SCOR Working Group Proposal

(max. 6000 words, excluding Appendix)

Title: Bubble-mediated Air-Sea Exchange of climate-relevant and environmentally important gasses

Acronym: SCORsASE

Summary/Abstract (max. 250 words)

It has been long recognized that bubble-mediated gas transfer constitutes a significant portion of global air-sea exchange. Yet, this process is often neglected in Earth System Models, contributing to the disagreement between present estimates of air-sea gas fluxes and observations, especially in high exchange conditions like storms. This has major implications for our ability to constrain ocean and land sinks of carbon, the supply of oxygen to the interior ocean, and produce accurate future projections of the ocean's role in regulating climate.

Current knowledge of bubble-mediated processes comes from isolated field/laboratory experiments and modeling efforts, which are limited in scope. Bubble formation, transport, lifespan, and effects on the overall gas exchange on relevant scales have rarely been examined in a consistent way for gasses of varying properties under a range of conditions using multiple independent approaches. The fundamental problem is our inability to represent the underlying chemical and physical processes behind bubble-mediated exchange, knowledge about which is scattered among disciplines and research groups that often do not overlap.

The proposed working group will define the current gap in our mechanistic understanding of the processes, mapping out a route to explicit bubble-resolving gas exchange parameterizations. By leveraging cross-disciplinary expertise, we will identify and promote activities needed to refine the conceptual representation of exchange processes at high winds. We will strengthen capacity by offering training/workshops on air-sea interactions, determining recommended practices, and engaging the broader air-sea community, especially modelers, to incorporate up-to-date high wind speed exchange mechanisms in their work.

Scientific Background and Rationale (max. 1250 words)

Models suggest that the bubbles from breaking waves contribute up to 40% of the global net CO_2 flux into the ocean (Reichl and Deike, 2020; Zhang, 2012). Atamanchuk et al. (2020) provide evidence that bubble-mediated exchange is responsible for about 60% of oxygen uptake in regions of deep-water formation. Misinterpretation, or lack of recognition, of the mechanisms and amplitude of oxygen supply into the deep ocean may contribute to observed patterns of ocean deoxygenation (Schmidko et al., 2017). A larger, 'direct' O_2 supply to deep waters implies faster turnover of O_2 in the deep ocean and greater sensitivity to circulation changes linked with climate change, such as shutdown or reduction in ocean convection.

Despite growing recognition of its importance, bubble-mediated exchange is currently represented poorly, or not at all, in models in part due to a lack of detailed understanding of the fundamental physical processes at play, particularly under high wind conditions where wave-breaking and bubble formation are dominant controls. A recent analysis of sea- and air-borne observations of CO_2 and O_2 fluxes concluded that current global models significantly underestimate gas uptake, especially oxygen, in regions of deep water formation by up to an order of magnitude (Atamanchuk et al., 2020; Jin et al., 2023). The higher rate of oxygen uptake shows a clear correlation with high winds (Atamanchuk et al., 2020), so nearly two-thirds of the annual flux occurs during 40 days of winter.

There are two major reasons that bubble-mediated exchange is still relatively unconstrained. Firstly, most studies in this area are focussed on processes and measurements with a large footprint (tens of meters to several kilometers) and so cannot interrogate the medium-scale (1-100m) heterogeneities in the top few meters of the ocean, which are relevant to stochastic wave-breaking processes and near-surface water flow patterns. The second is the lack of field data that directly connects bubble processes to the gas flux. However, two recent field campaigns (HiWinGS in 2013 and BELS in 2023) have measured bubbles and gas fluxes simultaneously, and this provides a valuable opportunity to reexamine past field data in light of this new understanding. Relevant field data has been collected over the past few decades, and we are proposing to survey and reinterpret this in order to map out the gaps in knowledge and to plot a route to far better parametrizations of bubble-mediated gas transfer. Harmonization and major improvements to the gas-exchange parameterization are essential to accurately quantify the size of the present and future ocean sink for anthropogenic CO_2 and its sensitivity to climate perturbations. There is a risk of introducing a major uncertainty in the future carbon budget if the exchanges under extreme conditions remain unresolved in the Earth System Models (ESMs).

Global change issues such as increasing temperatures, ocean acidification, and ocean deoxygenation are interlinked and demonstrate the importance of understanding ocean-atmospheric gas exchange within the Earth system. In order to understand the changes in uptake, biogeochemical cycling, and feedback processes of environmentally important gasses, mechanisms controlling their air-sea exchange must be understood (Emerson et al., 2016).

Air-sea gas exchange theory and approaches

Diffusive and bubble-mediated components of gas flux act together to drive the total flux across the air-sea interface. The diffusive gas flux is commonly described as the product of the concentration difference across the interface and the gas transfer velocity. Equations for the bubble-mediated component are more diverse (Emerson et al., 2016) and are based on either empirical studies or theoretical bubble physics (e.g. Woolf, 1997; Jenkins, 1988; Liang et al., 2013; Stanley et al., 2009; Vagle et al., 2010). Many classical parameterizations do not perform well at wind speeds higher than 10 $m\ s^{-1}$ when bubble-mediated exchange becomes more important through white cap formation, wave breaking, and bubble formation.

