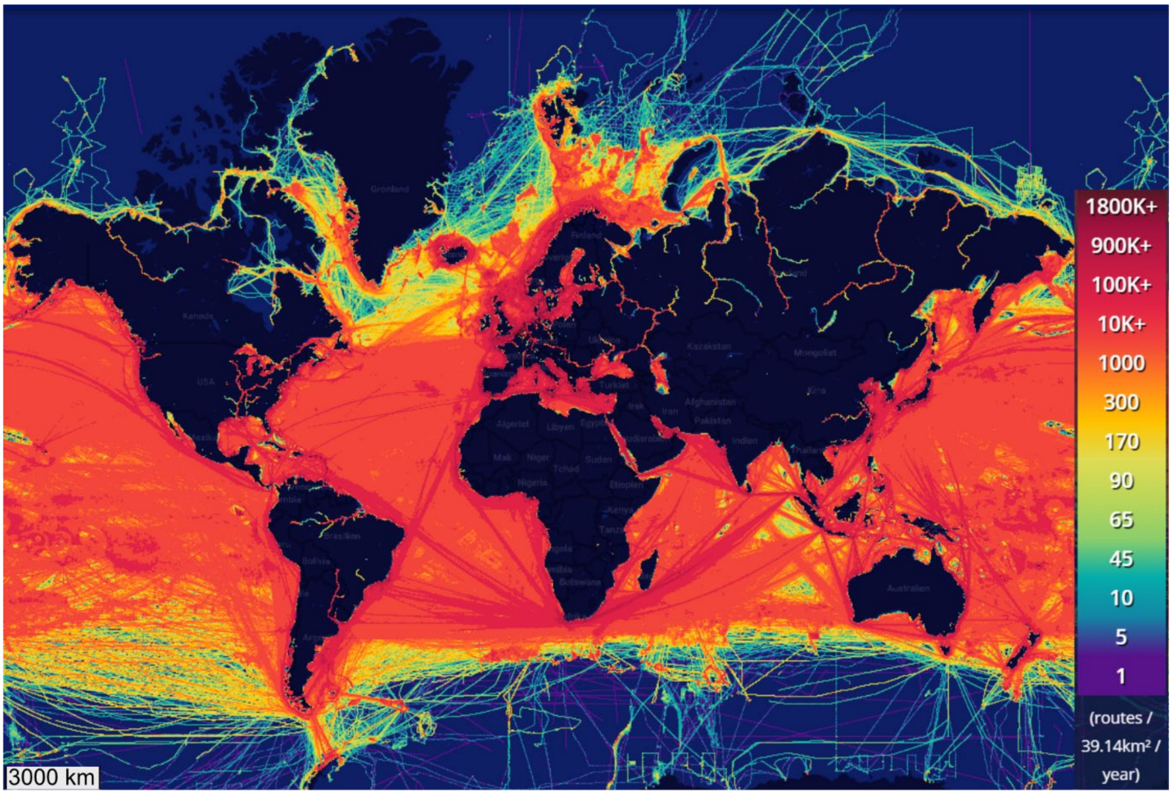

Figure 1. Density map of the global accumulated ship traffic in 2019. Figure from Marine Traffic, based on AIS data https://www.marinetraffic.com.

To assess the environmental impact from ship-induced turbulence in shipping lanes, the observations used to characterise the turbulent wake must reflect the variation of ships that operate in the major shipping lanes. Thus, it is necessary to investigate how the ship size, type, and operation affects the development of the turbulent wake extent. Environmental conditions such as water column stratification, currents, and waves, also affect the development of the turbulent wake (Loehr et al., 2001, Voropayev et al., 2012, Somero et al., 2018), hence it is important to observe turbulent wakes in natural conditions.

The available observations of the spatial and temporal extent of turbulent wakes are from a limited number of ships and ship types (Table 1), thus none of these studies have characterised the spatiotemporal extent of the turbulent wake for a large set of ship types in natural conditions. The number of studies considering the environmental impact from ship-induced turbulence are even fewer. There is one study from 2001 (Lindholm et al., 2001), conducted in the Åland archipelago, where a deepened stratification was observed, and the potential impact on the biogeochemistry was discussed. The study site was a narrow shipping lane in shallow water, and the environmental impact from ship induced turbulence in open waters was not fully considered, hence, there is a current knowledge gap regarding the environmental impact from the ship induced turbulence itself.

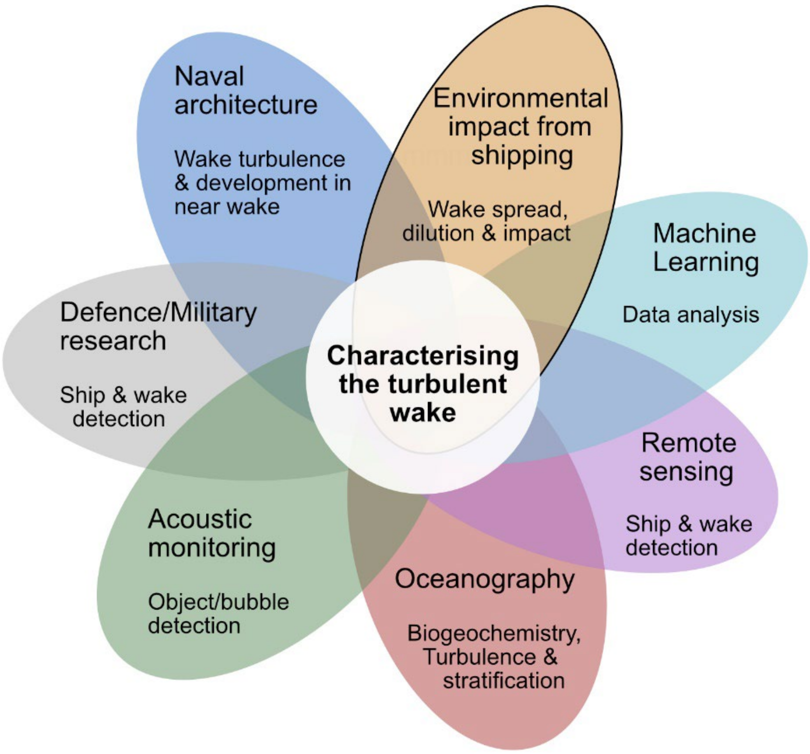

Figure 2. Research fields relevant for the study of turbulent ship wakes.

Therefore, the focus of this thesis is to characterise the spatiotemporal extent of the turbulent wake *in situ*, for a large set of different ship types. This requires identifying the current knowledge gaps within the field of turbulent wake research and finding appropriate methods for observing and describing the temporal and spatial extent of the turbulent wake. The study of turbulent wakes is complex and inherently interdisciplinary, and observations of turbulent ship wakes and relevant methodologies, can be found in a diverse set of research fields (Figure 2). The starting point of this thesis is within the field of environmental impact from shipping and it adds the dimension of environmental impact to the study of the turbulent wake. Oceanography, the study of ocean systems and processes, provides a basis for the work, and the other fields in Figure 2 provide methodologies for observing different parts of the turbulent wake. Therefore, an interdisciplinary approach is needed, and collaboration with field experts is necessary to apply the different methods required to observe the entire extent of the turbulent wake.

1.1 THESIS AIM

The overarching aim of this research project is to assess the environmental impact from ship-induced turbulence in areas with intense ship traffic. The specific aim of this thesis is to take the first step in reaching that goal, by conducting *in-situ* observations of turbulent ship wakes.

The specific objectives for this thesis are to:

Investigate and test methods that can be used to observe/estimate the spatiotemporal extent of the turbulent wake *in situ*.

Answer the questions:

- What is the *in situ* spatiotemporal extent of turbulent ship wakes?
- Can machine learning models be trained to accurately detect ship wakes in acoustic data, with only a limited dataset to train on?

The first objective and question are addressed in Paper I, the last question in Paper II.

2 BACKGROUND

The study of turbulent ship wakes is interdisciplinary and require insight into a diverse set of research fields (Figure 2). To assess the environmental impact from ship-induced turbulence, knowledge from both the maritime industry and marine science field is needed. There are few previous studies where the spatiotemporal extent of turbulent ship wakes has been observed (Table 1), and of these, less than a handful studied the turbulent wake in relation to environmental impact. The previously reported observations of turbulent wake extent, and relevant methodologies for the study of turbulent ship wakes, can be found in several different research fields. Moreover, only by combining methodologies from different fields, is it possible to study the entire

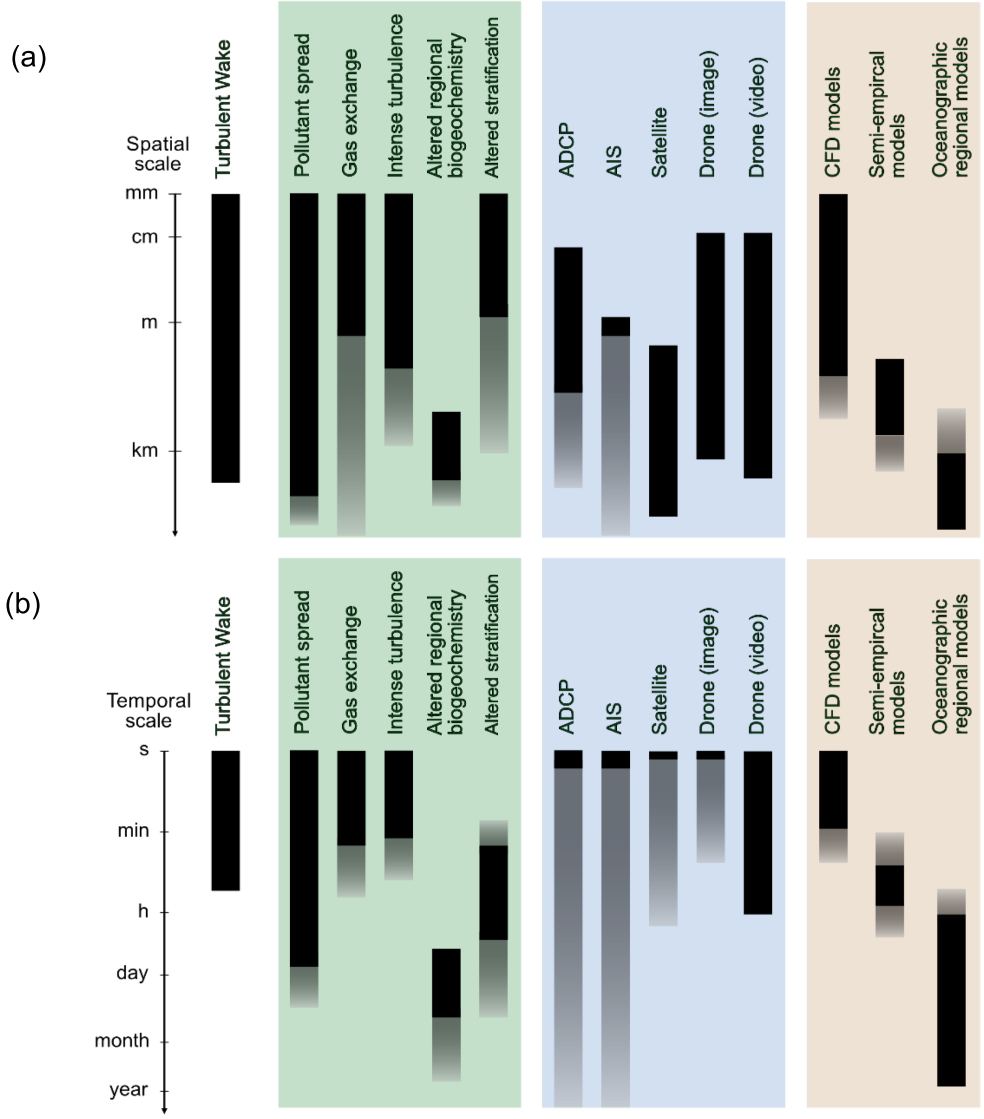

Figure 3. The spatial (a) and temporal (b) extent of the turbulent wake (white background), potential environmental impacts (green), methods for observing the turbulent wake (blue), and models relevant for studies of turbulent wakes (orange). The scales are logarithmical. The filled sections of the bars represent the area where an environmental impact occurs, or direct observations/model estimates can be made. The shaded sections of the bars represent areas where environmental impacts might occur (green), where the extent can be inferred from direct observations (blue), or models could be extended (orange). The extent of the turbulent wake is further described in section 2.1 and the potential environmental impacts in section 2.3. Methods for observing and modelling the turbulent wake are presented in section 3.

spatiotemporal extent of the turbulent wake and its impact. The following sections will describe the spatiotemporal extent of the turbulent wake, its possible environmental impacts, and available methodologies to observe and model the turbulent wake (summarised in Figure 3).

