



Figure 1: The students and lecturers of the 7th SOLAS Summer School in front of the scientific institute (Institut d'Etudes Scientifiques de Cargèse) in Cargèse, Corsica, France. © Jessica Gier

committee consisting largely of past summer school alumni and lecturers. Ultimately, skilled logistical support from Jessica Gier, SOLAS executive director, and Erik Ferrara assured everything went smoothly in the end. This summer school was dedicated to Roland von Glasow, alumni of the first SOLAS Summer School in 2003, later a member of the SOLAS Scientific Steering Committee, and a beloved colleague, who died in 2015.

As during the previous six summer schools, the lectures during the first three days presented fundamental - albeit often complex - information on the atmosphere and ocean sciences, to assure that all the students had basic knowledge of both sides of the air-sea interface. Poster sessions at the end of these first days also allowed them to share their own science with their colleagues and the lecturers. These three intense lecture-days were followed by three days of practicals which initiated the students into specific aspects of SOLAS science, including modeling, sea-air flux measurements, remote sensing, etc. These practical sessions also included a series of half-day cruises on-board the French research

vessel *Téthys II*, a sought-after experience for those who had never been on a scientific ship. And certainly a good occasion to test their sea legs....

After a one-day rest, the students dove into a series of more specialised SOLAS-oriented lectures on topics such as the impact of atmospheric depositions on ocean biogeochemistry, the ocean biogeochemical control on atmospheric chemistry, SOLAS science and society, and geoengineering, to name a few. It was also during this second week that the students had the opportunity to improve their communication skills with short presentations of their research, as well as team reports on the practicals. All in all, two very busy but formative weeks for the students, who also found time to socialise and swim in the Mediterranean Sea! And how not to mention the lunar eclipse that graced the first week?! A memorable moment for all of us.

Those who had been involved with previous summer schools had forgotten how exhilarating and energising it is to share time with so many talented and determined students from different backgrounds and roots. The lecturers want to

personally thank all the students for their contribution to the success of the school. The experience has also reminded all of us of the challenge in bringing different disciplines together, oceanography and atmospheric science in our case; two components of the Earth system in constant interaction. Understanding the functioning of one of these two components is already an immense task. Understanding how they 'speak' to each other is, well, a life-time challenge, but a challenge that for all of us involved in organising the SOLAS Summer School has become a passion, a passion that we hope we have been able to transmit to all the students.

The following pages present articles written by a number of the students, summarising their research. Due to space restriction, we had the difficult task of picking only examples of the excellent research being conducted by these young scientists. Nonetheless, we feel these summaries reflect both the diversity of the research and the diversity of the participants, the two most powerful aspects of the SOLAS Summer School.

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Mohamed Ahmed is currently a PhD candidate in Geography Department at the University of Calgary, Canada. He got his Master degree in Geomatics from Lund University, Sweden. Ahmed's research project is focusing on combining field observations and remote sensing techniques to estimate the sea-air carbon dioxide fluxes in the Canadian Arctic.

Estimation of sea-air carbon dioxide fluxes in a changing Arctic system by using a combination of field observations and remote sensing techniques

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Whether using field measurements, sensors in the oceans, satellite images from the space, or simply talking with people who live in the Arctic, you will get the same answer: The Arctic climate is changing. Several studies report the significant impact of global warming on ecosystems and cultures in the Arctic region (e.g. Bates and Mathis, 2009; McGuire *et al.*, 2009; Duarte *et al.*, 2012), which may be irretrievable on long timescales and has a massive potential to cause striking consequences in our planet system.

The Arctic Ocean has been suggested to be a net sink for atmospheric carbon dioxide (CO₂) due to its cold temperature, low salinity, and relatively high biological production (e.g. Macdonald *et al.*, 2009). Although the Arctic Ocean is mostly ice-covered and occupies only 3% of the world's ocean surface area, the Arctic Ocean absorbs CO₂ on the order of -66 to -199 Teragram (Tg) carbon (C) year⁻¹ (Tg C = 10¹² g C) contributing to 5-14% to the global balance of CO₂ sinks and sources (Bates and Mathis, 2009).

However, the oceanic uptake of CO₂ in the Arctic Ocean is uncertain and controversial due to relatively field observations and expected variations

as a result of rapid climate change. For example, Bates *et al.* (2006) estimated the sink of CO₂ in the Arctic Ocean has tripled over the last three decades due to sea ice loss. On the other hand, a slowdown in the CO₂ uptake in certain regions of the Arctic Ocean was found (Cai *et al.*, 2010). Therefore, understanding the global carbon cycle along with the processes controlling air-sea CO₂ exchange is crucial to quantify the effect of the changing Arctic Ocean.

Figure 2 summarises the major processes affecting the organic and inorganic carbon flows in the Arctic Ocean. Generally, the major inputs that are affecting the Arctic marine carbon cycle are terrigenous inputs (river and underground water discharge, coastal erosion, and aeolian input), and biological processes (primary production, remineralization, and calcium carbonate formation). While, there are other important factors such as sea-ice processes, air-sea gas exchange, sinking and sedimentation, horizontal circulations, vertical mixing and upwelling between the polar mixed layer, halocline layer, and deep waters.