Methods that directly derive the gas transfer coefficient, such as eddy covariance (EC) and dual tracer (DT), have shown mixed results related to bubble exchange contributions for gas fluxes. When compared with models, recent measurements of simultaneous DMS and CO_2 EC fluxes attempting to elucidate bubble exchange (Zavarsky et al., 2018; Bell et al., 2017; Blomquist et al., 2017) find an inconsistent bubble contribution. Zavarsky et al. (2018) compiled the environmental conditions of the campaigns, illustrating that differences in temperature, flux magnitude, and mean flux direction may influence the bubble-mediated exchange. Memery and Merlivat (1985) proposed an asymmetry in the bubble-mediated gas transfer, where flux into the ocean is more affected by bubbles than flux out of the ocean. It should be noted that a recent wind-wave tank study performed in hurricane wind conditions suggests that bubble-mediated transfer is not significant for CO_2 (Krall et al., 2019). Analysis by Asher and Wanninkhof (1998) indicates that DT is relatively insensitive (only ~5% increase) to bubble-mediated gas exchange at wind speeds below 10.6 m s^{-1}, but at 17 m s^{-1}, this increases to ~10%. Finally, noble gas measurements have been instrumental in providing field evidence of bubble-mediated gas transfer, but investigations using surface measurements have only had limited time resolution (Hamme and Emerson, 2006; Stanley et al., 2009). Modeling work indicates that a high-resolution time series in the late fall in the Labrador Sea could readily detect bubble fluxes (Hamme and Severinghaus, 2007), but needs further investigation.

Accounting for bubble-mediated exchange

Detailed measurement of subsurface bubbles in high winds is challenging. The vast majority of existing data come from acoustical measurements, because bubbles are highly compressible and scatter sound very strongly. However, sonar and other single-frequency acoustical techniques provide limited information, as they indicate bubble presence only and cannot measure bubble size distributions or void fractions. Broadband acoustical techniques (resonators, Czerski et al., 2011) or specialized bubble cameras (Al-Lashi et al., 2017) can measure bubble size distributions but have been deployed rarely in the open ocean.

Furthermore, these techniques only provide measures of bubble presence, and the critical information for gas flux studies is bubble flux: how many bubbles were formed, how they moved and changed, and what was the ultimate fate of their contained gas? The recent HiWinGS data (Czerski et al., 2022) significantly advance our understanding of the structure of the bubble plumes and provide a way to estimate their lifetime (an essential parameter for converting bubble presence to flux).

This complex interaction between bubble production mechanisms and upper ocean flow structures may explain why it has not been possible to formulate a simple parameterization for bubble-mediated gas uptake. The path towards resolving this complexity is by combining recent advances in bubble process understanding with comprehensive flow, gas saturation and gas flux measurements, monitoring scales from 0.1-100 meters simultaneously, and directly observing bubble-mediated gas uptake mechanisms. The first time such a comprehensive data set was collected at high wind speeds was the cross-disciplinary study in the winter of 2023 in the Labrador Sea (BELS).

Why a working group?

To effectively address the open questions about the drivers and role of bubble-mediated fluxes, we need to bring together an international group of experts to work on synthesizing the cross-disciplinary knowledge and proposing adequate research strategies. The key research communities, such as modelers and practitioners, need to come up with an integrated vision of the path toward improving parameterizations of the bubble fluxes in the models. The group will facilitate such interactions by not only ensuring adequate participation of experts from various fields but also by connecting international groups with regional expertise. Such work would be impossible to support sustainably through national or regional funding.

Terms of Reference (max. 250 words)

1. **To re-examine the available peer-reviewed literature on the drivers, parameterizations, and methodological approaches of the research in the bubble-mediated exchange of climate-relevant gasses in light of more recent knowledge.** Synthesize community knowledge in the field to date in a structured way to help identify the sources of similarities, disagreements and knowledge gaps. **TR1**
2. **To examine and validate the outcomes from recent large targeted field and**

laboratory campaigns and process studies. Synthesize and contrast the new findings with prior knowledge of the bubble-mediated exchange, its drivers and mechanisms (from TR1 synthesis). **TR2**

3. **To reconcile the individual assessments of drivers and/or forcings of bubble-mediated exchange and/or gas tracer distributions.** Identify and prioritize the mechanisms and measurements that are most likely to be important for producing useful metrics such as flux parameterizations. **TR3**
4. **To provide recommendations and set up the hypotheses for future research aimed at addressing the identified research priorities.** These include recommended practices for the development of better parameterization of fluxes, design of future experiments/process studies, and endorsed community practices. **TR4**
5. **To raise the urgency and engage with the wider oceanographic community, especially modelers, to recognise and act on improving the bubble-mediated flux parameterizations and their implementation in the models.** Develop recommended practices for flux intercomparison based on metrics from observation and ESMs. **TR5**

Deliverables (max 250 words)