2.1 THE TURBULENT WAKE

A ship moving through water will create a wake behind the ship, which gives rise to surface waves, bubbles, and turbulence. The characteristic surface waves that spread in a V-shape behind the ship are referred to as the Kelvin wake envelope, with diverging wakes following the V-shape and transverse wakes across the wake field (Figure 4a) (Stanic et al., 2009). The focus of this study is the turbulent wake aft of the ship, which is induced by the ship's movement and the propeller (Figure 4a) (NDRC, 1946, Soloviev et al., 2010, Voropayev et al., 2012, Francisco et al., 2017). The turbulent wake is characterised by an increased turbulence and a dense bubble cloud. The wake depth, width, and longevity (Figure 4b) varies depending on the ship's geometry, speed, and manoeuvring, and environmental conditions including water column stratification, currents and waves (Loehr et al., 2001, Voropayev et al., 2012, Somero et al., 2018). There is currently a knowledge gap regarding how these vessel specific and environmental parameters interact and affect the spatiotemporal extent and intensity of the turbulent wake.

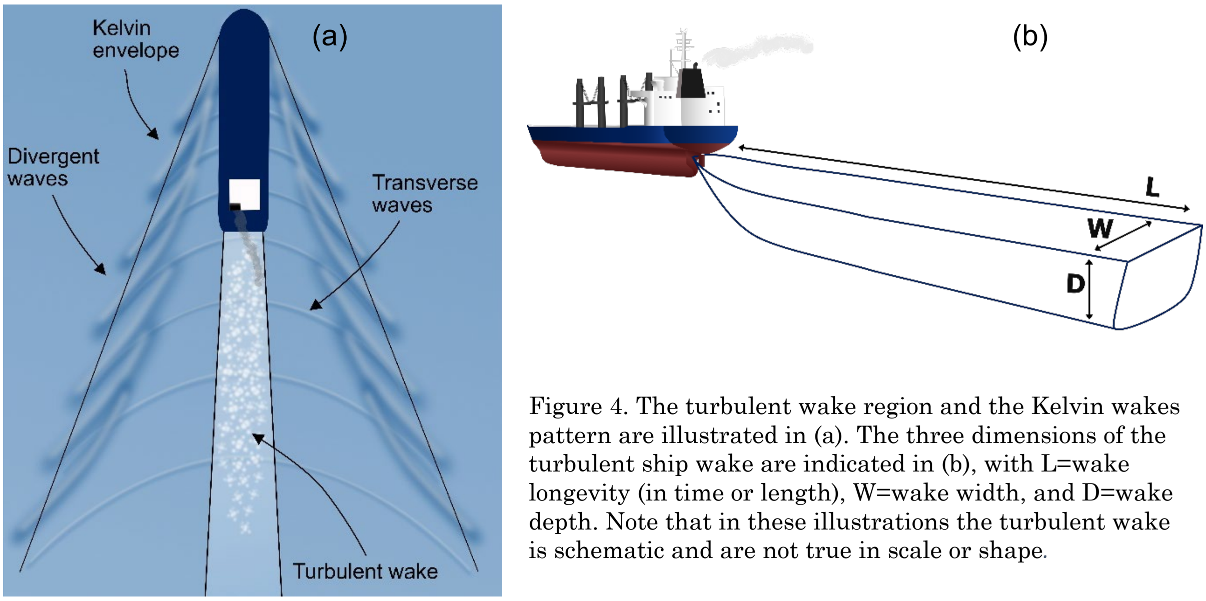

Figure 4. The turbulent wake region and the Kelvin wakes pattern are illustrated in (a). The three dimensions of the turbulent ship wake are indicated in (b), with L=wake longevity (in time or length), W=wake width, and D=wake depth. Note that in these illustrations the turbulent wake is schematic and are not true in scale or shape.

2.1.1 Field observations

Until now, *in situ* observations of turbulent ship wakes have mainly been conducted with the aim of detecting or identifying ships through their wakes, and mostly for military purposes (Smirnov et al., 2005, Liefvendahl and Wikström, 2016).There are a few publicly available studies about ship-induced turbulence where field measurements of the spatiotemporal extent of the turbulent wake have been presented (Table 1, adapted from Paper I). The reported extent ranges between 3–18 m for the wake depth, 10–250 m for the wake width, and 10–60 min/1–22 km for the wake longevity (Figure 3).

Only three of the studies in Table 1 were conducted with the aim to assess the environmental impact or extent of ship induced turbulence, and only four include simultaneous measurements of wake depth, width and longevity (NDRC, 1946, Trevorrow et al., 1994, Loehr et al., 2001, Ermakov and Kapustin, 2010). Moreover, the number of investigated vessels and vessel types are few, with a predominance of smaller vessels (< 50 m long); hence, there is a current lack of field measurements of the turbulent wake of real-size ships (Carrica et al., 1999, Parmhed and Svennberg, 2006, Ermakov and Kapustin, 2010, Golbraikh and Beegle-Krause, 2020).

Table 1. Previously reported field measurements of the spatial and temporal scales of the turbulent wake. The method used to estimate the turbulent wake is indicated in the "Method" column. For studies where only the temporal wake longevity was measured, an estimate of the wake length has been calculated using the wake duration and a ship speed of 12 knots.

Study	Method	Wake depth [m]	Wake length [km]	Wake duration [min]	Wake width [m]	Nr. of Vessels	Vessel type
NDRC (1946)	Acoustic/ thermal	3–10	11–22	30–60	40–90	1–3	Naval, research
Trevorrow et al. (1994)	Acoustic	6–12	2.8*	7.5	66 (avg.)	3	Research
Loehr et al. (2001) ¤	Acoustic	3–18	5–6*	15–17	76–155	2	Cruise ship
US-EPA (2002) ¤	Dye concentration	12–18				4	Cruise ship
Katz et al. (2003)	Dye and paper pulp concentration	8–10	3**			1	Naval
Weber et al. (2005)	Acoustic	8	6	15		1	Research
Stanic et al. (2009)	Acoustic		1.5–2	20	10	1	Research
Ermakov & Kapustin (2010)	Acoustic	4–8	3.7–5.5*	10–15	40–80	1	Small passenger
Soloviev et al. (2010)	Acoustic	10–15	4–10*	10–30		2	Container, cargo
Gilman et al. (2011)	Visible surface trace				100–250	1	Cruise ship
Soloviev et al. (2012)	Acoustic	7				1	Cargo
Francisco et al. (2017)	Acoustic	6–12	0.5*	1.5		2	Passenger ferry

*Calculated based on temporal longevity and a ship speed of 12 knots, **Distance at which the max width was documented, ¤ Report, not peer reviewed.

The majority of the studies reporting turbulent wake depths, made observations of the bubble cloud in the turbulent wake using acoustic sensors (i.e. multibeam, sonars, Acoustic Doppler Current Profilers (ADCPs), fathometers)(Table 1). As bubbles reflects sound more efficiently than water, the bubbly wake can be clearly distinguished as an elevation in echo amplitude in acoustic data (NDRC, 1946, Trevorrow et al., 1994, Marmorino and Trump, 1996, Weber et al., 2005, Ermakov and Kapustin, 2010, Francisco et al., 2017, Paper I). A visualisation of the elevated echo amplitude induced by the bubble cloud in the turbulent wake is presented in Figure 5. In addition to the acoustic measurements of wake depth, two studies added dye to the turbulent wake and measured its spread and dilution, based upon which a wake depth estimation could be made (US-EPA, 2002, Katz et al., 2003).

The observed wake widths vary, with the studies by Gilman et al. (2011) and Loehr et al. (2001), providing the markedly widest estimates at 100-250 m. Gilman et al. (2011) was the only study using imagery of the visible surface trace to estimate the wake width; all others used acoustic methods. Gilman et al. (2011)'s use of imagery of the visible surface trace could be one explanation to the larger estimate of wake width. However, the vessel size, type, and speed can also impact the wake characteristics. The cruise ships studied by Gilman et al. (2011) and Loehr et al. (2001) were roughly three times wider (32.6–38.6 m) compared to the vessels in the other studies reporting wake widths (range 6–12.2 m). The wake width/ship width ratio for most of the studies was between 2–7, except for two smaller vessels which had a ratio of 12–13.

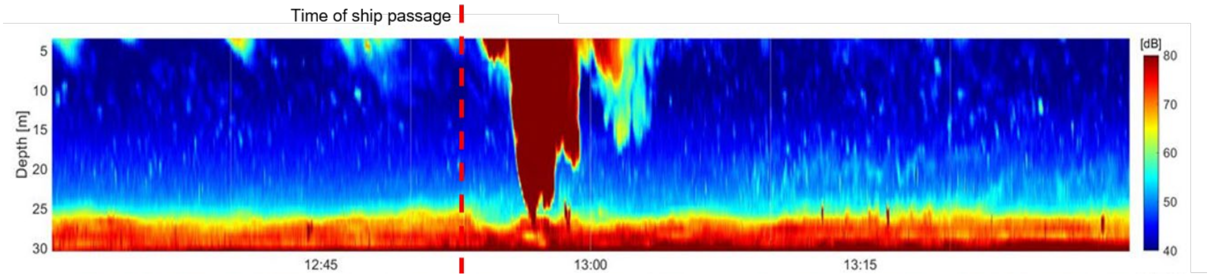

Figure 5. Example of ADCP measurement from field studies included in this thesis, showing the signal of the bubble cloud in the signal strength/echo amplitude data.

The observed wake longevity can be expressed either as the distance aft of the ship (spatial longevity) where the wake is still detectable, or the time it takes for the wake to disappear after ship passage (temporal longevity). Temporal longevity has been reported more frequently than spatial longevity in the currently available literature, and the temporal duration can be used to calculate an estimated distance based on the vessel speed (Table 1). Previously reported longevities also show a wide range, from temporal longevities of 1.5 minutes up to 60 minutes, which corresponds to a spatial longevity of 0.5–22 km respectively, for a vessel speed of 12 knots. Similar to the wake width, the method of observation, vessel size, and speed, as well as the environmental conditions, varied between the studies reporting turbulent wake longevities, which is one possible explanation to the broad range.

2.1.2 Model scale observations and numerical modelling

In addition to the field observations presented in the previous section, there are also numerical modelling studies and observations of turbulent wakes from model-scale ships. Most of the available studies of turbulent ship wakes, are modelling studies focusing on the near field of the wake close to the ship hull. For the near wake (up to a few ship lengths behind the ship), high resolution computational fluid dynamic (CFD) models have been developed for the purpose of optimising the ship hull and propeller design (for brevity refered to as CFD models from now on). However, due to the limited spatial extent of the CFD models', they are insufficient to capture the full extent of the turbulent wake (Figure 3).The CFD models are often validated using observations from towing tank experiments with model-scale ships e.g. (Carrica et al., 1999, Parmhed and Svennberg, 2006, Fu and Wan, 2011, Liefvendahl and Wikström, 2016), often during idealised conditions without stratification, currents or waves. Using model scale results to estimate the spatiotemporal extent of the turbulent wake, is not ideal, as the Reynolds numbers at model scale are too small to represent turbulence induced in full scale and natural conditions.