In Figure 2, including the temporal and seasonal

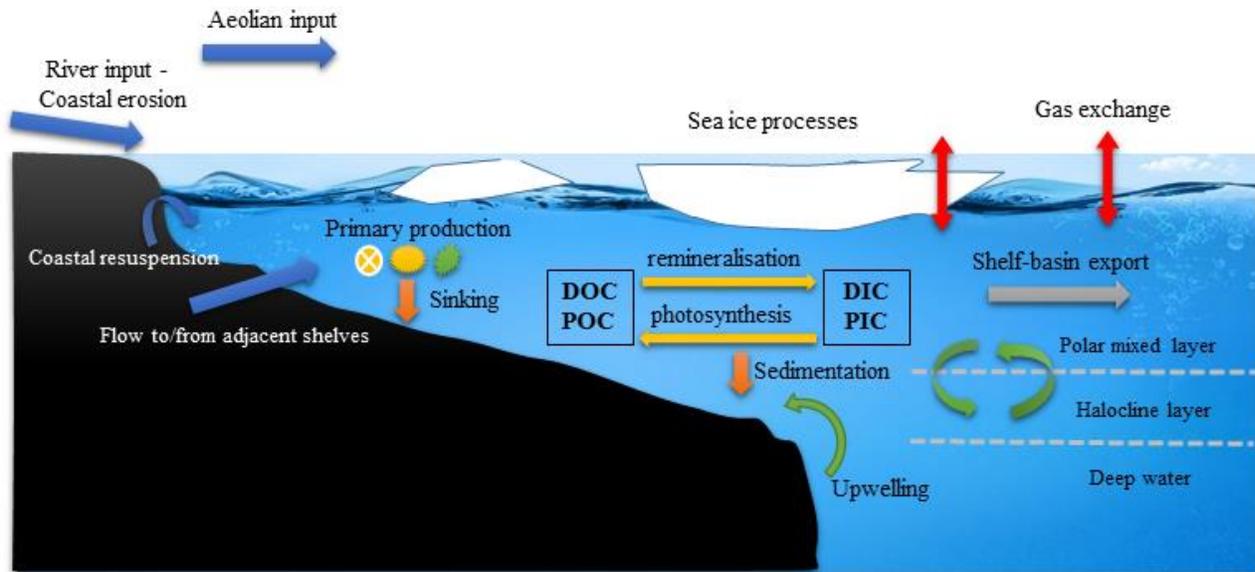


Figure 2: A schematic diagram summarising the factors controlling marine carbon cycle in the Arctic Ocean. Red arrows depict the air-sea gas exchange, while blue arrows represent the terrigenous and carbon stocks from rivers, coastal erosion, and adjacent shelves. DOC represents dissolved organic carbon, POC represents particulate organic carbon, DIC represents dissolved inorganic carbon, and PIC represents particulate inorganic carbon.

variations that will affect the transport and production of the Arctic marine carbon cycle have been neglected.

The fluxes of CO₂ across sea-air interface is a major concern and have potential effects on biogeochemical cycle in the ocean with fluxes averages about 2.2 Gigatons (Gt) C yr⁻¹ into the ocean from the atmosphere (Takahashi *et al.*, 2009), and expected to increase in the future in response to the steadily increasing in the global atmospheric CO₂ concentration. This means that the oceans are absorbing around ~30% of anthropogenic emissions, and are responsible for more than half of the total global CO₂ sink. However, there is spatial and temporal variability in the ocean sink with some regions may act as strong sinks (absorbing atmospheric CO₂) such as North Atlantic Ocean, while others act as a minor sink or even as a source for atmospheric CO₂ such as the tropical regions in the Pacific Ocean (Figure 3). These significant regional variations could be accounted to physical, chemical, and biological processes, which are generally fluctuating seasonally and can cause a region to alter between a sink and a source over time (Takahashi *et al.*, 2009).

Therefore, it is important to study the marine carbon cycle at each region, separately, in the Arctic Ocean.

My research project seeks to overcome the spatial and temporal limitations of ship observations by using remote sensing products to assess air-sea CO₂ exchange in the regions of Canada's Arctic most likely to undergo rapid industrial development such as Hudson Bay and the Canadian Arctic Archipelago. This will be accomplished through collecting field datasets of surface salini-

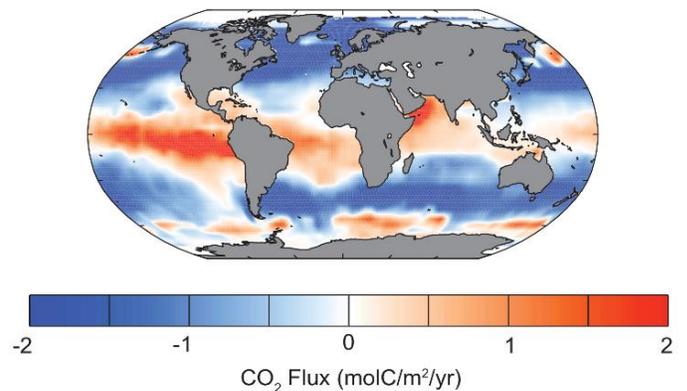


Figure 3: Annual mean air-sea CO₂ flux, estimated by Takahashi *et al.* 2009. Positive is from ocean to atmosphere, negative from atmosphere to ocean.

ty, sea surface temperature, ocean colour, and dissolved CO₂ in seawater and scaling it up by using remote sensing products from numerous sensors (e.g., MODIS, SMOS, MERIS, ASCAT) in order to provide weekly and monthly CO₂ flux maps, and describe the key factors of air-sea CO₂ exchange.

This study will benefit greatly from collaborations within the Hudson Bay System Study (BaySys), which aims to study the role of climate change and hydroelectric regulation of freshwater on Hudson Bay marine and coastal ecosystem. Broadly speaking, the results from this study will have a big significance for the scientific community by filling the current knowledge gaps about air-sea CO₂ exchange over Hudson Bay and the Canadian Arctic Archipelago in response to climate change.

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Kathryn Moore completed a Bachelor in Chemistry at Colby College in Maine, USA, in 2014. She started a Master of Science/PhD program at Colorado State University, Colorado, USA, in 2017, which is focused on ice nucleating particle production and cloud microphysical processes over the Southern Ocean.

Southern Ocean cloud phase modulation by ice nucleating particles

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Aerosols contribute the largest uncertainty to global radiative forcing estimates, with natural aerosols responsible for a significant portion of this (Carslaw *et al.*, 2013). As the natural aerosol burden and its effects are largely unknown, our ability to constrain and predict the influence of anthropogenic aerosols on climate sensitivity, radiative forcing, and cloud processes has been hindered (Carslaw *et al.*, 2013). An increased understanding of natural aerosol budgets is thus required to improve model simulations of aerosols and predict their effects on global climate in the future.

The limited anthropogenic and terrestrial aerosol sources impacting the Southern Ocean (SO) makes it a unique site to study the production of primary sea spray aerosols (SSA) and their role in cloud properties, such as phase, precipitation formation, lifetime, and radiative forcing. Ice nucleating particles (INPs), which are important for cloud glaciation, exhibit very different immersion freezing temperature spectra depending on their source (DeMott *et al.*, 2016).

Thus, not only INP concentrations,

but also their chemical and physical characteristics, affect the consequent aerosol-cloud interactions. Recent laboratory studies examining INP emissions from nascent SSA (DeMott *et al.*, 2016) are in agreement with the lower bounds of the sparse existing INP measurements from the SO (Bigg, 1973). Observed low INP numbers, its remote location, and recent modeling work (Burrows *et al.*, 2013) support the idea that the SO INP population is dominated by marine SSA and distinct from that found in the northern hemisphere, though direct field confirmation is still needed (Figure 4).