1. A synthesis paper summarizing the current state of knowledge of bubble-mediated fluxes across disciples, their drivers and mechanisms, especially in light of more recent advances in the field. (**TR1**)
2. Publications stemming from the analysis of new data collected and methods employed in more recent field and process studies. (**TR2,3**)
3. A recommended practices report, a report on the recommended design of the future study, a scoping workshop, or a ship-time request based on the outcomes in **TR4**.
4. A guidebook/protocol on examining and comparing the sensitivity of ESMs to bubble flux parameterizations and their forcings. (**TR5**)

Working plan (max. 1000 words)

To fulfill **TR1,** we will assemble an interdisciplinary team consisting of full and associate WG members and their associates to perform a thorough review of the available to-date data about the state of research into the bubble-mediated gas exchange. This task will be led by Yuanxu Dong, an Early Career Ocean Professional (ECOP), focusing their research on drivers of air-sea gas transfer and the integration of field and lab results. We aim to synthesize information about specific ocean bubble measurements, near-surface ocean physics and chemistry, isotope studies, small-scale physics models focussed on bubbles, and bubble surface coating studies relating to gas dissolution. We will focus on the available to-date gas exchange parameterization to examine the sources of their disagreement and convergence. These will include the environmental conditions, the type of gas of interest, the physical/chemical processes considered, the forcings used and the verification methods. In this context, the WG will benefit from the local knowledge of the region-specific studies and environmental conditions that it could tap into due to the wide geography of the WG members. The **TR1** will culminate into a synthesis paper.

To fulfill **TR2 and 3,** we will focus on the direct measurements of near-surface bubble processes – their formation, advection downwards, and dissolution - from two field campaigns, plus wind-wave tank experiments and computational physical studies. This information will be leveraged to investigate the role of bubbles in the distribution of gas concentrations in the water column. Gas distributions and the gas transfer coefficient derived from the near-surface turbulence profiles will provide a powerful tool to examine the contribution of bubble-mediated exchange to the overall gas flux. These will be compared to measured gas exchange rates by direct eddy covariance and by gas tracer experiments, convective mixing and gas distributions and (3) simulate the observations with 3D numerical modeling (J. Liang, Louisiana State Univ.). Increasing the accuracy of air-sea gas exchanges in both observational data products and numerical models.

To address **TR4** we will work on recommendations for cross-disciplinary research programs, based on our collective experiences and resulting from the outcomes from **TR2 and 3.** We will organize a series of webinars to share the results and collect feedback.

To fulfill **TR5,** we will propose a plan, such as model intercomparison or a sensitivity study, with the incorporation of new findings to assess the efficacy and importance of bubble-mediated exchange.

Timeline

Month 1: First online working group meeting to outline and organize the work plan for the coming year, set priorities and identify a strategy to entrain external scientists into the WG efforts.

Months 2-12: Continue bi-monthly online meetings; work in sub-groups; first in-person meeting coupled to workshop/training; finalization of synthesis paper (**TR1**).

Months 13-24: Continue bi-monthly online meetings; discussion of the compiled data in **TR2** and TR3, drafting data papers; second in-person meeting coupled with workshop/training.

Months 24-36: Continue bi-monthly online meetings; deliver recommended practices and research priorities report (**TR4**), a protocol for incorporating bubble parameterizations and testing model sensitivity (**TR5**); final in-person meeting coupled with workshop/training.

Capacity Building (max. 1500 words)

It is clear that climate change research is of global concern, and most important for the younger generations. The issues that SCORsASE aims to tackle are an integral component of climate change science and, thus, we see the clear need to engage a global community, highlighting the direct participation of early career researchers (ECRs).

Participation of the Global South (GS) and developing countries in the global efforts and contribution to the research activities often hinges on limited funding, access to the equipment or facilities, and logistical challenges. The capacity-building efforts will address these barriers by engaging the scientists in a way that would promote their participation in global ocean research. We will focus our efforts on preparing joint proposals and participating in exchange activities (seminars, exchange visits, invited speakers) to facilitate closer ties to the established WG-related programs and projects (IOCCP, SOLAS, OASIS).

In order to build capacity in this area of marine science, we will:

1. hold WG meetings in the GS countries corresponding to the full WG members (i.e., in South America, West Africa, South Africa). There is evidence that scientists from many GS countries are underrepresented in international scientific organizations (e.g. SOLAS)

and by holding our meetings in GS, we will increase the participation of local/regional scientists. At least two of the meetings will take place in GS countries.
2. couple the WG meetings with workshops/trainings that are identified as needed by the local community. Our WG is composed of experts across many disciplines, and this expertise can be leveraged to build grassroots collaborations and exchange knowledge.
3. promote ECRs and scientists from GS countries to participate in/lead related papers and workshops.
4. provide training and exchange opportunities during the lifetime of the WG and beyond. We commit to raising additional funding to further develop our common research interests through exchange visits.

Specifically related to point 4, the WG members are ideally positioned to promote capacity-building in this area of marine sciences through their active roles in organizing the IOCCP (https://www.ioccp.org/index.php/training) and the SOLAS (https://www.solas-int.org/events/solas-summer-school.html) summer training schools. Both summer schools are committed to training multi- and interdisciplinary students and early career marine and atmospheric scientists. Both schools have a track record of attracting participants from developing countries and under-represented groups and could become great platforms to build on.