To estimate the turbulent wake extent, the few studies that have used *in situ* and model-scale observations to develop semi-empirical models of the turbulent wake (Katz et al., 2003, Voropayev et al., 2012), are more useful than CFD models. The semi-empirical models cover the intermediate and far wake, thus including a larger portion of the turbulent wake extent, and partly overlapping with the region covered by the CFD models (Figure 3). Despite the benefits of a large spatiotemporal range, they are simplified numerical models, valid for the vessels and conditions they have been verified for. Furthermore, the models were not developed with the aim of characterising the extent and development of the wake turbulence, but focused on dilution of pollutants (Katz et al., 2003) or the thermal signal of the turbulent wake (Voropayev et al., 2012).

Katz et al. (2003) modified an existing computational model for wake mixing of naval ships, originally used for tracking microbubble wakes. The model was modified to predict the dilution and distribution of solid waste discharged in the wake, for the near and intermediate part of the wake (0.5 < ship lengths < 30 behind the vessel). The modelled results were in excellent agreement with the field observations (presented in Table 1) and were considered to reliably predict the fate of solid waste discharged in the wake behind the investigated US navy ship. In addition, the results give an indication of the spatiotemporal extent of the turbulent wake, as the waste particles can be used as a proxy for the water in the turbulent wake (see section 2.3.1).

Voropayev et al. (2012) is one of the few turbulent wake studies considering the effect of stratification. In their experiments, a model ship was towed in a tank with thermally stratified water, where the stratification depth was 2.5 times the draught of the model. The mixing induced by the model ship created a thermal signal of the wake (thermal wake) visible at the water surface. The thermal wake was 1–2 °C colder compared to the surrounding water and detectable 30 ship lengths behind the vessel. For a 150 m long vessel that would correspond to 4.5 km, which is in the same range as the field observations in Table 1. The results further indicated that the turbulence in the wake region was sustained for about 10–15 ship lengths behind the ship (1.5 km for a 150 m vessel) and that the turbulent mixing subsides at about 30 ship lengths behind the ship. Voropayev et al. (2012) also presents a semi-empirical model estimating the temperature difference in the wake, at medium to large distances from the ship (the near wake was not well captured by the model). As the model only predicts the temperature difference at the sea surface, and not the vertical distribution or wake turbulence, its use for estimating the spatiotemporal extent of the turbulent wake is limited to estimating the thermal wake longevity.

2.1.3 Every ship is unique and so is the environment it moves in

Observing and characterising turbulent ship wakes *in situ* is complex, because both the environmental conditions and the ship design and operation, impacts the wake development (Stanic et al., 2009). Thus, it is important to investigate which of the vessel-specific and environmental parameters that contributes most to the development of the turbulent wake.

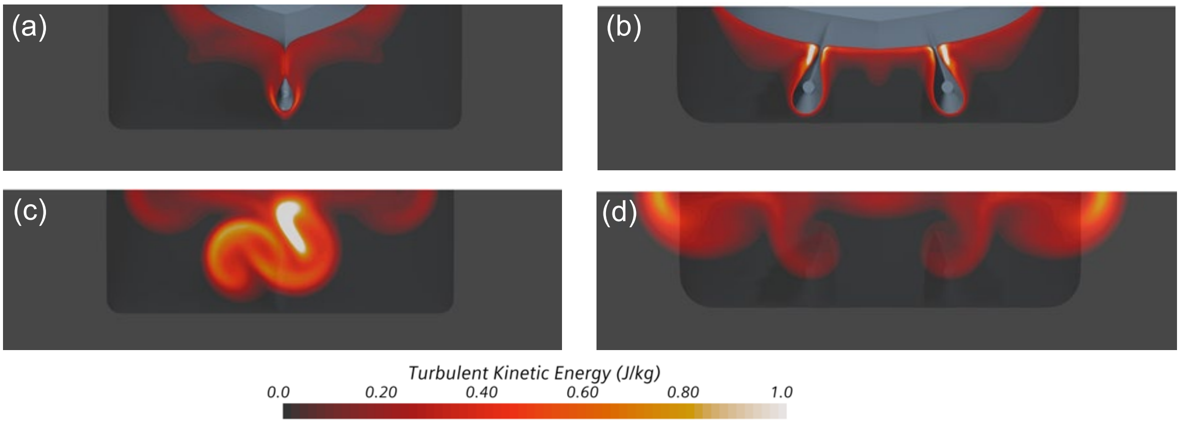

Figure 6. Results from a CFD model using a Reynolds-Averaged Navier-Stokes (RANS) approach, showing the turbulent kinetic energy distribution behind a tanker ship with a single propeller (a, c) and a RoPax ship with twin propellers (b, d). (a) and (b) is before the propeller plane and indicates the hull shape. (c) and (d) is from 300 m behind the ship and shows the difference in turbulent wake development between the two propeller configurations. Visualisation: Arash Eslamdoost.

Ships come in a variety of sizes and hull shapes, and are optimised for an intended speed and cargo (Stopford, 2008). To only consider the length, draught, and beam (width) of a ship, is not enough, because a slender hull shape will have a very different displacement volume compared to a bulky hull with the same measurements. Additionally, the number, design, and rotation of the propellers, will also affect the development of the turbulent wake. Figure 6 illustrates how the number of propellers can impact the development and shape of the turbulent wake, where the single propeller wake is more intense and reaches deeper compared to the twin propeller configuration. The twin propeller, however, has a larger horizontal distribution, resulting in a wider wake. Furthermore, the twin propeller rotation in Figure 6 is inward and upward, which gives a shallower and wider wake compared a rotation in the opposite direction, which would give a downward rotation. The impact of the number of propellers have been observed in the field, where the bubble wake induced by twin propeller ships have been observed to create two distinct bubble trails, instead of one (Marmorino and Trump, 1996, Weber et al., 2005). In addition to the vessel and propeller design, the ship speed and manoeuvring will affect the wake, as the direction and input of energy will differ.

Environmental conditions such as wind, waves, current, and water column stratification, also affect the development of the turbulent wake. Field observations have shown that strong currents and shear can alter the wake signal (Loehr et al., 2001, Somero et al., 2018), and if the water is stratified, the turbulent wake will interact with the stratification. A strong stratification can reduce the vertical extent of the turbulent wake, compared to unstratified conditions (e.g. Voropayev et al. (2012). The turbulent wake can also create mixing across the stratification (Lindholm et al., 2001, Loehr et al., 2001, Paper I), and thereby entrain deeper water from below the stratification into the wake, and potentially weaken the stratification.

2.2 ENVIRONMENTAL IMPACT FROM SHIPPING

The shipping industry holds a key role in today's globalised society. 80–90 % of all global trade is transported via ship (Balcombe et al., 2019)(UNCTAD, 2020). Before the COVID-19 pandemic, the maritime trade was predicted to increase by 3.4 % annually until 2024 (UNCTAD, 2019). In 2020, however, the pandemic caused disruption in maritime trade, which has resulted in a predicted drop of 20 % for 2020 (UNCTAD, 2021). Although still uncertain, forecasts predict in the negative trend to turn in 2021 (UNCTAD, 2021). The large demand for maritime transport of goods results in an intense ship traffic across the globe, and especially concentrated in coastal areas (Figure 1). In highly trafficked areas such as the Baltic Sea, the major shipping lanes have up to one passage every 10 minutes (HELCOM, 2010, Swedish Maritime Administration, 2015). These ships impact the marine environment in different ways, and in coastal regions, the environmental impact of shipping is one of the largest stressors on the marine environment (Halpern et al., 2019).

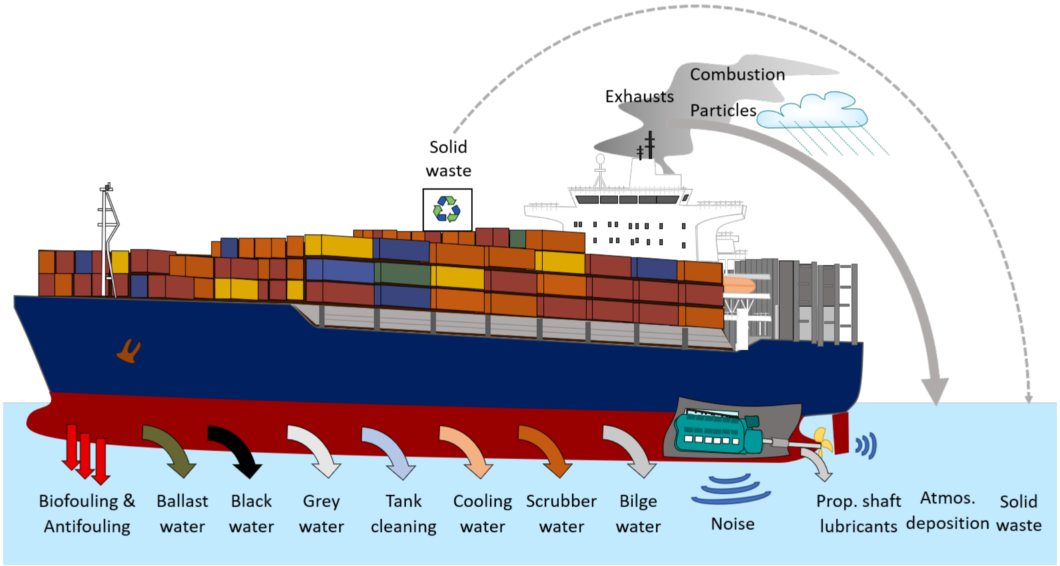

Figure 7. Operational emissions and discharges from ships. Adapted from Hassellöv et al. (2019).

During operation, ships emit and discharge a multitude of pollutants and create physical disturbances (Andersson et al., 2016, Moldanová et al., 2018, Hassellöv et al., 2019). It is beyond the scope of this thesis to give an exhaustive description of all environmental pressures and stressors from ships. In short, contaminants, eutrophying and acidifying substances, and non-indigenous species from ships enter the marine environment through a range of pathways such as bilge-, grey-, black-, and ballast water, solid food waste, tank cleaning, wash water from exhaust gas cleaning systems (scrubbers), antifouling paints, and indirect deposition of atmospheric emissions. In addition, noise is generated from both the engine and the propeller (Figure 4).

Compared to other types of ship generated pollution, there have been less focus on the impact of physical disturbances from shipping, i.e. energy introduction through noise, temperature (cooling water), turbulence, or waves. However, since the adoption of the Marine Strategy Framework Directive (MSFD) in 2008 (MSFD, 2008/56/EC), EU member states must include the effect of physical disturbances in their marine management plans, as the eleventh quantitative descriptor for determining good environmental status requires that the "*Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment*" (European Parliament, 2008). To meet the requirements set in the MSFD, there is therefore an immediate need for more knowledge about how anthropogenic introduction of energy affects the marine environment.

There are numerous studies about the impact of underwater noise on the marine environment (e.g. Popper and Hawkins (2016), Duarte et al. (2021)), and there have also been studies of physical effects of erosion caused by wake wash (Soomere, 2007, Scarpa et al., 2019). However, there is one type of physical disturbance from shipping that has been overlooked, and that is the energy input from ship-induced turbulence. In areas with low tidal energy, and where the natural input of turbulence comes from wind and waves, intense ship traffic can contribute with a substantial part of the turbulent energy input in the upper surface layer, on a local/regional scale (Paper I). Hence, there is a need to characterise the intensity and extent of the ship's turbulent wake, in order to be able to estimate during which circumstances the impact is relevant to include in holistic assessments of the environmental impact from shipping.

2.3 ENVIRONMENTAL IMPACT FROM SHIP-INDUCED TURBULENCE

The turbulent wake has the potential to affect several processes which can lead to an impact on the marine environment (Figure 3). The ship-induced turbulence will govern the initial spread of contaminants discharged from the ship, have direct effects on the plankton community, and in areas with frequent ship passages, the energy input through vertical mixing could potentially lead to changes in regional/local hydrography (Figure 8). In addition to these effects, the turbulence and bubble cloud will also affect the gas exchange in the wake region (Weber et al., 2005, Emerson and Bushinsky, 2016). In shallow areas, were the wake depth and water depth are similar, the turbulent wake can also lead to increase turbidity and erosion.