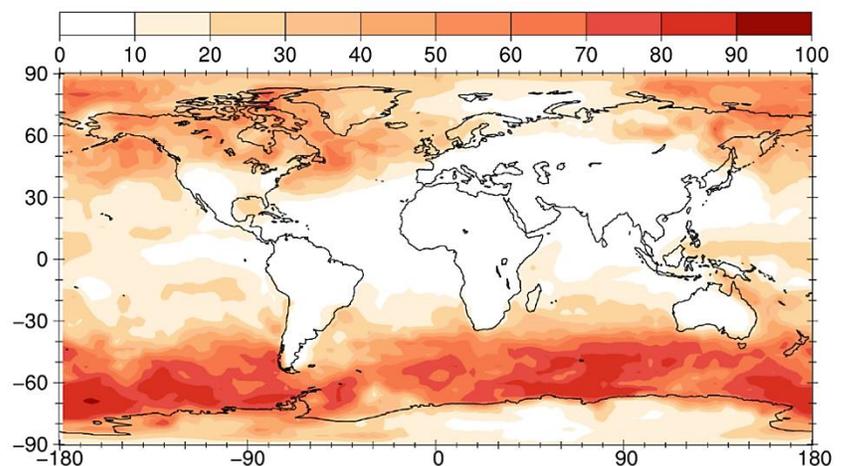


Figure 4: Modeled relative contribution of marine biogenic INPs to marine boundary layer INPs at -15 °C (Burrows *et al.*, 2013).

Global climate model (GCM) simulations and satellite observations of SO clouds show poor agreement, including a systematic positive bias in model estimates of absorbed shortwave radiation poleward of 55°S, particularly during Austral summer (Trenberth and Fasullo, 2010). This leads to associated errors and uncertainties in predicting other model outcomes (Trenberth and Fasullo, 2010). The SO influences oceanic and atmospheric circulation on both local and global scales, and the poor representation of SO atmospheric processes in GCM simulations is a major limitation on our ability to accurately predict responses to future climate change.

Underestimation in the number and lifetime of supercooled clouds, particularly low and midlevel clouds in the cold sector of cyclonic storms appears to account for the bulk of GCM overestimation of absorbed shortwave radiation in the SO (Bodas-Salcedo *et al.*, 2014). The unusually high proportion of supercooled liquid water (Morrison *et al.*, 2011) is consistent with low numbers of INPs in this region and indicates that INP concentrations and composition may strongly control cloud phase and precipitation formation over the SO.

For my graduate studies, I am undertaking field (Figure 5) and laboratory measurements to better understand the source, composition, and variability of INPs over the SO, focusing on their climate implications. In particular, I aim to assess the extent to which marine INPs are responsible for cloud glaciation in the SO, in contrast to long-range transported aerosols, cloud dynamics, secondary ice formation, or other processes. Several research objectives will be undertaken to achieve this: 1) verify local SSA are the primary source of SO INPs, 2) determine the influence of the observed INPs on cloud phase in the SO, and 3) quantify the source production of SO INPs and collaborate with modelers to improve their representation in GCMs.

If SO INPs are indicated to strongly control SO cloud phase, their distribution, chemical, and physical properties would have significant impli-

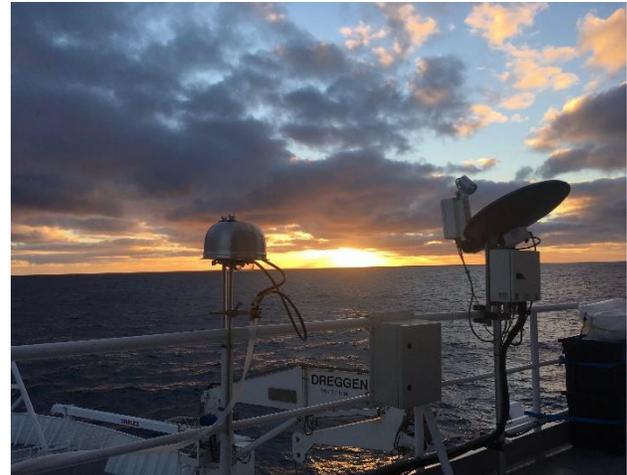


Figure 5: Filters for INP collection on the deck of the RV Investigator during the Southern Ocean Clouds, Radiation, Aerosol Transport Experimental Study (SOCRATES) field campaign. © Kathryn Moore

cations for radiative forcing over high latitude regions, and so a more accurate representation in GCM simulations would be expected to improve model outputs of absorbed solar radiation and related properties. Knowledge of the SO INP number distribution in and out of clouds, and their sources, will provide much-needed and missing parameterisations and validation datasets for GCMs, while simultaneously reducing the significant model uncertainties attributed to aerosols (Carslaw *et al.*, 2013).

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Matias Pizarro-Koch obtained the degree in Marine Biology at the University Católica del Norte, Chile, in 2009. He is currently doing his PhD in Oceanography at the University of Concepción, Chile. His scientific interest are the physical/biogeochemical coupled numerical modelling of the ocean, particularly the spatio-temporal variability of the Oxygen Minimum Zone (OMZ) in the eastern South Pacific Ocean and the main drivers controlling its variability.

Temporal variability of the Oxygen Minimum Zone off Chile (30-38°S): a 3-D coupled physical-biogeochemical modelling approach

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Despite the large primary productivity that takes place along the coast off Central Chile during the upwelling season, surface waters are commonly undersaturated with oxygen (Letelier *et al.*, 2009). Near the coast, subsurface waters with very low dissolved oxygen (DO) are transported to the surface by upwelling circulation cells. In fact, the presence of an intense and relatively shallow oxygen minimum zone (OMZ) is one of the most striking oceanographic features along the eastern boundary of the Pacific Ocean (Wyrtki, 1962). Combined effects of the microbial decomposition of organic matter that is remineralised in subsurface waters (contributing to the subsurface DO depletion) and a sluggish subsurface circulation that prevents efficient ventilation, generate these oxygen-poor environments in different eastern ocean boundaries (Karstensen *et al.*, 2008).

In the eastern South Pacific (ESP) such conditions generate a large, shallow and very intense OMZ (Paulmier *et al.*, 2006). This OMZ region in the Open Ocean may frequently reach values of

DO in the suboxia range, which are lower than 40 μM , (Naqvi *et al.*, 2010), and even anoxic zones (Ulloa *et al.*, 2012). Such oxygen-poor waters impact marine communities, the biogeochemical cycling of carbon and nitrogen, and the climate system (Helly and Levin, 2004; Stramma *et al.*, 2011).

Most of OMZs studies have been carried out in the tropical zone, focusing mainly on the biogeochemical processes and bacterial communities, while the extra-tropical borders or the OMZ boundaries and its physical drivers are still unknown (Brand *et al.*, 2010). Therefore, during my PhD study, I have been focusing on the extra-tropical OMZ off central Chile. In this region, the OMZ is related to the Equatorial Subsurface Water mass (ESSW), a water mass relatively warm (12.5°C), characterized by a subsurface salinity maximum (>34.9), nutrient rich and high phosphate content (Silva *et al.*, 2009), and its southward transport along the continental slope through the Peru-Chile Undercurrent (PCUC).