In addition, we see this area of air-sea interaction research as being neglected by the broader community. An emphasized focus on bubble-mediated flux exchange could be easily integrated into the courses' curricula, promoting the importance of the topic and engaging the students in the discussion.

Training of ECRs/ECOPS is paramount to ensuring the wide and lasting reach of the capacity-building efforts. To that end, we will encourage and enable the inclusion of researchers in major research efforts through programs such as the SCOR and Ocean Frontier Institute (OFI) visiting scholar programs.

Furthermore, by promoting our findings through integrating/testing in models at different temporal and spatial scales and determining recommended practices for incorporating these findings in future work, we will address the major knowledge gap in our community.

We aim to organize a workshop on air-sea interactions under high exchange conditions at Dalhousie University in Halifax (funded through e.g. Ocean Frontier Institute's Seed Grant Program) to promote the participation of all group members but also a wider community with relevant expertise in the topic.

Working Group composition (max. 500 words)

The full members were selected to span the range of disciplines needed for this work, including in-situ measurements of the relevant air-sea exchange parameters using a variety of techniques and end-users of this type of data. End-users are modelers and biogeochemists who seek to understand oxygen and carbon cycles, both of which use parameterizations to calculate air-sea fluxes. The team is gender balanced, with 30% of the team as ECOPs and 30% coming from Global South countries.

Full Members

Name	*Gender*	*Early career status*	*Place of work*	*Expertise relevant to proposal*
1 Dariia Atamanchuk -Co-Chair	F	no*	Dalhousie University, Canada	Chemical oceanography, air-sea flux measurements
2 Christa Marandino - Co-Chair	F	no	GEOMAR, Germany	Direct covariance air-sea flux measurements
3 Ian Brooks	M	no	University of Leeds, UK	Boundary layer processes, turbulence, air-sea interaction, polar boundary layers
4 Helen Czerski	F	no	Univ College London, UK	Breaking waves and bubbles
5 Kee Onn Fong	M	yes	University of Washington, USA	Physical oceanography, air-sea interactions
6 Iury Ângelo Gonçalves	M	no	Universidade Federal do Espírito Santo, Brazil	Seaspray, carbon chemistry, modeling
7 Roberta Hamme	F	no	Univ of Victoria, Canada	Inert gasses, air-sea exchange
8 Junhong Liang	M	no	Louisiana State University, USA	Gas-exchange modeling
9 Precious Mongwe	M	yes	CSIR, South Africa	Ocean carbon cycle, modeling
10 Margaret Ogundare	F	yes	Federal University of Technology, Nigeria	Ocean carbon cycle, ocean acidification

*<10 years past the highest degree if counting eligible career breaks

Associate Members

Name	*Gender*	*Early career status*	*Place of work*	*Expertise relevant to proposal*
1 Falilu Adekunbi	M	yes	Nigerian Institute for Oceanography and Marine Research, Nigeria	Ocean carbon cycle observations
2 Jose Martin Hernandez Ayon	M	no	Instituto de Investigaciones Oceanológicas (OII) of the University of Baja California (UABC), Mexico	Coastal biogeochemistry, ocean acidification, air-sea CO_2 exchange in coastal oceans
3 Ryo Dobashi	M	yes	University of Hawaii, USA	Dual tracer technique
4 Yuanxu Dong	M	yes	GEOMAR/Heidelberg University, Germany	Integration of field and lab work on bubble-mediated air-sea gas exchange, lab experiments on bubble-mediated exchange
5 Johannes Karstensen	M	no	GEOMAR, Germany	Physical oceanography, high latitude meridional overturning circulation
6 Craig McNeil	M	no	University of Washington, USA	Physical oceanography, air-sea interactions at high winds
7 Ruth Musgrave	F	no	Dalhousie University, Canada	Near-surface turbulence
8 Fangli Qiao	M	no	First Institute of Oceanography, China	Waves, bubbles, air-sea interactions, models
9 Doug Wallace	M	no	Dalhousie, Canada	O_2 and CO_2 ocean uptake and biogeochemical cycling, scientific advisor

Working Group contributions (max. 500 words)

Dariia Atamanchuk is an expert on observations of oceanic cycles of oxygen and carbon using autonomous oceanographic sensors and platforms, air-sea interactions at extreme conditions and their parameterizations, and works with the Ships of Opportunity Program (SOOP). She was a co-proponent of the large-scale field campaign BELS investigating the role of bubbles on gas exchange in the Labrador Sea.

Christa Marandino is an expert on direct measurements of gas exchange (deriving k) and has published work on direct covariance measurements and bubble exchange (Zavarsky et al., 2018). She was the chief scientist of BELS.

Helen Czerski is an expert on in-situ bubble measurements in the ocean, particularly in high wind conditions, and participated in both HiWinGS and BELS. She has published on bubble physics, the development of bubble sensing techniques, and detailed studies of bubble presence and movement in the ocean under a wide range of conditions.

Ian Brooks is an expert on boundary layer processes and turbulent exchange. His work on wave properties in collaboration with H. Czerski on HiWinGS and BELS is critical for understanding gas exchange in high winds.