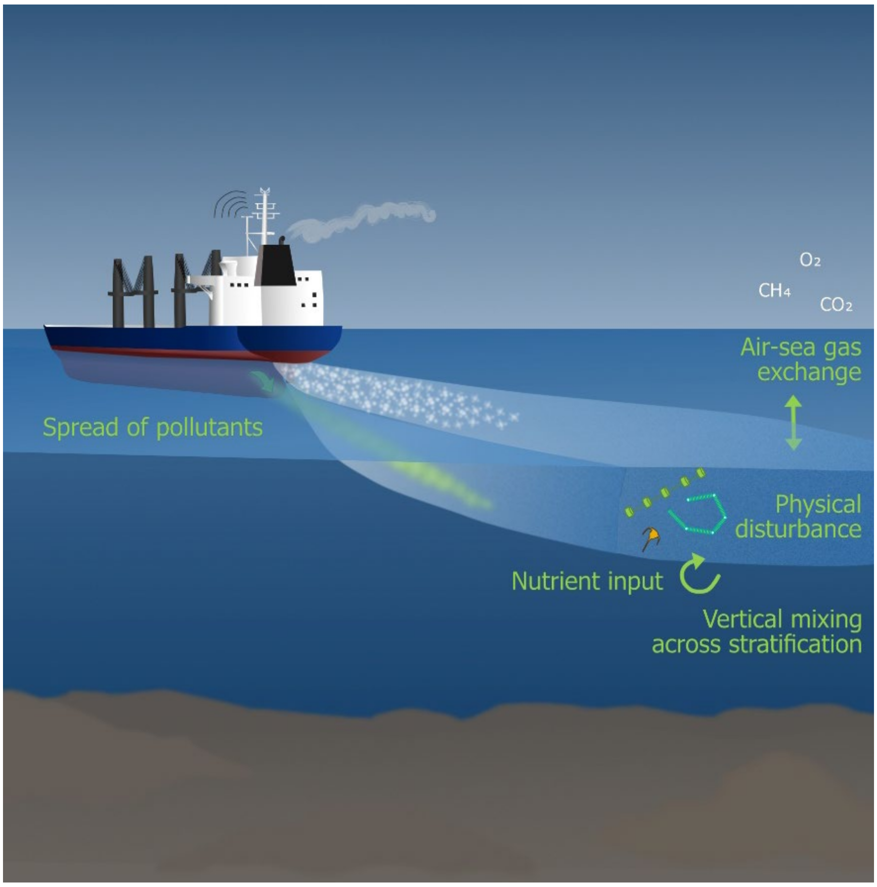

Figure 8. Environmental impacts from a turbulent ship wake.

From a single ship passage, the environmental impact is mainly connected to how the turbulent wake affect the distribution of pollutants and direct physical disturbance on plankton in the wake region. However, in areas with intense ship traffic the repeated episodes of high-intensity turbulence could be high enough to expand the potential environmental effects to include regional effects on the plankton community, biogeochemical cycles, ecological connectivity, and hydrography.

2.3.1 Distribution of pollutants

A large part of the contaminants and nutrients discharged from ships end up in the turbulent wake (Figure 4). The turbulence in the wake region will affect the spread and distribution of contaminants and nutrients discharged from the ship, as well as those already present in the water at ship passage (US-EPA, 2002, Katz et al., 2003, Loehr et al., 2006, Golbraikh and Beegle-Krause, 2020). To estimate how contaminants and nutrients from shipping spread, where the impact will be the largest, and which concentrations that are to be expected, it is necessary to characterise the extent and mixing in the turbulent wake.

The knowledge of when and where discharges occur, is important for the environmental impact assessment. Some discharges occur continuously (antifouling, wash water from open and closed loop scrubbers), whereas other are only allowed 12 nautical miles (nm) from land (food waste, black-, grey-, and bilge water), which will lead to a difference in spatial distribution between the two modes of discharge (Moldanová et al., 2018, Raudsepp et al., 2019, Jalkanen et al., 2020). As the direction and strength of currents can vary between depths, it is necessary to know the vertical distribution of pollutants to estimate the horizontal spreading.

2.3.2 Effect on ecology and biogeochemical cycles

The episodic intense turbulence induced by a ship passage can have a negative impact on the local plankton community (Bickel et al., 2011, Garrison and Tang, 2014). *In situ* observations in an area with intense ship traffic by Bickel et al. (2011), showed that 34 % of the investigated copepod population consisted of copepod carcases, which was 28 % more than in nearby undisturbed areas. The results from their laboratory experiments also indicated that the turbulence observed in turbulent ship wakes, would cause a mortality of 100 % for the copepod *Acartia tonsa*. Laboratory experiments with phytoplankton, have shown similar results (Garrison and Tang, 2014). Garrison and Tang (2014) reported that 45 seconds of exposure to turbulent kinetic energy dissipation rate levels of 2.5 $cm^2\ s^{-3}$, reduced the abundance of diatoms up to 32 %, and increased the number of dead cells with 22 %. In areas with intense ship traffic, the frequency of episodic turbulence could thus lead to local/regional effects in plankton mortality, composition, and release of nutrients (Bickel et al., 2011, Garrison and Tang, 2014). This in turn would be of importance for the transport of organic matter in the food web, as it would change the nutrient availability for phytoplankton and the microbial loop, as well as the food availability at higher trophic levels (Bickel et al., 2011, Garrison and Tang, 2014).

In addition to the direct effect of repeated ship passages in the local/regional ecosystem, the local hydrography could also be impacted by the ship induced turbulence. As hydrographic conditions such as stratification, determines the environmental conditions, changes in hydrography would also have indirect ecological impacts. In marine systems where the natural vertical mixing is mainly wind driven (no tides or strong currents), the nutrient supply is dependent on vertical mixing (Reissmann et al., 2009). In such areas, ship induced turbulence could contribute with a substantial part of the vertical mixing during certain periods of the year (Paper I). With a stratification depth similar to the vertical extent of the turbulent wake, frequent ship passages have the potential to affect the stratification depth, strength, and create mixing across the stratification. If the stratification is limiting the nutrient input to the surface layer (Reissmann et al., 2009, Snoeijs-Leijonmalm and Andrén, 2017), increased mixing across the stratification from turbulent ship wakes, could alter the nutrient supply to the photic zone. This implies, that ship-induced vertical mixing could be an overlooked part of the local/regional hydrography and biogeochemistry, as the nutrient input to the photic zone could be larger than what would be expected from only wind generated vertical mixing (Paper I). However, the potential impact from turbulent ship wakes on regional/local hydrology and biogeochemistry has not yet been studied, which motivates the need for further studies to assess/estimate the potential impact.

3 REVIEWING AND COMBINING METHODS FROM DIFFERENT FIELDS

There are a number of research fields relevant to the study of turbulent wakes (Figure 2). What all the fields have in common, is that 1) they only concentrate on an isolated aspect of the turbulent wake, and 2) the primary focus of the research is never the turbulent wake itself. Therfore, one of the main aims of this thesis is to identify available methods specifically targeted at studying the extent and impact of the entire turbulent wake. The overarching aim if the research project, also involves adding the dimension of environmental impact to the study of the turbulent wake. This involves using observations of the turbulent wake, and then apply the knowledge of ocean systems and the shipping industry, to make an assessment of the impacts on the natural system. Consequently, it relies on integration of knowledge and collaboration with experts from different fields and requires an interdisciplinary approach. Drawing on the knowledge from existing research fields, possible contributions and limitations to the study of turbulent wakes have been identified, and informed the choice of methodology for the *in situ* turbulent wake observations. The methods discussed here are not all-encompassing, but reflect the methodologies most frequently used in previous studies.

To characterise the extent and development of the turbulent wake, methods of observation need to cover the turbulent wake in its entirety. The temporal scales of the turbulent wake range from seconds to hours, whereas the possible impact from the turbulence could remain at even longer timescales (Figure 3b, Table 1, Paper I). The relevant spatial scales are similar for both the wake and its impacts, stretching from micrometres to tens of kilometres (Figure 3a, Table 1, Paper I). There exists multiple methods which can be used to observe or model the extent of the turbulent wake of a ship (Figure 3), but none of them are able to capture the entire development of the wake at all relevant temporal and spatial scales.

3.1 OBSERVATIONS USING ACOUSTIC INSTRUMENTS

Acoustic instruments send out acoustic signals and record the signal echo amplitude, which can be visualised as echograms (see Figure 5 for example). Most of the previous observations of turbulent ship wakes have been made with acoustic instruments (e.g. multibeams, ADCPs), where the bubble trace of the turbulent wake has been used as a proxy of wake longevity and distribution (Table 1). However, bubbles will eventually either dissipate or float up to the surface, resulting in the disappearance of the bubbles (Carrica et al., 1998, Ermakov and Kapustin, 2010). Although the distribution of the bubbles is related to the turbulence in the wake, as bubbles found at depth must have been transported there by turbulence, the positive buoyancy of the bubbles will cause an upward transport. This could lead to an underestimation of the turbulent wake depth, when the bubble cloud is used as the main proxy (Golbraikh and Beegle-Krause, 2020). In addition, the longer lasting effects of the turbulent wake, i.e. the vertical mixing, is not captured by the bubble cloud.

ADCPs can measure velocity at multiple layers in the water column, from which estimates of the turbulence itself (i.e. dissipation rate of turbulent kinetic energy (ε)) can be calculated (Wiles et al., 2006, Lucas et al., 2014, Togneri et al., 2017). The velocity is a more direct measure of the turbulence compared to the bubble cloud, which is a proxy for the extent of the turbulence. Moreover, the velocity is not affected by a net upward motion like the bubbles and will therefore give a better estimate of the vertical distribution of the wake. By using an ADCPs, it is thus possible to observe both velocity and echo amplitude, which provides a more robust estimate of the wake extent compared to using only the bubbles. It also provides a measure of the intensity of the wake turbulence. Depending on the instrument type, acoustic frequency, and settings (bin size and ping frequency), the turbulent length scales that can be calculated from the velocity measurements will differ (Wiles et al., 2006), which must be taken into consideration.

ADCPs use 3-4 beams to calculate horizontal and vertical current speed and direction, where each beam gives the temporal development in a cross section of the wake in one point. The area that they cover (their footprint), is limited to around 30 m when using the high-resolution instruments that are required to study the effects of ship traffic. To increase the spatial coverage of the observations, it is possible to use a multibeam, which uses multiple acoustic beams at different angles and frequencies. However, multibeams only measures signal strength, hence, can only provide estimates of the extent of the bubble cloud, not velocities. Thus, to increase the spatial coverage, multiple ADCP instruments deployed side by side is preferable.

3.2 OBSERVATIONS USING DYE OR TEMPERATURE PROXIES

Another approach to estimating the turbulent wake extent, is to observe proxies of the impact from the turbulent wake. One physical effect of the turbulent wake that can be observed, is the change in temperature and density induced by the vertical mixing of the water column. In the case of a thermally stratified water column, which is common during summer periods in temperate regions like the Baltic Sea (Stigebrandt, 2001, Leppäranta and Myrberg, 2009), ship-induced vertical mixing has the potential to change the density of the water in the turbulent wake. If lighter/warmer surface water is mixed with the deeper/colder water below the stratification, the density and temperature in the turbulent wake will be different compared to the surrounding water. This effect of the turbulence is potentially longer lasting compared to the bubble cloud and turbulence, but will depend on the sea state (wind, wave, currents) and stratification strength (NDRC, 1946). The larger the density difference between the water in the turbulent wake and the surrounding water, the longer it will take for a contaminant or particle to be diluted in the water column. Thus, observed changes in water density or temperature in the turbulent wake region can be used as a proxy for the turbulent wake impact, and potentially also give information about the spread and dilution of contaminants and particles in the wake.

Changes in density and temperature in the turbulent wake can be observed both *in situ* and *ex situ*. *In situ* measurements can be done using Conductivity Temperature Depth (CTD) instruments, which can be towed in transects across the wake, or placed on moorings in the water column. However, unlike the acoustic instruments which measure the entire water column from a distance, the CTD instruments need to be in direct contact with the water they are measuring. Thus, it is not possible to place moorings of CTDs directly in a shipping lane for continuous measurements, as they would have to be distributed in the entire water column, and thereby risk being damaged by the passing vessels.