The aim of my study is to analyse the seasonal

and interannual variability of the southern tip of the eastern ESP-OMZ (30°S to 38°S) using a coupled physical-biogeochemical model simulation between ROMS (hydrodynamic model) and BioEBUS (biogeochemical model) (Gutknecht *et al.*, 2013).

Historical physical and biogeochemical in situ data from the study region were used for model validation. Based on this coupled simulation, the seasonal variability of the OMZ and its relationship with the meridional changes of the southward PCUC transport were analysed, together with the interannual variability and its association with EL-Niño-La Niña cycles.

Regarding the preliminary results and in light of the model assessment, the model has a fair skill in simulating the main features of the Eastern Boundary Upwelling System (EBUS; Figure 6), e.g. the upwelling dynamics, the subsurface poleward current (PCUC), the vertical structure of the OMZ associated with the ESSW and the

eddy mesoscale variability, that allows the process studies focusing on seasonal and interannual timescale. The seasonal cycle of the OMZ off Chile showed during the first half of the year, which was associated with an intense southward PCUC transport and eastward-westward zonal jets. The OMZ volume is maximum (July) and the DO content (respectively, salinity) is minimum (maximum). Conversely, in the second half year, due to weakening of the PCUC transport, the volume decreased and the DO average content increased (Figure 7).

The interannual variability (2000-2008) also showed high consistency with the PCUC variability, i.e. high volume or positive anomalies (negative) were related with the intensification (weakening) of the PCUC. However, the PCUC showed better correlation $r=0.8$ with the DO content within volume than with the volume itself. Maximum and minimum values of the OMZ-volume anomalies were observed during 2001

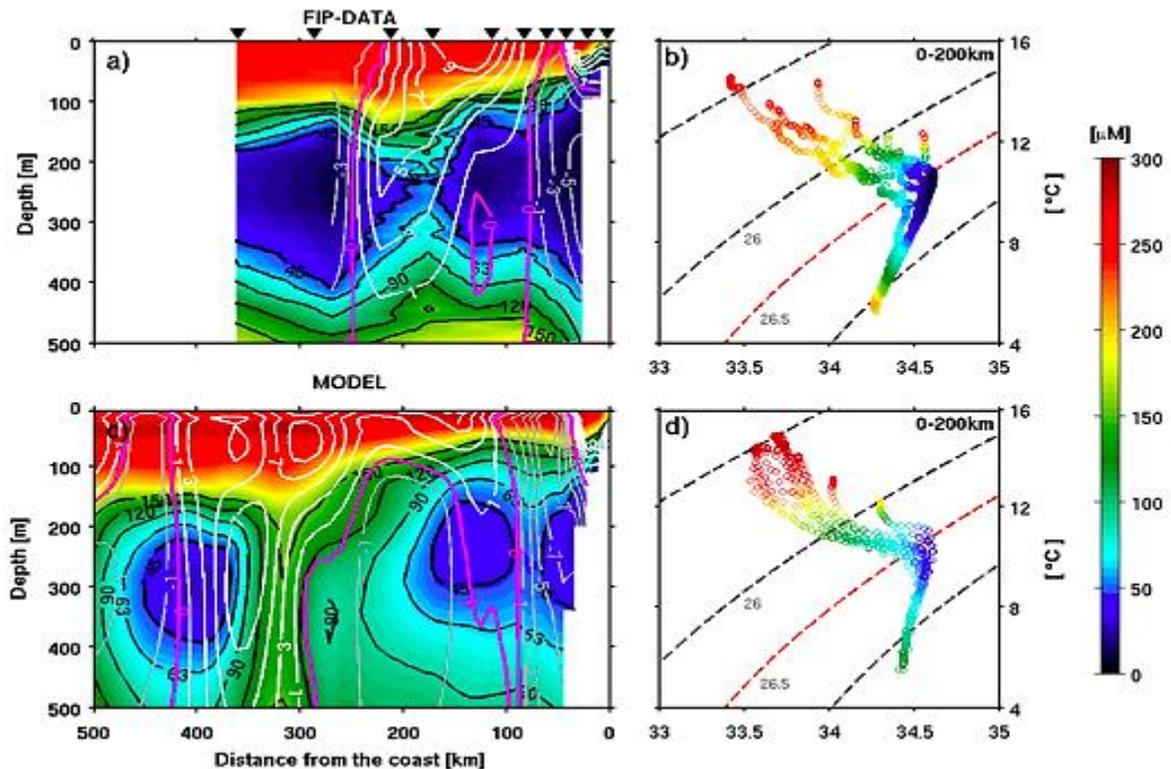


Figure 6: Cross-shore section comparison between dissolved oxygen (DO) modelled and cruise DO data during November 2004 (FIP cruise Letelier *et al.*, 2009; a and c). The background colors show DO (μM). The white (respectively, grey) contour indicate northward (respectively, southward) flows, while that magenta contour indicate zero velocity. The diagrams (b and (d) obtained from 0-200 km from the coast represent (b) in-situ data and (d) from ROMS/BioEBUS data. The colored dots represent the DO.