Junhong Liang is an expert on modeling the role of bubbles in air-sea exchange. His model will be used primarily to test the findings of the WG.

Roberta Hamme is an expert on dissolved noble gas measurements, which can be used to unravel the different drivers of air-sea gas exchange. Her field observations provide a quantitative and integrated assessment of how bubbles influence gas transfer.

Kee Onn Fong is an expert on multiphase flows, sprays, and particle-turbulence interactions. His recent work with BELS on bubble-turbulence interaction and co-located dissolved gas measurements under high wind and wave conditions is an independent method for computing gas exchange due to bubbles.

Iury Angelo Gonçalves is an expert on sea spray's influence on carbon cycling. Sea spray is another phenomenon that co-occurs in the presence of bubbles and should be accounted for in conjunction with bubble exchange.

Precious Mongwe is an expert in ocean carbon modeling. The correct representation of all mechanisms underlying air-sea gas exchange is both important and testable in his models.

Margaret Ogundare is an ECR investigating carbon cycling in the ocean. Understanding all mechanisms underlying air-sea carbon exchange is critical to her work, and she can inform the WG of the needs of the carbon observational community.

Associated members have been pinpointed due to their work on bubbles in the lab and in models, as well as their work on gas exchange, as well as carbon fluxes and their impacts.

Relationship to other international programs and SCOR Working Groups (max. 500 words)

The mechanisms and impacts that are addressed by SCORsASE have been identified by members of an international community of air-sea interactions experts. Understanding bubble-mediated gas transfer and processes occurring at high wind speeds suffers from serious knowledge gaps that have become more relevant with observed climate change. Although our international community pinpointed uncertainties and unknowns related to processes occurring at high winds quite some time ago, the problem remains. It is only by actively bringing together teams of multi- and interdisciplinary scientists that we can fully address this knowledge gap. This applies to SCORsASE and to the greater community. Members of our working group are enthusiastically involved in the following related international programs and previous SCOR working groups representing the air-sea interactions community:

Surface Ocean-Lower Atmosphere Study (SOLAS) - Christa Marandino is the co-chair of SOLAS and committed to integrating the larger air-sea interactions community. This WG fits directly into Themes 1 and 2 of SOLAS, but its outcomes will impact the calculation of trace gas fluxes related to Themes 3, 4, and 5.

Observing Air-Sea Interactions Strategy (OASIS) - Christa Marandino is the co-chair of OASIS, which is a strong physical air-sea interaction community. The results of this WG will help bridge the biogeochemical-physical gap between the OASIS and SOLAS communities and directly feed into OASIS' The Grandest Idea of All - Theory of Change, as well as Grand Idea #3 on modeling and process studies.

International Ocean Carbon Coordination Project (IOCCP) - Dariia Atamanchuk is on the steering committee of IOCCP and is, thus, committed to enabling the most accurate estimates of carbon fluxes possible through increased observations and process studies. The results from this WG will be used by the carbon community for understanding the current budget and forecasting future changes.

International Carbon Ocean Network for Early Career (ICONEC) - An upcoming early career community with an interest in the ocean carbon cycle, involved with GOA-ON. Margaret Ogundare is on the steering committee of ICONEC. The results from this WG will help the community to improve on the quantification of the CO_2 fluxes in relation to the ocean acidification effect.

Key References (max. 500 words)

1. Al-Lashi, R. S., *et al.* (2018). A Novel High-Resolution Optical Instrument for Imaging Oceanic Bubbles. *IEEE Journal of Oceanic Engineering, 43*(1), 72-82.
2. Asher, W. E., & Wanninkhof, R. (1998). The effect of bubble-mediated gas transfer on purposeful dual-gaseous tracer experiments. *JRL: Oceans, 103*(C5), 10555-10560.
3. Atamanchuk, D., *et al.* (2020). Rapid transfer of oxygen to the deep ocean mediated by bubbles. *Nat. Geosci., 13*, 232–237.
4. Bell, T. G., *et al.* (2017). Estimation of bubble-mediated air–sea gas exchange from concurrent DMS and CO2 transfer velocities at intermediate–high wind speeds. *Atmospheric Chemistry and Physics, 17*, 9019–9033.
5. Blomquist, B. W., *et al.* (2017). Wind Speed and Sea State Dependencies of Air-Sea Gas Transfer: Results From the High Wind Speed Gas Exchange Study (HiWinGS). *JRL: Oceans, 122*(10), 8034-8062.