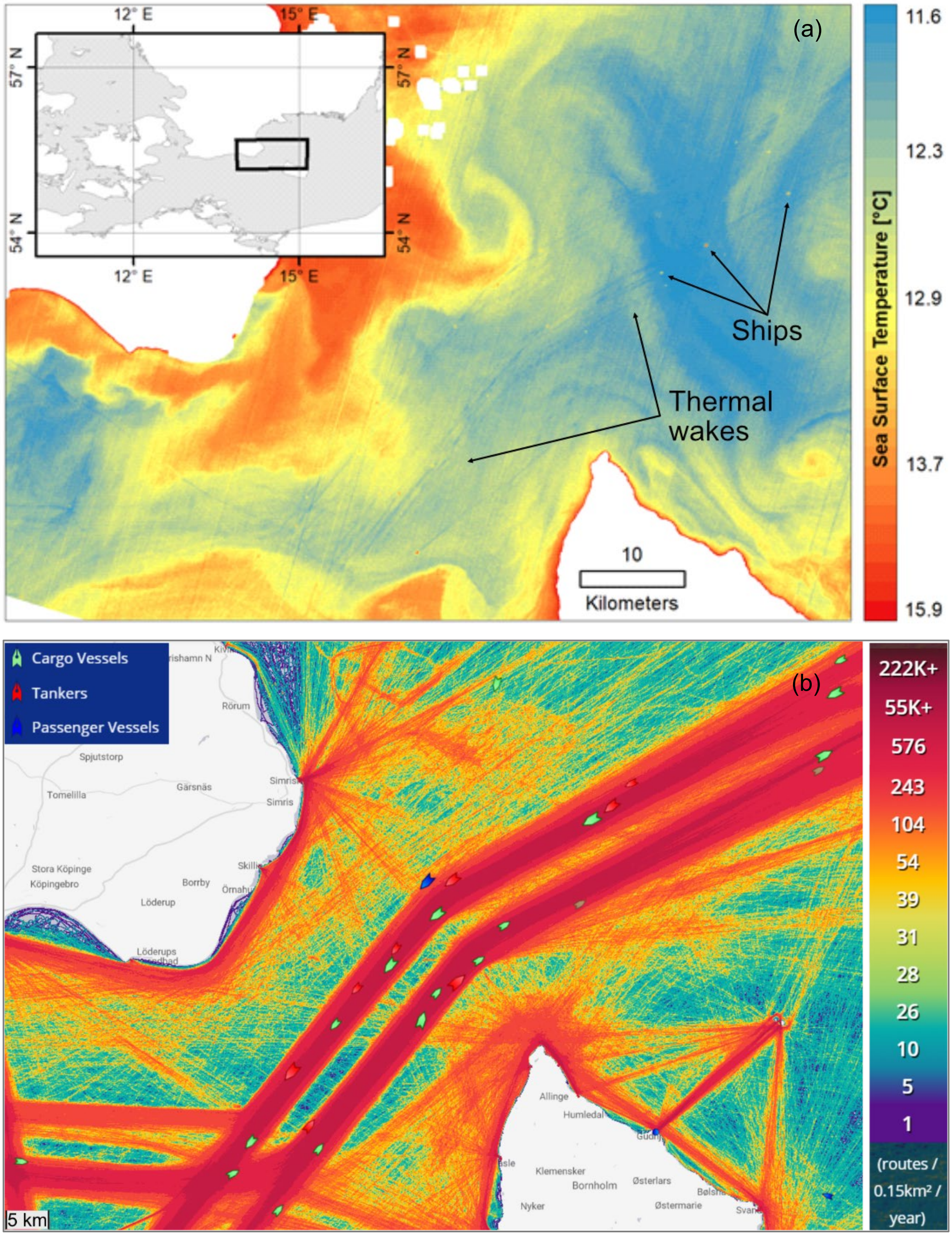

Figure 9. (a) Satellite image of sea surface temperature (SST) north of Bornholm, Baltic Sea, in 2013-06-07. (b) 2019 Ship traffic density plot of the same geographical area, indicating the location of the major shipping lane north of Bornholm (dark red colour). The small ship icons indicate the live tracking location of cargo, passenger, and tanker vessels at 15:00 2021-03-29. Looking at the location of the shipping lane in the SST image (a), there are several small yellow dots (warmer), which are trailed by blue (colder) lines (indicated by arrows). These dots are ships and the colder line trailing them is the signal of the temperature difference in the turbulent wake (thermal wake). The thermal wake lines are sustained for tens of kilometres behind the ship and follow the shipping lanes exactly. The density plot is from Marine Traffic https://www.marinetraffic.com, and based on AIS data.

Ex situ observations of temperature differences in sea surface temperature (SST) can be made using infra-red (IR) imagery from remote sensing, such as satellites, airplanes, and drones (NDRC, 1946, Voropayev et al., 2012). Remote sensing techniques have already been applied in ship wake research but has mainly relied on Synthetic Aperture Radar (SAR) (Fujimura et al., 2016, Soloviev et al., 2012), which are based on observations of sea surface roughness, or images in the visual spectrum (Gilman et al., 2011). Of these, neither is directly related to the extent of the turbulent wake. However, for the purpose of describing the extent and impact of the turbulent wake, SST imagery is better suited than SAR imagery, as the temperature decrease in the wake region is a proxy for the vertical mixing caused by the ship-induced turbulence, and is thus directly related to the extent of the turbulent wake's impact (Voropayev et al., 2012). As illustrated in (Figure 9), it is possible to detect wakes of colder water (thermal wakes) stretching tens of kilometers behind the ships in SST satellite imagery.

Another approach focusing on the impact of the turbulent wake, is the method applied by Katz et al. (2003) and Loehr et al. (2006), where a dye was discharged in the turbulent wake. This approach is useful for estimating how the turbulent wake will affect the spread of pollutants discharged from ship. However, the spreading will be affected by the properties of the pollutants (buoyancy, size etc.), hence the dye used must be similar to the pollutant of interest. The distribution and dilution of the dye can also be used as a proxy for the wake extent.

3.3 SHIP TRACKING (AIS)

Since 2002, Safety of Life at Sea (SOLAS) regulation V/19 require all passenger and large (> 300 GT) vessels to be equipped with an Automatic Identification System (AIS). Every 2–10 seconds, the AIS transmits information about the vessel, its speed, current operation, and position. For the Baltic Sea region, the Baltic Marine Environment Protection Commission (Helsinki Commission - HELCOM) compile monthly AIS datasets from all ships operating in the Baltic Sea (HELCOM, 2018).

3.4 USING MACHINE LEARNING TO AUTOMATICALLY DETECT TURBULENT WAKES IN ACOUSTIC DATA

Machine learning models can be used to analyse big datasets and to identify statistically significant patterns (LeCun et al., 2015, Malde et al., 2019, Guidi et al., 2020). A sufficiently accurate machine learning model can greatly improve the efficiency of data analysis, such as detecting turbulent ship wakes in echograms. Convolutional Neural Networks (CNNs) is a class of deep learning machine learning models, which are effective in image and pattern recognition (Krizhevsky et al., 2012). This makes CNNs suitable for the task of automatically detecting wakes in echograms. However, state-of-the-art CNNs require a large set of labelled data to train on, which limits the usefulness in cases where data is limited. Fortunately, machine learning models can also be used to address data scarcity, as additional training data can be generated based on the true samples (Van Dyk and Meng, 2001). Furthermore, by including an expert evaluation of the generated dataset, an additional feedback can be given to the algorithm. This approach, called expert-in-the-loop framework (Holzinger, 2016, Guo et al., 2016), can improve the training time and accuracy of the model.

4 METHOD

In the work of this thesis, different methodologies for observing and assessing the spatiotemporal extent of the turbulent wake, were used. In addition to the following summary of the applied methods, in depth descriptions of the field work and machine learning framework, are presented in Paper I and Paper II.

4.1 FIELD OBSERVATIONS

To cover the entire extent of the turbulent wake, a combination of remote sensing and *in situ* observations were used (Figure 10). During the *in situ* observations, a SonTek CastAway®-CTD was also used to measure salinity and temperature profiles at the time of the instrument deployment and retrieval. For both observation methods, ship tracking data from the HELCOM AIS database was used to identify the ships inducing the detected wakes, and additional vessel information was retrieved from Marine Traffic (https://www.marinetraffic.com).

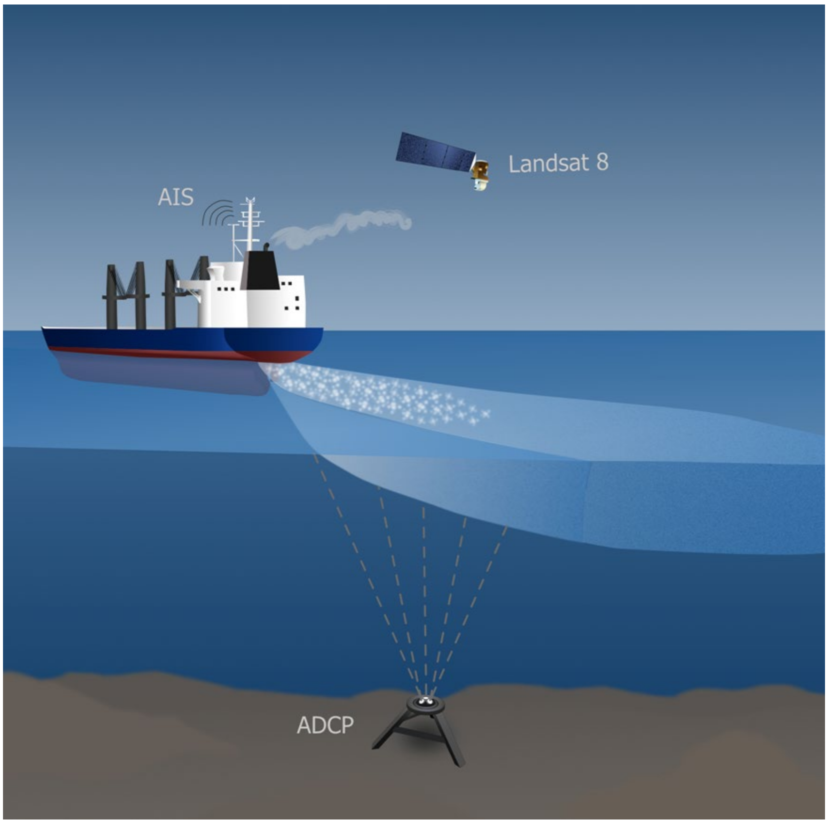

Figure 10. Methods used for observing turbulent ship wakes: bottom mounted Acoustic Doppler Current Profiler (ADCP), satellite imagery from Landsat 8, and ship tracking data from Automatic Identification System (AIS).

The vertical extent of the wake was observed using a Nortek Signature 500 kHz broadband ADCP, which was placed on the sea floor under a well trafficked shipping lane (Figure 10). The ADCP measured the changes in along beam current velocities and echo amplitude in the water column above it. Using an ADCP with 5 beams, of which four were slanted at a 25° angle (ping frequency 1 Hz, cell size 1 m on all beams), and the last was vertical, made it possible to use the along beam current velocities to calculate both mean velocities and the dissipation rate of turbulent kinetic energy (ε).

The ADCP could therefore provide two different proxies for the turbulent wake extent; the bubble cloud (from the signal strength) and ε (calculated). Although the instrument was stationary after ship passage, the ship moved away from the instrument, hence the stationary observations correspond to measurements made at different distances/times along the wake. Thus, the ADCP provided observations of the vertical and temporal extent of the turbulent wake. Using a bottom mounted stationary instrument made it possible to collect continuous observations of turbulent wake for a long period of time, gathering a large dataset of turbulent wakes induced by different vessels types and a variety of environmental conditions.

The horizontal extent of the turbulent wake was estimated using thermal wake observations in satellite imagery as a proxy for the water impacted by the turbulent wake. The IR and near-IR bands of the Landsat 8 satellite was used to provide satellite imagery of SST (Figure 9). The cloud free images (< 23 % clouds) where then analysed to detect ships and thermal wakes. As the satellite images covered a large spatial extent, they made it possible to observe the entire thermal wake extent at the same time. Although the satellite image represented a snapshot in time, the spatial wake length could be used to calculate an estimated temporal longevity, using an estimate of the ship speed.