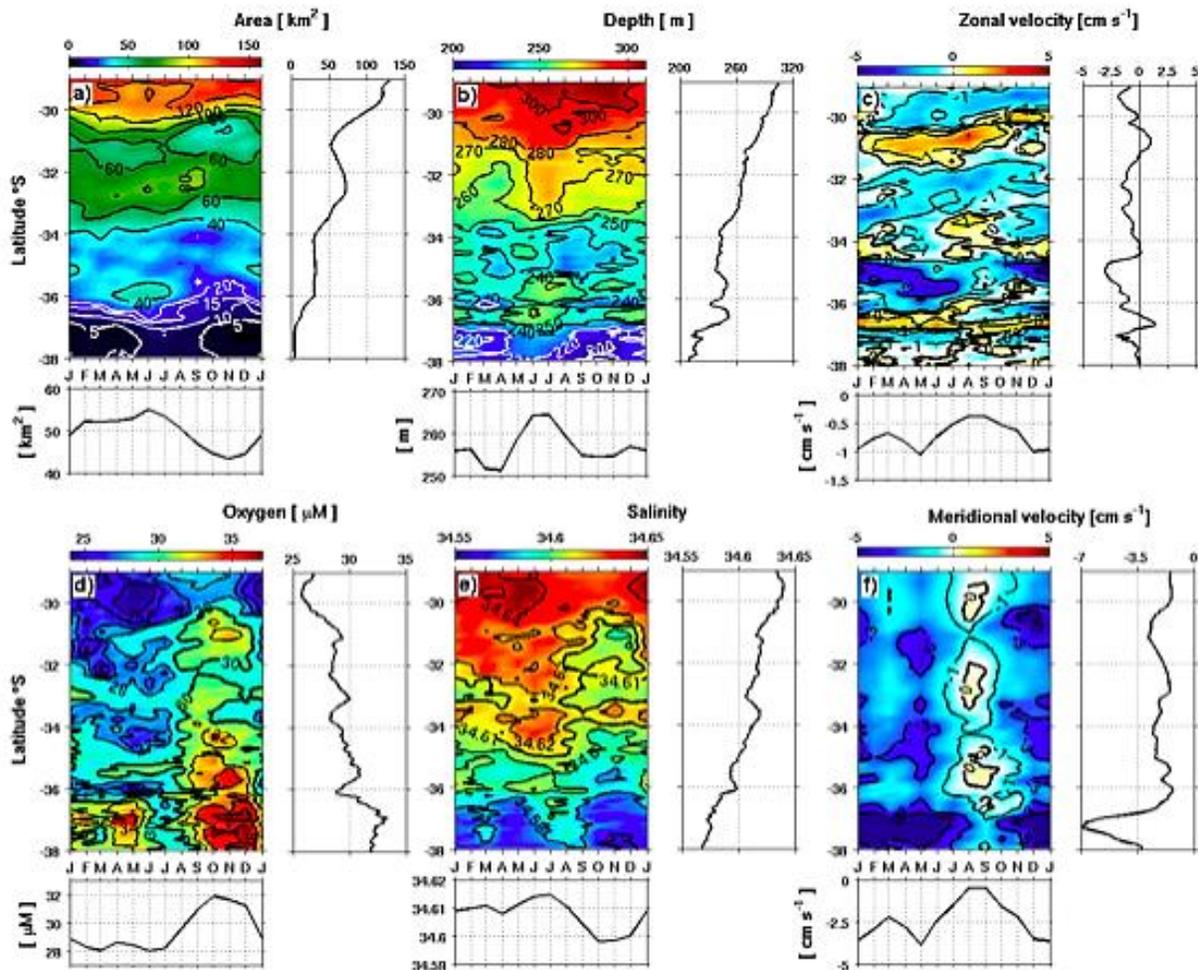


Figure 7: Seasonal cycle of different metrics that characterise the alongshore oxygen minimum zone (OMZ) southern tip (the OMZ was defined as the volume enclosed by the isopleth of $DO \leq 45 \mu\text{M}$, see Figure 6). Whereas (a) is the area in km^2 (cross-shore extension), (b) mean depth (m), (c) zonal velocity (cm s^{-1}), (d) dissolved oxygen (DO) concentration (intensity; μM), (e) salinity and (f) meridional velocity (cm s^{-1}). The insets at the right and bottom of the main panels show the annual mean at different latitude and the mean seasonal cycle meridionally averaged of the corresponding variable, respectively.

and 2007, respectively. In 2001, the OMZ- volume increased up to $\sim 33\%$ related to the mean value for the study period, displaying a large decrease in the mean oxygen concentration, together with a greater offshore and southward extension, as well as an increase in temperature and salinity. In contrast, in 2007 the OMZ volume was reduced by $\sim 23\%$ and became more oxygenated, showing a lesser offshore and southward extension, together with a decrease in temperature and salinity. These changes of the OMZ volume are related to changes in the PCUC transport, i.e., positive (negative) OMZ volume anomalies are associat-

ed with the intensification (weakening) of the PCUC (Figure 8).

Finally, the OMZ volume showed a significant correlation ($r=0.6$) with the equatorial index (ONI; Oceanic El Niño index). The seasonal and interannual DO budget analysis within OMZ reveals that the main drivers of its variability are the physical processes (90% contribution) and these in turn are dominated by the advective terms. In contrast, the biogeochemical fluxes and the mixing terms could be playing only a secondary role over the DO budget ($\sim 10\%$ contribution).

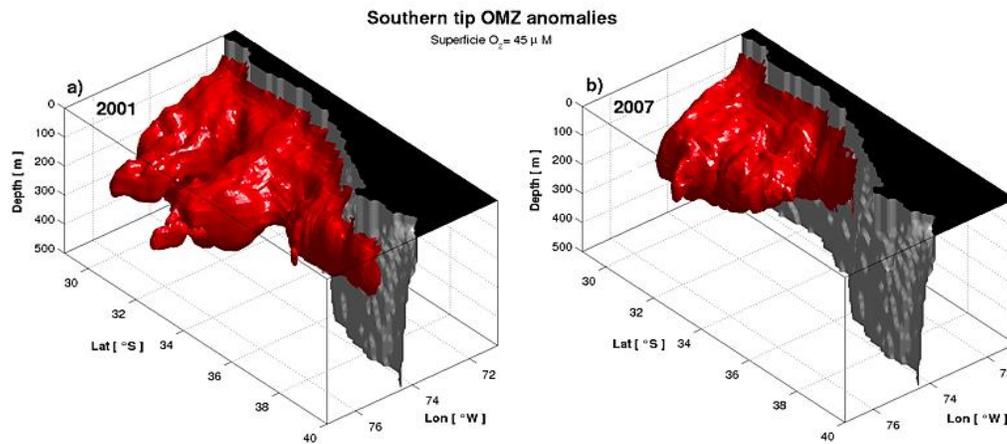


Figure 8: 3-D distribution of the southern tip of the Oxygen Minimum Zone. (Top panels) displays the whole OMZ volume ($<45 \mu\text{M}$) and (bottom panels) shows the OMZ core ($<20 \mu\text{M}$; bottom panels) during 2001 (positive anomaly; left panels) and 2007 (negative anomaly; right panels) periods.

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Yanjie Shen studied environmental science in Lanzhou University, Lanzhou, China, in 2016. In 2017, Yanjie started her PhD at the Ocean University of China, Qingdao, China, to investigate the new particle formation in atmosphere.