6. Czerski, H., *et al*. (2022). Ocean bubbles under high wind conditions – Part 1: Bubble distribution and development. *Ocean Sci., 18*, 565–586.
7. Czerski, H., *et al.* (2022). Ocean bubbles under high wind conditions–Part 2: Bubble size distributions and implications for models of bubble dynamics. *Ocean Sci., 18*, 587-608.
8. Emerson, S., & Bushinsky, S. (2016). The role of bubbles during air-sea gas exchange. *JRL: Oceans, 121*(6), 4360-4376.
9. Hamme, R. C., & Emerson, S. R. (2006). Constraining bubble dynamics and mixing with dissolved gasses: Implications for productivity measurements by oxygen mass balance. *JMR, 64*(1), 73-95.
10. Hamme, R. C., & Severinghaus, J. P. (2007). Trace gas disequilibria during deep-water formation. *Deep Sea Research Part I: Oceanographic Research Papers, 54*(6), 939-950.
11. Jin, Y., *et al.*(2023). Seasonal Tropospheric Distribution and Air-Sea Fluxes of Atmospheric Potential Oxygen From Global Airborne Observations. *GBC, 37*(10), e2023GB007827.
12. Jenkins, W. (1988). The use of anthropogenic tritium and helium-3 to study subtropical gyre ventilation and circulation. *Phil.Trans.R.Soc.Lond.A, 325*, 43-61.
13. Krall, K. E., *et al.* (2019). Air–sea gas exchange at wind speeds up to 85 m s−1. *Ocean Sci., 15*, 1783–1799.
14. Liang, J.-H., et al. (2013). Parameterizing bubble-mediated air-sea gas exchange and its effect on ocean ventilation: bubble-induced supersaturation. *GBC, 27*, 894–905.
15. Memery, L., & Merlivat, L. (1985). Influence of gas transfer on the CO2 uptake by the ocean. *JRL: Oceans, 90*(C4), 7361-7366.
16. Reichl, B. G., & Deike, L. (2020). Contribution of sea-state dependent bubbles to air-sea carbon dioxide fluxes. *GRL, 47*, e2020GL087267.
17. Schmidtko, S., *et al.* (2017). Decline in global oceanic oxygen content during the past five decades. *Nature, 542*, 335–339.
18. Stanley, R. H. R., *et al.* (2009). Noble gas constraints on air-sea gas exchange and bubble fluxes. *JRL, 114*, C11020.
19. Vagle, S., *et al.* (2010). Upper ocean bubble measurements from the NE Pacific and estimates of their role in air-sea gas transfer of the weakly soluble gasses nitrogen and oxygen. *JRL: Oceans, 115*(C12).
20. Woolf, D. K. (1997). Bubbles and their role in gas exchange. In P. S. Liss, & R. A. Duce (Eds.), *The Sea Surface and Global Change* (pp. 173-206). Cambridge University Press.
21. Xin Zhang. (2012). Contribution to the global air–sea CO2 exchange budget from asymmetric bubble-mediated gas transfer. *Tellus B: Chemical and Physical Meteorology, 64*(1).

Appendix

Dariia Atamanchuk

Atamanchuk, D., Koelling, J., Send, U., & Wallace, D. W. R. (2020). Rapid transfer of oxygen to the deep ocean mediated by bubbles. *Nature Geoscience, 13*.

Koelling, J., Atamanchuk, D., Karstensen, J., & Wallace, D. W. R. (2023). Decadal variability of oxygen uptake, export, and storage in the Labrador Sea from observations and CMIP6 models. *Frontiers in Marine Science, 10*, 1202299.

Rutherford, K., Fennel, K., Atamanchuk, D., Wallace, D., & Thomas, H. (2021). A modeling study of temporal and spatial CO2 variability on the biologically active and temperature-dominated Scotian Shelf. *Biogeosciences Discussions, 1–25*.

Atamanchuk, D., Palter, J., Palevsky, H., Le Bras, I., Koelling, J., & Nicholson, D. (2021). Linking oxygen and carbon uptake with the meridional overturning circulation using a transport mooring array. In *Frontiers in Ocean Observing: A Supplement to Oceanography, 34(4)*, P. 9.

Arruda, R., Atamanchuk, D., Cronin, M., Steinhoff, T., & Wallace, D. W. (2020). At‐sea intercomparison of three underway p CO2 systems. *Limnology and Oceanography: Methods, 18(2)*, 63-76.

Christa Marandino

Yang, M., Bell, T. G., Bidlot, J.-R., Blomquist, B. W., Butterworth, B. J., Dong, Y., Fairall, C. W., Landwehr, S., Marandino, C. A., Miller, S. D., Saltzman, E. S., & Zavarsky, A. (2022). Global Synthesis of Air-Sea CO2 Transfer Velocity Estimates From Ship-Based Eddy Covariance Measurements. *Frontiers in Marine Science, 9*, 826421.

Zavarsky, A., & Marandino, C. A. (2019). The influence of transformed Reynolds number suppression on gas transfer parameterizations and global DMS and CO2 fluxes. *Atmospheric Chemistry and Physics, 19(3)*, 1819-1834.

Zavarsky, A., Goddijn-Murphy, L., Steinhoff, T., & Marandino, C. A. (2018). Bubble-Mediated Gas Transfer and Gas Transfer Suppression of DMS and CO2. *Journal of Geophysical Research: Atmospheres, 123(12)*, 6624-6647.

Miller, S. D., Marandino, C., de Bruyn, W. J., & Saltzman, E. S. (2009). Air-sea gas exchange of CO2 and DMS in the North Atlantic by eddy covariance. *Geophysical Research Letters, 36*, L15816.

Marandino, C., De Bruyn, W. J., Miller, S. D., & Saltzman, E. S. (2007). Eddy correlation measurements of the air/sea flux of dimethylsulfide over the North Pacific Ocean. *Journal of Geophysical Research, 112(D3)*.