4.2 DATA ANALYSIS

The turbulent wakes detected in the ADCP and satellite data, were analysed to get the spatial and temporal extent of the observed wakes. The HELCOM AIS dataset was then used to identify the ships inducing the detected wakes, which provided the vessel specific details for each wake. The manually detected wakes in the ADCP data, was also used to train the machine learning algorithm described in Paper II.

4.2.1 Field observations and vessel/AIS data

The ADCP measurements provided data on echo amplitude and along beam current velocity. High resolution figures of the signal strength data were used to manually identify the turbulent wakes in the ADCP dataset, as the dense bubble cloud gave rise to an elevated signal strength in the wake region (see Figure 5 for an example). The measured along beam current velocities were used to calculate the current velocity at each depth, as well as ε, using the structure function method (e.g. Lucas et al. (2014)) (see Paper I for further details).

A Python script was developed to match the AIS data with the detected wakes, one each for the ADCP and Satellite datasets, thus combining the vessel specific details with spatiotemporal extent for each wake. The ADCP version of the script also calculated the horizontal distance between the ADCP instrument and the ship inducing the wake, and the maximum wake depth and wake longevity for the detected bubble and ε wakes. To analyse the impact of vessel size and speed on the wake extent, a quantity representing the vessel force was also calculated for each wake, using the vessel details for width, draught, and speed (Paper I).

The satellite images were analysed using automatic ship detection (Matlab) and manual digitalisation of the visible thermal wakes (ArcMap). The digitalised wakes gave the wake length and the wake widths were calculated by making 400 m long cross sections every 250 m along the wakes, in which the outer borders of the thermal wake signal were identified.

4.2.2 Automatic detection of ship wakes in acoustic data

The aim of the developed machine learning framework was to automatically detect turbulent wakes in echograms from ADCP measurements. The problem was approached as a classification problem, with the aim of classifying the echogram data frames into either positive (containing a wake) or negative (no wake/background) samples. The model development was divided into two parts: *in situ* data collection and labelling, and the development of the deep learning model.

The ADCP dataset from the field observations were used as training data, as all wakes in the dataset were already identified and labelled. As the training dataset was too small to train the deep learning model (165 positive wake samples), additional training data was generated from the labelled dataset, using a simple probabilistic Gaussian Mixture Model (GMM) (Reynolds, 2009). However, the acoustic dataset needed to be compressed before the GMM could be applied. To preserve the patterns of the wake during the compression, a simple CNN-based autoencoder (Figure 11) was trained using the original wake dataset. The autoencoder compressed the original wake dataset, after which an additional compression using principal component analysis (PCA) was performed, and the GMM model was finally fitted to the compressed representation. The GMM model was then used to generate 1000 new wake samples, which where run through the inverse PCA model and the decoder, generating the final augmented training dataset. As an additional feedback step, the samples from the augmented dataset was approved by the domain expert, an approach referred to as the expert-in-the-loop framework (Holzinger, 2016, Guo et al., 2016).

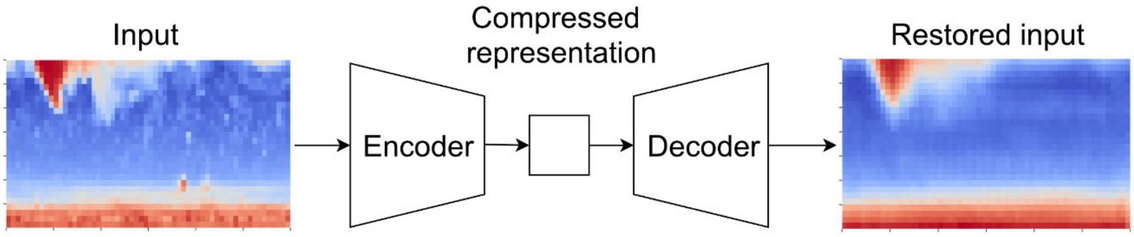

Figure 11. The architecture of an autoencoder.

Two models were then developed and trained using the original and augmented data, and they were based on a small ResNet18 CNN model (He et al., 2016), consisting of 18 convolutional layers. One of the models used the baseline ResNet18 architecture and a balanced dataset. The other model used the same architecture, but with an added example reweighting technique to increase model robustness for imbalanced training datasets (Ren et al., 2018). The models were trained using 5 data sets with different percentage of positive samples: 50%, 20%, 10%, 5%, and 2.5%. The models' accuracy and False Negative Rate (FNR), were then evaluated based on 10 test runs. In addition, a set-aside subset of the original wake dataset from a period with a lot of waves, was used to assess performance on an independent and noisy dataset.

5 RESULTS

In Paper I, a bottom mounted ADCP and SST satellite imagery, were used to observe and estimate the spatiotemporal extent of the turbulent wake. In Paper II, a deep learning model for automatic ship wake detection in acoustic data, was developed and evaluated.

5.1 PAPER I – OBSERVING THE SPATIOTEMPORAL EXTENT OF THE TURBULENT WAKE

During the *in situ* ADCP measurements in the shipping lane outside Gothenburg, 333 ships passed within 184 m of the ADCP, of which 96 (29 %) induced a clearly visible wake. For the vessels passing within three ship lengths of the ADCP (close passage), a wake was detected in 57 % of the cases. The median wake depth for the close ship passages was 11.5 m (std 4.3 m) for the bubble wake and 13.5 m (std 3.7 m) for the ε wake (Figure 12). There was a tendency for the wake depth to increase with increased vessel force (N), but it was not statistically significant. The 25 % of the close passages had bubble wake depths > 13.5 m and ε wake depths > 14.5, with the deepest wakes reaching 27.5 m and 30.5 m for the bubble and ε wake respectively. These maximum values are >10 m deeper than previously reported maximum wake depths. The median temporal wake longevity for the close passages observed with the ADCP, was 09:59 min (std 06:34 min) for the bubble wake and 06:30 min (std 03:18) for the ε wake (Figure 12). There was no statistically significant correlation between vessel force (N) and wake longevity. The observed temporal wake longevities were within the range of previously reported longevities (Table 1). The maximum ε values ranged between 1–100 $cm^2\ s^{-3}$.

Of the analysed satellite scenes with a cloud cover of < 23 %, 48 % (n=11) scenes had visible thermal wakes. In these 11 scenes, 21 % of the ships induced a thermal wake. The median thermal wake length was 13.7 km (std 11.8 km), with 25 % ≥ 20.9 km. For a ship speed of 13 knots, this would correspond to median thermal temporal wake longevity of 34 minutes. The longest thermal wake was 62.5 km, which would correspond to a temporal longevity of 1 h 42 min (the speed of the wake-inducing ship was 20 knots). The median thermal wake width was 157.7 m (std 28.6 m).

An estimation of the area affected by thermal wakes was also calculated for the traffic separated shipping lane North of Bornholm. Using the median values from the field observations, the estimated thermal wake area was 2.16 km^2. Thus, with a shipping lane area of 150 km^2, and 4–8 ships present in the shipping lane at any given time, 5.8–11.5 % of the shipping lane area would be covered by thermal wakes.

A scoping calculation of the energy input from ship induced turbulent mixing was also made and showed a yearly input of 0.0044 $W\ m^{-2}$, averaged for the entire Baltic Sea surface. The dissipation rate of turbulent kinetic energy induce by ships, would then be twice that from wind and wave driven mixing in summer, and half of the natural input during winter conditions.

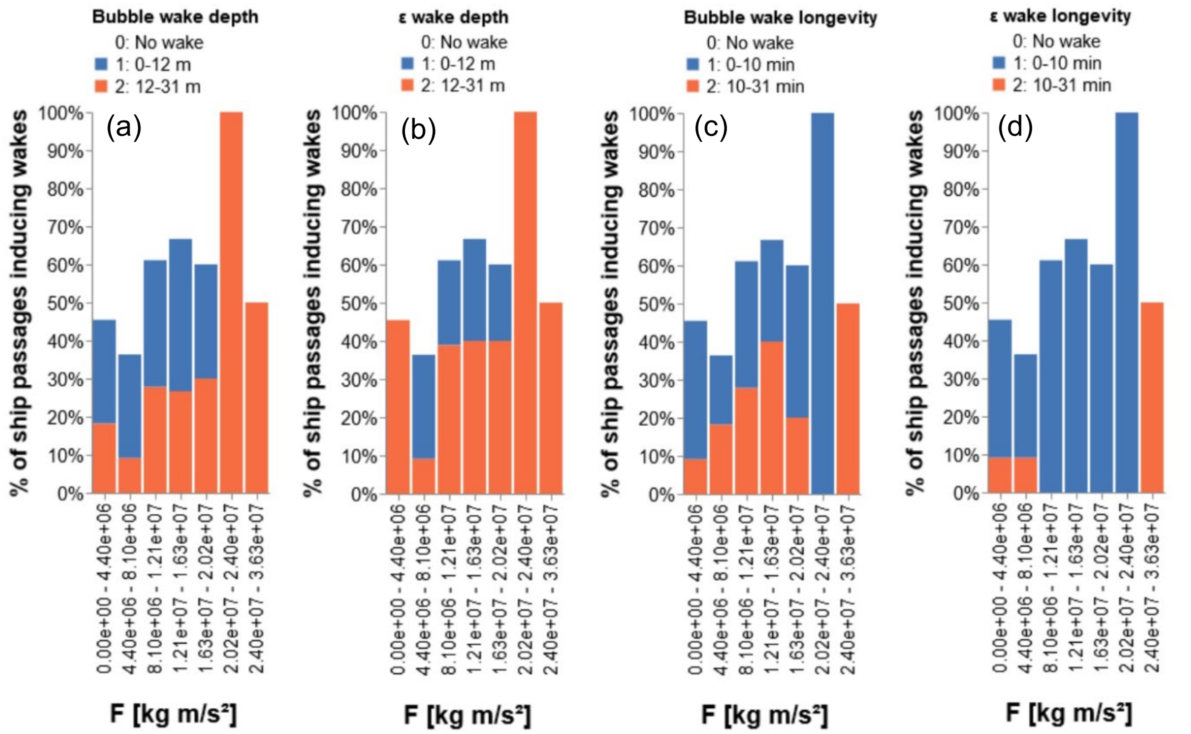

Figure 12. Maximum wake depth and longevity for the (a, c) bubble wake and (b, d) dissipation rate of turbulent kinetic energy (ε) wake, for the close ship passages. The x-axis shows the force (F) of the vessel in Newton. Wake depths ≤ 12 m are shown in blue and wakes depths > 12 m are shown in orange. Wake temporal longevities < 10 min are shown in blue and wake longevities of 10–31 min are shown in orange.

5.2 PAPER II – AUTOMATIC WAKE DETECTION IN ECHO SOUNDER DATA

In Paper II, a framework for automatic detection of turbulent wakes in echograms was developed and evaluated. Using the expert-in-the-loop framework, augmented data was generated and used to train a deep neural network (Figure 13).

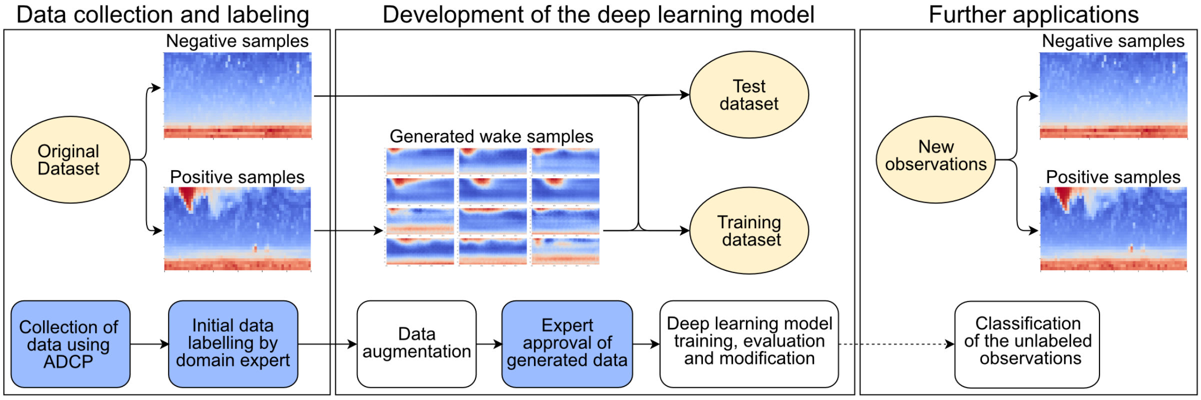

Figure 13. A pipeline representation of the developed framework, showing all major steps and possible further applications. The blue coloured steps are the ones involving the domain expert.