New particle formation events observed in remote tropical marine atmospheres over the South China Sea

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New particle formation (NPF) is a common atmospheric phenomenon which has been observed globally in various continental and marine environments (Gong *et al.*, 2010). The grown

newly formed particles are proposed to affect the climate by scattering sunlight directly or by affecting cloud formation indirectly (Kulmala *et al.*, 2004). In the boundary layer of continental at-

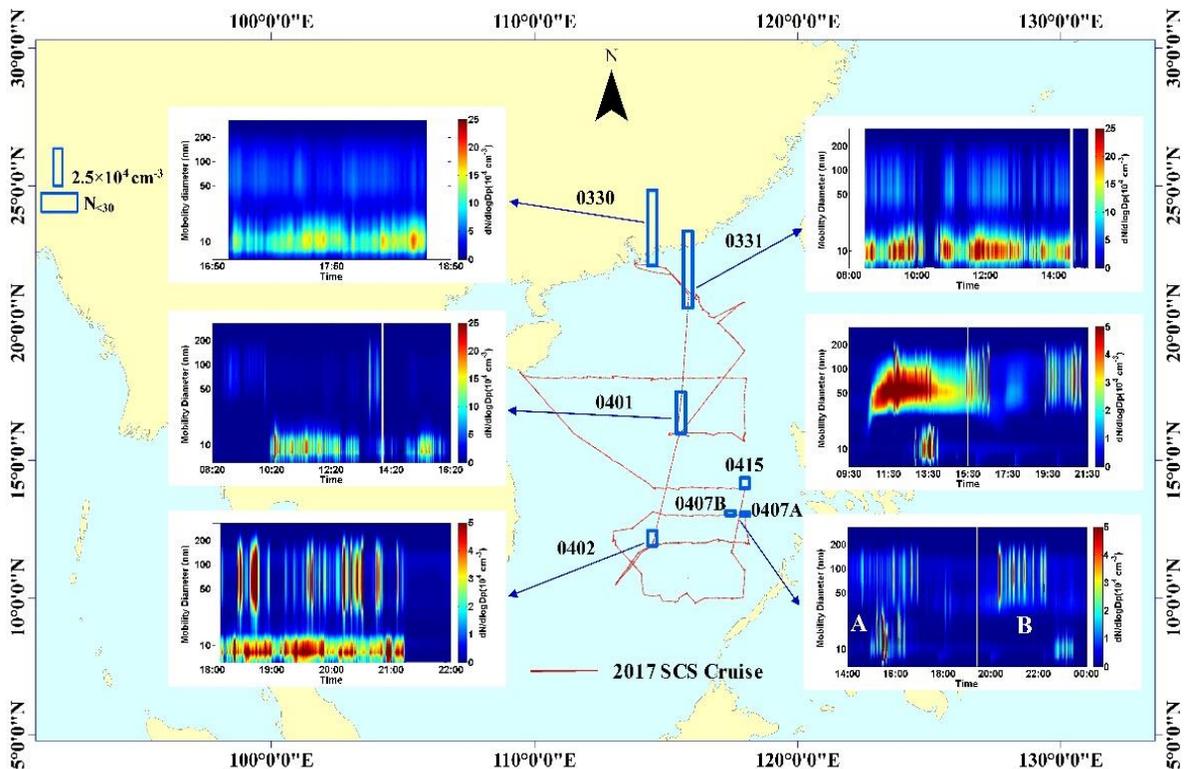


Figure 9: New particle formation (NPF) events observed in the atmosphere across South China Sea (SCS), the blue bars represent the number concentration of the 5.6-30 nm particles ($N_{<30}$), the red line represents the cruise track across SCS during the period of 29 March to 2 May 2017.

mospheres, sulfuric acid vapor is widely recognised as the necessary precursor for atmospheric nucleation while ammonia (NH_3) and organics have been reported to greatly enhance atmospheric nucleation therein (Zhang *et al.*, 2004). In the boundary layer of marine and coastal atmospheres, the oxidation products of dimethyl sulphide (DMS) such as sulfuric acid as well as reactive iodine compounds are proposed to induce atmospheric nucleation (O'Dowd *et al.*, 2002). Relative to the abundant observations in the continent atmospheric boundary layer, the observations of the occurrence of NPF in the marine atmospheric boundary layer are scarce (Sellegri *et al.*, 2016), thus one of my PhD work is to study the NPF events across South China Sea (SCS).

In this study, a spring cruise campaign across the SCS was organised by National Natural Science Foundation of China using a search vessel Shiyan-1. The route is shown in Figure 9. During the whole cruise campaign, seven NPF events were observed (Figure 9). All seven NPF events occurred under clear weather conditions with ambient relative humidity (RH) exceeding 70%. This raised a possibility that these NPF events were not likely induced by sulfuric acid vapour. The observation of night-time NPF events supported this theory because of the lack of photochemical reactions. In addition, the typical “banana-shape” particle growth in any of the seven NPF events identified over the SCS was not observed. The geometric mean diameter (GMD) of newly formed particles remained invariant at ~10 nm in these NPF events. The 24-hour back trajectories during these NPF events showed that air masses travelled over the marine atmosphere (Figure 10). However, 24-hour back trajectories during the NPF events (grown up >10nm) across Northwest Pacific Ocean showed that air masses travelled over the continent.

Based on the comparison, it can be argued that the atmosphere over the SCS during the observational period lacks key precursors from the continent to support the growth of newly formed particles.

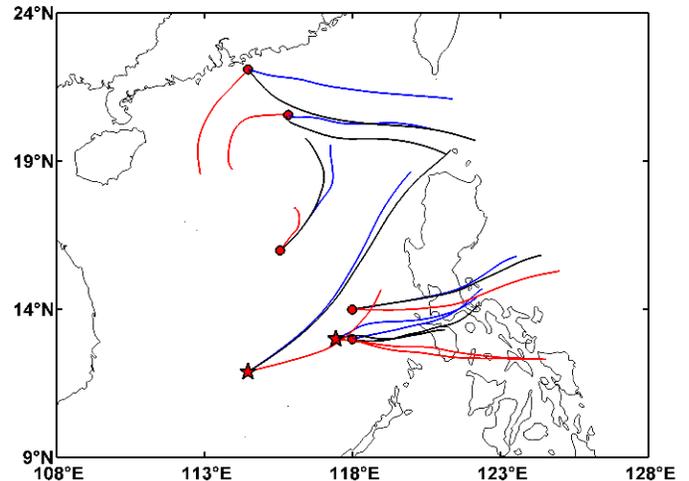


Figure 10: Air mass back trajectories in the latest 24 hours (100m, 500m and 1000 m) at the new particle formation (NPF) initial time on NPF days across South China Sea (SCS).

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Source characterisation of atmospheric trace metal deposition around Australia

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An important component of the Earth's carbon cycle system is the land-atmosphere-ocean transport of vital minerals and micronutrient trace elements (Jickells *et al.*, 2005). One part of this system is the biogeochemical cycle of iron (Fe), in which Fe-rich aerosols are delivered from the land masses to the oceans as aerosols from soils erosion, bushfire, and anthropogenic emissions. After deposition into the ocean some fraction of this Fe and other micronutrients contained in aerosols are available for marine biota consumption.