Ian Brooks

Salisbury, D. J., Anguelova, M., & Brooks, I. M. (2013). On the variability of whitecap fraction using satellite-based observations. *Journal of Geophysical Research, 118*, 1-22.

Brumer, S. E., Zappa, C. J., Blomquist, B., Fairall, C. W., Cifuentes-Lorenzen, A., Edson, J. B., Brooks, I. M., & Huebert, B. (2017). Wave-related Reynolds number parameterizations of CO2 and DMS transfer velocities. *Geophysical Research Letters, 44*.

Brumer, S. E., Zappa, C. J., Brooks, I. M., Tamura, H., Brown, S. M., Blomquist, B., Fairall, C. W., & Cifuentes-Lorenzen, A. (2017). Whitecap coverage dependence on wind and wave statistics as observed during SO GasEx and HiWinGS. *Journal of Physical Oceanography, 47*, 2211-2235.

Blomquist, B. W., Brumer, S., Fairall, C. W., Huebert, B., Zappa, C. J., Brooks, I. M., Yang, M., Bariteau, L., Prytherch, J., Hare, J. E., Czerski, H., Matei, A., & Pascal, R. W. (2017). Wind speed and sea state dependencies of air-sea gas transfer: results from the High Wind speed Gas exchange Study (HiWinGS). *Journal of Geophysical Research, 122*.

Norris, S. J., Brooks, I. M., Hill, M. K., Brooks, B. J., Smith, M. H., & Sproson, D. A. J. (2012). Eddy Covariance Measurements of the Sea Spray Aerosol Flux over the Open Ocean. *Journal of Geophysical Research, 117*, D07210.

Junhong Liang

Liang, J.-H., D'Asaro, E. A., McNeil, C., Fan, Y., Harcourt, R., Emerson, S., Yang, B., & Sullivan, P. P. (2020). Suppression of CO2 outgassing by bubbles under a hurricane. *Geophysical Research Letters, 47(18)*.

Liang, J.-H. (2020). Studying the role of gas bubbles on air-sea gas transfer using computer models. In P. Vlahos & E. Monahan (Eds.), *Recent Advances in the Study of Oceanic Whitecaps*. Springer Nature Switzerland AG.

Liang, J.-H., Emerson, S., D'Asaro, E. A., McNeil, C. L., Harcourt, R. R., Sullivan, P. P., Yang, B., & Cronin, M. F. (2017). On the role of sea-state in bubble-mediated air-sea gas flux during a winter storm. *Journal of Geophysical Research: Oceans*.

Liang, J.-H., Deutsch, C., McWilliams, J. C., Baschek, B., Sullivan, P. P., & Chiba, D. (2013). Parameterizing bubble-mediated air-sea gas exchange and its effect on ocean ventilation. *Global Biogeochemical Cycles, 27(3)*, 894-905.

Liang, J.-H., McWilliams, J. C., Sullivan, P. P., & Baschek, B. (2012). Large Eddy Simulation of the bubbly ocean: New insights on subsurface bubble distribution and bubble-mediated gas transfer. *Journal of Geophysical Research, 117*, C04002.

Iury Gonçalves

Gonçalves, I. A., Innocentini, V., Caetano, E., et al. (2024). Evaluation of three shortwave spectrum representations on the air-sea momentum flux. *Boundary-Layer Meteorology, 190*, 26.

Innocentini, V., Gonçalves, I. A., Caetano, E., et al. (2021). Partitioning the flux mediated by droplets released from breaking waves. *Boundary-Layer Meteorology, 178*, 21–41.

Gonçalves, I. A., & Innocentini, V. (2018). Analytical quantification of carbon dioxide exchange mediated by spume droplets. *Boundary-Layer Meteorology, 169*, 327–345.

Gonçalves, I. A., & Innocentini, V. (2017). Modelagem da difusão do gás CO2 na superfície de gotas esféricas. In *CNMAC 2016 XXXVI Congresso Nacional de Matemática Aplicada e Computacional, 2017, Gramado, 2016*, v. 5.

Innocentini, V., & Gonçalves, I. A. (2010). The impact of spume droplets and wave stress parameterizations on simulated near-surface maritime wind and temperature. *Journal of Physical Oceanography, 40*, 1373–1389.

Margaret O Ogundare

Ogundare, M. O., Fransson, A., Chierici, M., Joubert, W. R., & Roychoudhury, A. N. (2020). Variability of sea-air carbon dioxide flux in autumn across the Weddell Gyre and offshore Dronning Maud Land in the Southern Ocean. *Frontiers in Marine Science, 7*, 614263.

Helen Czerski

Czerski, H., Brooks, I. M., Gunn, S., Pascal, R., Matei, A., & Blomquist, B. (2022). Ocean bubbles under high wind conditions–Part 1: Bubble distribution and development. *Ocean Science, 18(3)*, 565-586.

Czerski, H., Brooks, I. M., Gunn, S., Pascal, R., Matei, A., & Blomquist, B. (2022). Ocean bubbles under high wind conditions–Part 2: Bubble size distributions and implications for models of bubble dynamics. *Ocean Science, 18(3)*, 587-608.