The generated augmented wake data was deemed sufficiently similar to the original data and was successfully used to train the deep learning models. The evaluation of the baseline and reweighted ResNet18 models are shown in Figure 14. When trained with a balanced dataset with 50 % positive samples, the experimental runs with the baseline model had a mean average accuracy of 93.40 ± 1.80 %, and a FNR of 9.87 ± 3.28 %. The reweighted model was more robust when trained with unbalanced data sets with ≤ 10 % positive samples, but the performance of both models dropped when the percentage of positive samples decreased.

Hence, for a balanced training dataset with low levels of background noise, 93.4 % of the wake predictions from the baseline deep learning model were accurate on average. As most of the incorrect predictions were due to false negatives, the model missed some of the wakes, but seldom classified non-wakes as wakes.

The results from the classification of the independent, set-aside test set of noisy data was poor, with a mean accuracy score of 60.6 % and FNR of 38.06, over 10 experiments. Improving the model performance when classifying data with high levels of background noise, is therefore the key issue to address in future work to further develop the model.

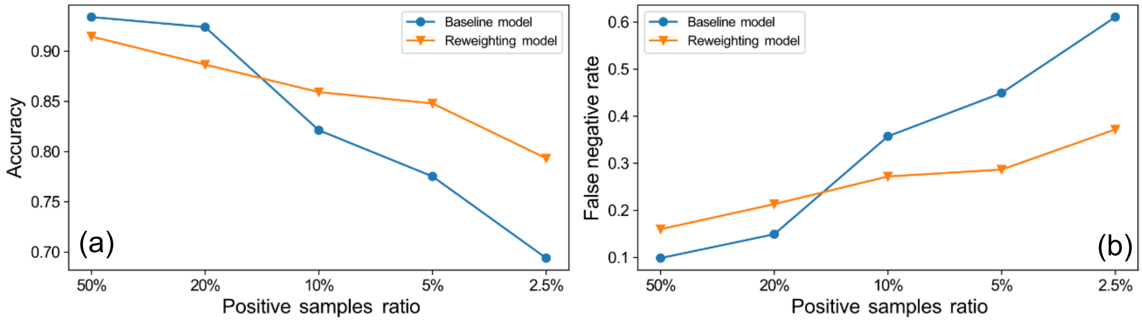

Figure 14. Evaluation scores for (a) accuracy and (b) false negative rate, mean average over 10 experiments, for the baseline and reweighted ResNet18 models. The different ratios of positive samples used in the training dataset are shown on the x-axis. The test set contained 75 positive (29 original + 46 generated) and 75 negative samples.

6 DISCUSSION

In Paper I, the spatiotemporal extent of turbulent ship wakes was observed for a large set of different ship types, using two different methodologies: ADCP measurements and SST satellite imagery. The observed wake depths and longevities were also related to the speed and size of the vessels inducing the wakes. In Paper II, a framework using deep-learning models for automatic detection of turbulent wakes in echograms was developed. For data with low levels of background noise, it was experimentally shown to achieve significant detection accuracy even with a limited dataset for training but needs to be improved performance classifying data with high levels of background noise.

6.1 IMPLICATIONS OF THE OBSERVED SPATIOTEMPORAL WAKE EXTENT

There was a large variation in the spatiotemporal extent of the observed turbulent wakes and several surprising results. To begin with, the observed extremes of both wake depth and thermal wake length, were larger than previously reported. When describing the turbulent wake, it is important to have both an estimate of the "median" wake and the wake extremes. Knowledge about the "median" wake is relevant for developing simple parameterisations of the wake impact, which can be used to incorporate the effect of ship induced turbulence in oceanographic models. However, from an environmental assessment point of view, the possible maximum extent is also of importance for assessing when and where an impact could be expected. Since both the maximum wake depths and the thermal wake longevities, are much larger than reported in previous studies (Table 1), it highlights the contribution and importance of having a large dataset of observations.

Also surprising, was that the observed extremes could not be explained by parameters such as current speed and direction, or ship size and speed. The vessel force showed a tendency to give deeper wakes with larger force, but it was not statistically significant. Furthermore, when analysing the wakes from vessels of similar size, type, and speed, there was a large variation in wake extent. The lack of stratification data made it impossible to make a full analysis of the parameters effecting the turbulent wake extent, but the results indicate an unexpectedly complex interaction between vessel and environmental parameters. The deepest detected wake (30.5 m) can serve as an example. The ship inducing the deepest wake in the ADCP dataset, and vessels with the same design and speed, passed the instrument several times during the observation period. Yet, only once was a wake depth of 30.5 m meters observed. Moreover, the ship was not especially large, with a beam of 25 m, length of 229 m, and draught of 7 m, and a similar Gross Tonnage (GT) to the average of container and Ro-Ro cargo ships in the Baltic Sea (HELCOM, 2018). Previous numerical estimates of the vertical extent of the turbulent wake, have often been given in terms of multiples of the wake draught, indicating an assumed relationship between wake depth and ship draught. Reported field measurements of wake depth/draught ratio range from 1.5–2.6 (NDRC, 1946, Trevorrow et al., 1994, Golbraikh and Beegle-Krause, 2020), and the calculated ratio from the field measurements in Table 1 range from 1.5–2.2. (Francisco and Sundberg, 2019) is an exception, as they observed wakes depths of 6-12 m from vessels width a draught of 1.1–1.4 m. The wake depth/draught ratio for the deepest observed wake in our observations had a ratio of 4.4, which is larger than previous estimates, and indicates an underestimation of wake depths derived from ship draught. To summarise, the analysis of our turbulent wake observations has indicated an unexpected complexity in the turbulent wake development, and further studies are needed to describe the parameters governing the spatiotemporal extent of the turbulent wake.

The possible environmental implications of the observed spatiotemporal extent of the turbulent wake, were also discussed in Paper I. The scoping calculations of the energy input from turbulent ship wakes, indicate that in areas with intense ship traffic and where the natural turbulence comes primarily from wind and waves, ship-induced turbulence can contribute with a substantial part of the yearly vertical mixing. One possible environmental impact of the frequent intense mixing from turbulent wakes, is an increased nutrient input and/or a deepening of the upper mixed layer, if there is vertical mixing across the stratification. Even though we were not able to quantify the vertical mixing across the stratification in the first part of the research project, we have indicative observations. The detected thermal wakes and the temperature difference of up to 1°C in the wake compared to the surrounding water, is a clear indication that vertical mixing of water masses with different temperatures have occurred. However, as there were no stratification measurements available from the time of the satellite images, it is unclear how deep the mixed layer depth was at the time or if several stratifications were present. Therefore, it is not possible to determine if the effect was from mixing across the seasonal stratification at 15–30 m depth, or from disturbing a shallower diurnal thermocline closer to the sea surface. Nevertheless, the observations made the first and last day of the *in situ* measurement period, when the stratification was known, includes a passage with a turbulent wake depth clearly exceeding the stratification depth (Paper I). Observations of wake depths deeper than the stratification depth, has been reported in coastal marine areas, by Loehr et al. (2001) and Lindholm et al. (2001). The latter reported a temperature decrease of 1.7 °C and detected a vertical extension of the upper mixed layer in the observed shipping lane. However, in the observations by Lindholm et al. (2001), the warmer surface water on the sides of the wake quickly flooded in from the sides and masked the effect of the strong mixing event. In contrast, the thermal wakes in the satellite observations from this study were detectable for tens of kilometers/up to hours, indicating either a more substantial impact or different environmental conditions. In the model scale experiments by Voropayev et al. (2012), the wake turbulence sustained the temperature difference in the wake for up to 30 ship lengths behind the vessel, but this is still much shorter distances than the thermal wakes observed in Paper I. Although there are indications that the stratification can be affected by ship induced turbulence, field observations focused on this aspect, as well as local/regional modelling of stratification and biogeochemistry, are needed to estimate the impact of the local/regional environment.

In addition to the possible effects from changes in vertical mixing and stratification, the nutrient availability could also be affected by the direct impact of intense turbulence on the plankton community. If the plankton community is impaired by the turbulence, or even killed, the altered nutrient uptake and increased remineralisation of dead organic matter, will affect the nutrient availability in the upper surface layer (Garrison and Tang, 2014). This is particularly important in areas with seasonal stratification where wind-driven mixing across the stratification is the main nutrient input to the upper surface layer. In their field observations, Bickel et al. (2011) found that 34 % of the investigated copepod population in the shipping lane consisted of carcases. Moreover, their laboratory experiments showed a linear corelation between increasing turbulence intensity and copepod mortality, at exposure times of 30 seconds and turbulence intensities of 1.31–2.24 cm^2 s^{-3}. A similar reduction of diatom abundance (32 %) were found in laboratory experiments after 45 seconds of exposure of turbulence levels of 2.5 cm^2 s^{-3} (Garrison and Tang, 2014). The ε values presented in Paper I, ranged between 1–100 cm^2 s^{-3}, with a large part of the observations > 2.5 cm^2 s^{-3}. Part of the observed ε values were two orders of magnitude larger than the ε values used in the laboratory experiments by Bickel et al. (2011) and Garrison and Tang (2014), indicating an impact on the plankton community which might be even greater than was found in the laboratory experiments. Thus, considering the median values of wake width and longevity presented in this study, and the estimate that 5–10 % of the Bornholm shipping lane could be covered by thermal wakes at any given time, the impact on the phytoplankton community and nutrient availability could be of local/regional importance and should be further investigated.

The observed spatiotemporal extent of the turbulent and thermal wake also has implications for monitoring, and sampling in areas with ship traffic. It is particularly relevant for the type of continuous monitoring performed using so called FerryBox systems (Petersen, 2014), as the vessels equipped with FerryBoxes often are ferries or liner ships, traveling in the major shipping lanes. Considering the longevity and extent of the thermal wakes observed in this study, a FerryBox system sampling water in a shipping lane, could very likely be sampling within a thermal wake. Hence, the observed temperature, and O_2 and pCO_2 concentration, could be biased due to the turbulent wake impact. In addition, if the intense ship traffic affects the local biogeochemistry in the shipping lane, the measurements from within the shipping lane would not be representative for the unaffected areas in the same region. Hence, the effect of ship-induced turbulence should be considered when using data collected from FerryBox systems. In addition to possible biases in sampled data, the turbulent wake also affects the fate of contaminants and nutrients emitted and discharged from ships. Knowing where and how contaminants and nutrients spread in the water column, is important for predicting and sampling their concentration. Apart from the dilution studies with dye and solid waste performed by Katz et al. (2003) and Loehr et al. (2006), and the semi-empirical models presented by them and Golbraikh and Beegle-Krause (2020), there are few estimates of how pollutants spread and dilute in the turbulent wake. However, based on the observations made in Paper I, it is likely that pollutants without a positive buoyance would spread to similar depths as the turbulent wake. Moreover, as current directions and speed can vary between depths, the vertical spread is relevant for estimating the continued horizontal spread by currents.

6.2 METHOD DISCUSSION

In the work of this thesis, a combination of different methodologies for observing the turbulent wake has been applied and evaluated. The ADCP measurements were very suitable to observe the vertical extent of the turbulent wake, but in order to get a reliable estimate the wake width and spatial longevity, a setup with multiple ADCPs would be necessary. Frequent CTD measurements are also necessary for future studies, as the stratification depth is a key parameter in the characterisation of the turbulent wake. The SST satellite imagery captured the large spatiotemporal scales of the turbulent wake. However, the satellites long orbital time and the need for cloud free conditions, indicates that drones would be more suitable for observing turbulent wakes.