In some regions, such as the Southern Ocean, the scarcity of Fe controls marine phytoplankton growth with consequential effects for the ocean's drawdown of atmospheric carbon dioxide (CO₂) (Boyd *et al.*, 2000). On the global scale, a high proportion of the CO₂ budget is consumed by photosynthetic organisms in oceans. This makes aerosols important for Earth's climate by influencing the atmospheric CO₂ concentration.

Deserts in North Africa and Central Asia are the most productive dust sources worldwide. The Southern Hemisphere is less abundant in mineral

dust sources with the main active sources located in Australia, Patagonia and South Africa. Two main Australian dust sources are the Lake Eyre and Murray Darling Basins, both are supplied by inland river systems that deliver sediments to the arid zone of the continent. From there, dust is transported by two main atmospheric pathways: towards the south-east and the north-west of the continent (Bowler, 1976).

With an average 339 × 10³ km² of land burned per year, Australia is the second largest source of biomass emission and contributes 11% of the global total direct carbon emission flux from wildfire or bushfire emissions (Ito and Penner, 2004). Bushfires are common especially in the northern tropics of Australia where significant areas of tropical savannah are burnt every year during the dry season (Russell-Smith *et al.*, 2007).

Furthermore, since the Australian coast is inhabited by the majority of the Australian population, it is also the most industrially developed. For that reason, the coastline is a significant source of anthropogenic aerosols. Despite these signifi-

cant aerosol sources of both mineral dust and biomass burning emission, the aerosol data available for the Southern Hemisphere is still sparse. My results will assist with building up the trace metal (TM) database for Australia and thus will improve the accuracy of existing global models for ocean trace element and nutrient cycling.

A key question for studying the atmospheric TM deposition into oceans is the quantity of bioavailable TM forms that are supplied for photosynthesis and other bio-chemical processes. Bioavailability depends on nutrient solubility in sea water. Consequently, measuring total element concentrations in aerosols is not as important as determining what proportion of the total element concentration is bioavailable. Aerosol Fe solubility

and bioavailability depend on its sources, particle size distribution and aging processes occurring during transport.

Most of atmospheric Fe worldwide comes from dust where Fe is contained in a variety of minerals. However, the fraction of soluble Fe in mineral dust is generally low, below 1% for most Fe oxides and between 4 and 6% for most alumina-silicates (Journet *et al.*, 2008). Desboeufs *et al.* (2005) found that Fe in alumina-silicate crystal clusters is much less soluble than Fe embedded in combustion products. They reported that Fe solubility for oil fly ash was as high as 36%. The high fractional solubility of combustion products was confirmed by Schroth *et al.* (2009) who reported Fe solubility from oil combustion reaching 81%, compared to much lower solubility of arid soils and glacial products: 1% and 2-3%, respectively.

Three sampling sites located in the proximity of

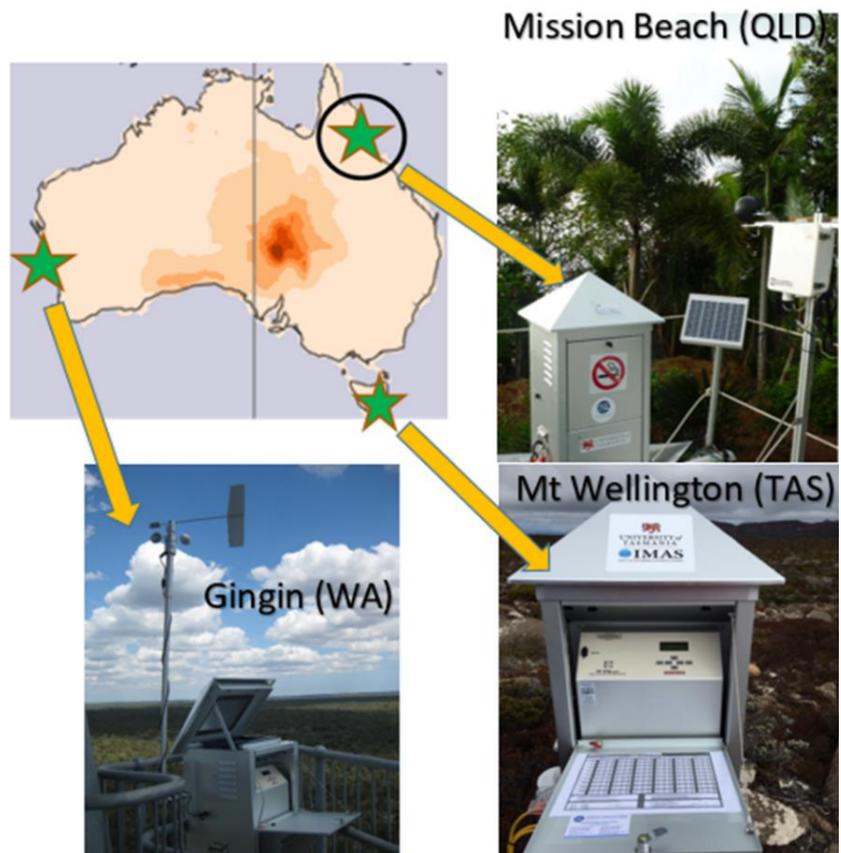


Figure 11: Dust dry deposition (left) and black carbon deposition (right) in Australia. Green Stars indicates sampling stations.

Source: <https://giovanni.gsfc.nasa.gov/>

the Australian coast are included in my research: Mission Beach (Queensland), Gingin (Western Australia), and Mount Wellington (Tasmania) (Figure 11). The last two stations are permanent sampling stations and allow observation of seasonal trends. Aerosol samples are collected on TM cleaned cellulose filters using air samplers. Leaching experiments followed by elemental analysis provide information about atmospheric concentrations of soluble, leachable and refractory forms of TM. Soluble TM data are correlated with markers of mineral dust, anthropogenic activity, and biomass burning to find their influence on soluble TM pool. Scanning Electron Microscopy analysis is used to study aerosol form and chemical composition.

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Lower atmosphere processes affecting the surface ocean: mixed and mixing layer depths

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The ocean surface boundary layer (OSBL) is typically well mixed as a result of different turbulent processes (due to the action of wind, waves, and buoyancy). The depth of the OSBL is controlled by the availability of turbulence and is characterised by vertically uniform temperature, salinity, and density. The OSBL controls relevant processes such as the transfer of heat, momentum, and trace gases between the ocean and atmosphere and represents an important element in the global climate system.