Blomquist, B. W., Brumer, S. E., Fairall, C. W., Huebert, B. J., Zappa, C. J., Brooks, I. M., ... & Yang, M. (2017). Wind speed and sea state dependencies of air-sea gas transfer: Results from the High Wind speed Gas exchange Study (HiWinGS). *Journal of Geophysical Research: Oceans, 122(10)*, 8034-8062.

Al-Lashi, R. S., Gunn, S. R., Webb, E. G., & Czerski, H. (2017). A novel high-resolution optical instrument for imaging oceanic bubbles. *IEEE Journal of Oceanic Engineering, 43(1)*, 72-82.

Czerski, H., Vagle, S., Farmer, D. M., & Hall-Patch, N. (2011). Improvements to the methods used to measure bubble attenuation using an underwater acoustic resonator. *The Journal of the Acoustical Society of America, 130(5)*, 3421-3430.

Roberta Hamme

Izett, R. W., Hamme, R. C., McNeil, C., Manning, C. C. M., Bourbonnais, A., & Tortell, P. D. (2021). ΔO2/N2' as a new tracer of marine net community production: Application and evaluation in the Subarctic Northeast Pacific and Canadian Arctic Ocean. *Frontiers in Marine Science, 8*.

Hamme, R. C., Nicholson, D. P., Jenkins, W. J., & Emerson, S. R. (2019). Using noble gasses to assess the ocean's carbon pumps. *Annual Review of Marine Science, 11*, 75-103.

Hamme, R. C., Emerson, S. R., Severinghaus, J. P., Long, M. C., & Yashayaev, I. (2017). Using noble gas measurements to derive air-sea process information and predict physical gas saturations. *Geophysical Research Letters, 44*, 1-9.

Ito, T., Hamme, R. C., & Emerson, S. (2011). Temporal and spatial variability of noble gas tracers in the North Pacific. *Journal of Geophysical Research: Oceans, 116*, C08039.

Hamme, R. C., & Severinghaus, J. P. (2007). Trace gas disequilibria during deep-water formation. *Deep Sea Research Part I: Oceanographic Research Papers, 54(6)*, 939-950.

Kee Onn Fong

Fong, K. O., Xue, X., Osuna-Orozco, R., & Aliseda, A. (2024). Gas-liquid coaxial atomization with swirl in high-pressure environments. *International Journal of Multiphase Flow, 104767*.

Fong, K. O., Xue, X., Osuna-Orozco, R., & Aliseda, A. (2022). Two-fluid coaxial atomization in a high-pressure environment. *Journal of Fluid Mechanics, 946*, A4.

Fong, K. O., & Coletti, F. (2022). Experimental analysis of particle clustering in moderately dense gas-solid flow. *Journal of Fluid Mechanics, 933*, A6.

Fong, K. O., Amili, O., & Coletti, F. (2019). Velocity and spatial distribution of inertial particles in a turbulent channel flow. *Journal of Fluid Mechanics, 872*, 367-406.

Wang, G., Fong, K. O., Coletti, F., Capecelatro, J., & Richter, D. H. (2019). Inertial particle velocity and distribution in vertical turbulent channel flow: A numerical and experimental comparison. *International Journal of Multiphase Flow, 120*, 103105.

Precious Mongwe

Mongwe, P., Gregor, L., Tjiputra, J., et al. (2024). Projected poleward migration of the Southern Ocean CO2 sink region under high emissions. *Communications Earth & Environment, 5*, 232.

Bange, H. W., Mongwe, P., Shutler, J. D., Arévalo-Martínez, D. L., Bianchi, D., Lauvset, S. K., Liu, C., Löscher, C. R., Martins, H., Rosentreter, J. A., Schmale, O., Steinhoff, T., Upstill-Goddard, R. C., Wanninkhof, R., Wilson, S. T., & Xie, H. (2024). Advances in understanding of air–sea exchange and cycling of greenhouse gasses in the upper ocean. *Elementa: Science of the Anthropocene, 12*.

Smith, T. G., Nicholson, S. A., Engelbrecht, F. A., Chang, N., Mongwe, N. P., & Monteiro, P. M. S. (2023). The heat and carbon characteristics of modeled mesoscale eddies in the South–East Atlantic Ocean. *Journal of Geophysical Research: Oceans, 128*.

Hauck, J., Gregor, L., Nissen, C., Patara, L., Hague, M., Mongwe, P., Bushinsky, S., Doney, S. C., Gruber, N., Le Quéré, C., Manizza, M., Mazloff, M., Monteiro, P. M. S., & Terhaar, J. (2023). The Southern Ocean Carbon Cycle 1985–2018: Mean, Seasonal Cycle, Trends, and Storage. *Global Biogeochemical Cycles, 37*.

Mongwe, N. P., Vichi, M., & Monteiro, P. M. S. (2018). The seasonal cycle of pCO2 and CO2 fluxes in the Southern Ocean: Diagnosing anomalies in CMIP5 Earth system models. *Biogeosciences, 15*, 2851–2861.