6.2.1 Turbulent wake observations

The ADCP measurements were successfully used to detect the bubble cloud and turbulence of the turbulent wake. Observing the wakes from underneath, made it possible to track the wake continuously, and to have a reliable estimate of the maximum wake depth. Alternative setups that have been used in other studies include a multibeam/echo sounders mounted on a ship, either moving in a serpentine pattern along the wake away from the wake inducing vessel, or placed on the side of the wake measuring across the turbulent wake (Marmorino and Trump, 1996, Stanic et al., 2009, Ermakov and Kapustin, 2010, Soloviev et al., 2010). Another approach has been to use acoustic instruments tethered to buoys/floats in the water column, either dropped in the wake after passage, or places on the side of the turbulent wake (Loehr et al., 2001). The benefit of using the hull mounted multibeam, is that by crossing the wake, it is possible to get an estimate of the wake width, as well as wake depth and longevity. However, the presence of surface going vessels or buoys may affect the operation of the wake inducing ships, as they will try to stay clear of buoys and other vessels.

Compared to a multibeam, ADCPs makes it possible to estimate the extent and intensity of the turbulence, as well as the bubble cloud. Furthermore, if the ADCP has several slanted beams, it is also possible to estimate a horizontal extent based on the water depth and angle of the beam. However, as the ADCP in Paper I detected wakes from 57 % of the close ship passages (< 3 ship lengths), and more seldom from passages further away (> 3 ship lengths), it indicates that the detection range for a single ADCP is more limited than a multibeam with a large swat range (Williamson et al., 2015, Melvin and Cochrane, 2015). Based on the experiences from the field work conducted in this project, using multiple bottom mounted instruments placed perpendicular across the shipping lane, would be the favoured set-up for further studies. Including both ADCPs and multibeams would also be beneficial.

The most time time-consuming part of the data analysis conducted in this project, was the identification of ship wakes in the ADCP dataset. The deep learning model for automatic wake detection development in this project, is a first step towards speeding up the process of identifying ship wakes in acoustic data. The developed model works well on data with low levels of background noise, but before the model can replace the manual work, it needs to be developed further to also classify wakes accurately in conditions with large waves and backscatter from biota. For that, more labelled training data is needed, hence more field observations of turbulent wakes. The next step would be to develop the model to determine the depth and longevity of the detected turbulent wakes, which would further increase the efficiency of the data analysis.

The use of satellites to detect the extent of thermal wakes, provided important information about the large spatiotemporal scales of the wake, but it was inflexible. Ideally, the ADCP measurements and remote sensing would have been conducted in the same area during the same time. However, the Landsat 8 satellite, which has high enough resolution in the IR and near-IR spectra to detect ship wakes, only pass once every 16 days (USGS, 2017). In addition, cloud free conditions are required, which is difficult to achieve in the coastal regions of Sweden, where the study was conducted (only 25 % of the satellite scenes between April 2013 to December 2018 were clear enough to analyse). Moreover, the satellite image gives a snapshot in time, which can be used to calculate temporal longevity, but it is not the same as following the development of a wake in real time. Therefore, drones equipped with high resolution IR cameras would be a more suitable remote sensing technique for studying turbulent wakes (Figure 3). Drones could be used in combination with *in situ* observations below water, thereby covering both the vertical and horizontal extent of the turbulent wake at the same time.

The most important change to make in the experimental setup in future studies, is to measure stratification frequently during the *in situ* observations. In the field measurements conducted in Paper I, CTD profiles were only taken when the instrument was deployed and retrieved. Without knowledge about the stratification depth and strength, an important environmental parameter affecting the wake development is lacking. The dataset in Paper I can therefore not be used to explain the detected variation in turbulent wake extent, only to describe it. Moreover, to investigate the interaction between the turbulent wake and the stratification, stratification observations made at or near the time of ship passage are also necessary. A recent study by Stranne et al. (2018), investigated if an echo sounder could be used to identify the mixed layer depth (stratification). The methodology worked well in the open ocean, but closer to shore there was more biological scatter (plankton) and a shallower stratification depth, which made the identification more difficult. If this methodology could be developed further, it would be an excellent way to study the impact of ship induced turbulence on stratification/mixed layer depth.

6.2.2 Challenging temporal and spatial scales

One of the specific research questions addressed in this thesis, is directly related to the spatiotemporal extent of the turbulent wake. Hence, the scales of the turbulent wake have been central in the delimitation of relevant methodologies and current knowledge gaps, and a discussion regarding the spatiotemporal scales captured by different methods of observations, is included in section 6.2.1. In addition to the research questions, the overarching aim of this research project is also related to scale, as the aim is to estimate the integrated impact of the turbulent wakes in areas with intense ship traffic. One single turbulent ship wake is unlikely to have a significant environmental impact, which is probably one of the reasons to why this effect has not been studied before. When the aspect of scale is added, however, and the knowledge of today's intense ship traffic is included in the assessment, turbulent ship wakes might be important to consider when estimating the environmental impact from shipping. Moreover, the potential impacts brought up (Figure 3), involve processes on spatiotemporal scales that are difficult to observe (e.g. small changes over large areas and episodic intense impact). In addition, the scales of interest are also difficult to model, and there are currently no models that can describe the entire extent of the turbulent wake (Figure 3).

An impact assessment on a regional scale, will require the integration of the turbulent wake impact in existing oceanographic models (Figure 3). There is currently a gap between the CFD models used for ship design optimisation, and the regional oceanographic models that are used for modelling the ocean environment and include local/regional processes such as stratification, air-sea gas exchange, phytoplankton blooms, spread and accumulation of contaminants, and nutrient availability (Figure 3). This gap can partly be attributed to the cost entailed with extending CFD models to more than a few ship lengths behind the ship, or in increasing the resolution of the oceanographic models to a meter scale. Consequently, the scales of the turbulent wake make it difficult and costly to study from a modelling perspective, which could be one explanation to why there is no turbulent wake model that can be used for environmental impact assessments. Semi-empirical models can be used to close the gap between CFD and regional oceanographic models (Figure 3). However, as they are semi-empirical, they will only be applicable for conditions similar to the ones where the observations were made. The most relevant existing semi-empirical models have been developed to describe the spread and dilution of pollutants (Katz et al., 2003, Loehr et al., 2006, Golbraikh and Beegle-Krause, 2020) and the thermal wake signal (Voropayev et al., 2012). Moreover, they are based on observations from a limited number of ships of similar type, and except from Voropayev et al. (2012), only in non-stratified conditions. Hence there is still a lack of models that can be used to parameterise the turbulence and the mixing it causes for the entire extent of the turbulent wake, in natural conditions, which is needed in order to include the wakes in regional oceanographic models, which, in turn, is needed for assessment of the regional environmental impact of the wakes.

7 FUTURE OUTLOOK

The next step of the research project involves analysing additional *in situ* observations of turbulent ship wakes. The observations have been conducted, and this time frequent CTD measurements of stratification were made, and the setup included multiple ADCP instruments. Using multiple ADCPs makes it possible to estimate the turbulent wake width, as well as depth and longevity, and together with the addition of stratification observations, these changes to the experimental setup will make it possible determine the most important vessel-specific and environmental parameters for the turbulent wake development. It was not possible to combine the *in situ* with *ex situ* observations using drones this time, but it will hopefully be possible to include in future studies. The observations were conducted in collaboration with the EU Horizon 2020 project EMERGE (EMERGE, 2020), which is focused on studying the environmental impact from scrubber water discharge from ships. This collaboration also enabled sampling of chemical parameters and contaminants in turbulent wakes and shipping lanes. The combined results from this joint field work, will increase the knowledge about how the turbulent wake affects the spread of contaminants in shipping lanes, and constitute another step towards the overarching aim of this research project: assessing the environmental impact from ship-induced turbulence in areas with intense ship traffic.

Another central step towards the overarching aim of assessing the environmental impact from ship induced turbulence in areas with intense ship traffic, is to develop a semi-empirical model for the turbulent wake in stratified conditions, based on and validated using field observations. This will include collaboration with field experts from; naval architecture, contributing with competence of CFD modelling of the near wake; military/defence research, with experience of developing semi-empirical models of the turbulent wake; oceanography, contributing with the expertise of the regional oceanographic models where the impact from turbulent ship wakes should be implemented; and maritime environmental science, contributing with the research question and environmental impact assessment. The aim of this interdisciplinary collaboration, is to develop a semi-empirical model that can bridge the gap between high resolution models of the turbulent wake, and regional oceanographic models (Figure 3). When the semi-empirical model is implemented into a regional oceanographic and biogeochemical model, it can be used to assess the impact of ship-induced turbulence on local/regional biogeochemistry, the spread of contaminants, and the effect on stratification and hydrography.

The last step of this project also relates to the assessment of the environmental impact from turbulent ship wakes and will focus on how the turbulent wake affects gas exchange. Methane release from turbulent ship wakes, will be studied, to investigate how ship induce turbulence affect the air-sea gas exchange of methane in shallow areas with microbial production of methane in the sediment. The study will include observations of methane release from turbulent ship wakes, made in the Gulf of Finland. These observations will be combined with estimates of the spatiotemporal extent of the turbulent wake, to assess the potential impact on methane release to the atmosphere.

Finally, more studies of the impact from ship-induced turbulence on plankton communities in intensely trafficked ship lanes are needed. There are currently very few *in situ* studies of plankton in ship lanes, but the high intensity episodic turbulence occurring in shipping lanes, is well above the intensities for which negative effects on plankton mortality have been reported.

8 CONCLUSIONS

The specific aim of this thesis was to investigate and test suitable methods for *in situ* observation of turbulent ship wakes and, based on a large set of collected observations, estimate the spatiotemporal extent of turbulent wakes. The observed spatiotemporal extents showed deeper turbulent wakes than previously observed, with a median of 13.5 m and a maximum of 30.5 m, the latter being > 10 m deeper than reported in previous studies. The analysed SST satellite data, also showed extensive thermal wake lengths, with a median of 13.7 km and a maximum of 62.5 km. The median thermal wake with was 157.7 m. The observed wakes showed a large variation in spatiotemporal extent, and the extreme values could not be explained by the current speed and direction, or ship size and speed. The variation and the extreme events highlight the importance of having data from a large number of observations when assessing the possible spatiotemporal extent of turbulent ship wakes.

The bottom mounted ADCP was successful in capturing the development of the vertical extent of the turbulent wake, and in estimating the temporal wake longevity. As the ADCP has a limited horizontal range, a setup with multiple instruments would be needed to observe the wake width. In future studies, frequent stratification measurements need to be included, as it is a key parameter for explaining the turbulent wake development. The SST satellite imagery captured the very large spatiotemporal extents of the turbulent wake but is difficult to combine with *in situ* observations. For that, drones with high resolution IR cameras would be more suitable. The developed deep learning model was successful in accurately detecting ship wakes in data with little background noise, even when trained with a limited dataset. However, the performance for noisy data needs to be improved, and future development should include automatic estimates of the turbulent wake depth and longevity.

The results of Paper I in this thesis, contributes to the field of turbulent wake research with a large set of turbulent wake observations, which can be used to estimate in which areas the impact of turbulent ship wakes should be further studied. The observations can also be used as a reference when developing models describing the turbulent wake extent. The overarching aim of the research project is to assess the environmental impact from ship-induced turbulence in areas with intense ship traffic. Although it was not the focus in this thesis, the presented results indicate that ship-induced turbulence can be frequent and extensive enough to warrant consideration when assessing the environmental impact from shipping.

Another important contribution of this work to the field of turbulent wake research, has been to integrate the knowledge from existing research fields (Figure 2). Possible contributions from, and limitations within each of the fields have been identified and discussed, in relation to the work of characterising the turbulent wake. This thesis also adds the perspective of assessing the environmental impact from the ship-induced turbulence itself, which has previously been lacking in the field of turbulent wake research.

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