To investigate the OSBL, the Air-Sea Interaction Profiler (ASIP) was designed to study the surface layer of the ocean with an integrated suite of small-scale measurements from a single upwardly rising and autonomous platform (Figure 12) (for further details see Sutherland *et al.*, 2013, Ward *et al.*, 2014, Esters *et al.*, 2018). ASIP provides high-resolution vertical profiles of temperature, conductivity, and dissipation rates of turbulent kinetic energy (ϵ).

The base of the OSBL can be represented using the mixed layer depth (MLD) or the mixing layer depth (XLD) (Brainerd and Gregg, 1995). The MLD represents the limit of the layer at which

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Figure 12: Image of the Air-Sea Interaction Profiler (ASIP) featured on the cover of the Journal of Geophysical Research (JGR) in March 2014.

temperature, salinity, and density are nearly constant with depth and the XLD represents the layer where turbulent processes are actively mixing the ocean surface. Using data collected with ASIP in the North Atlantic on board of the R/V Knorr from June 25 to July 6, 2011 (Figure 13), both parameters were estimated for the four deployments and then compared with local conditions.

The mixing in the OSBL is mainly produced by the contribution of three sources of turbulence: waves, wind, and buoyancy (Belcher *et al.*, 2012). Under specific conditions one of the parameters could have more influence on mixing rather than others. For example, under positive strong buoyancy flux (B0) convection is favourable and therefore the mixing can penetrate deeper. In this case, both MLD and XLD are nearly equal (Figure 14, deployment 2) and are controlled by changes in B0. In deployment 3 (Figure 14), there are rapid changes in the energy flux (E10), and the energy increased until a certain point where it drops abruptly and subsequently increases. The XLD shows a strong positive correlation with E10 since it is increasing

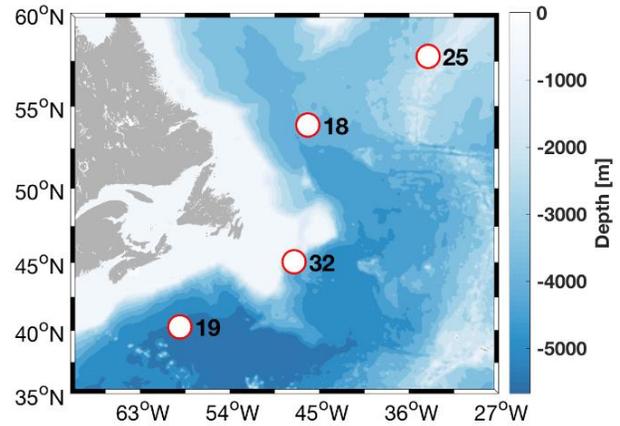


Figure 13: Bathymetry of the region of study. Red dots indicate the location of Air-Sea Interaction Profiler (ASIP) deployments and the total number of vertical profiles for each of them.

(and decreasing) at the same time that the energy is going up (or going down). The XLD is under the wind effects but the MLD seems to not have any relation to those changes. Since none of the turbulence sources takes over the others, the mixing in deployment 1 and 4 is a consequence of a combination among them. Another relevant aspect of this is that the MLD and the XLD are not equal. Most of the time, the MLD is deeper and only under strong convection conditions both can be identical.

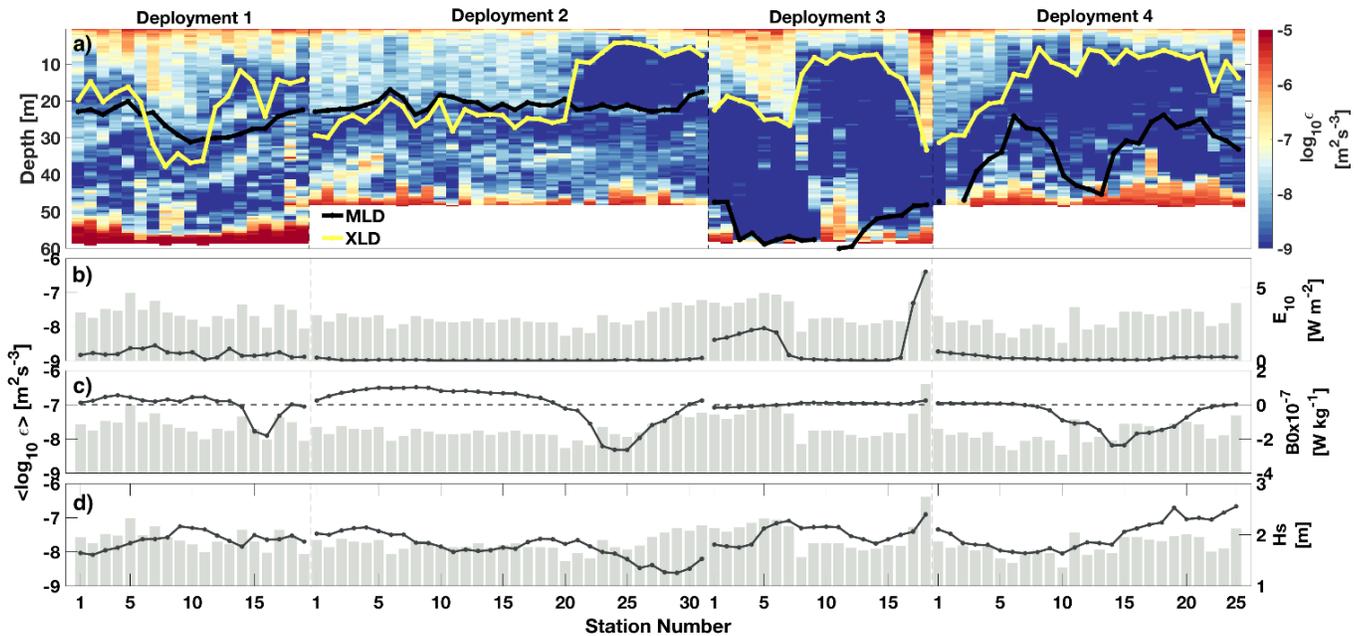


Figure 14: (a) Vertical profiles of $\log(\epsilon)$ for the four deployments of the Knorr cruise. Wind energy flux (E10) (b), buoyancy flux (B0) (c), and significant wave height (Hs) (d) for all stations (black lines). The grey bar charts in b-d represent the average of $\log(\epsilon)$ over the XLD.

The XLD is a better proxy of the turbulent mixing activity at the ocean surface.

Understanding the process that affects the air-sea exchanges is crucial to improving the climate and ocean general circulation models. Through the collection of on board measurements a better comparison between model outputs and in situ data can be made to reduce the lack of knowledge of physical processes at the ocean surface layer.

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