REVIEW

Sea surface microlayer in a changing ocean – A perspective

Oliver Wurl*, Werner Ekau[†], William M. Landing[‡] and Christopher J. Zappa[§]

The sea surface microlayer (SML) is the boundary interface between the atmosphere and ocean, covering about 70% of the Earth's surface. With an operationally defined thickness between 1 and 1000 μm, the SML has physicochemical and biological properties that are measurably distinct from underlying waters. Recent studies now indicate that the SML covers the ocean to a significant extent, and evidence shows that it is an aggregate-enriched biofilm environment with distinct microbial communities. Because of its unique position at the air-sea interface, the SML is central to a range of global biogeochemical and climate-related processes. The redeveloped SML paradigm pushes the SML into a new and wider context that is relevant to many ocean and climate sciences.

Introduction and definition

The sea surface microlayer (SML) is the boundary interface between the atmosphere and ocean, covering about 70% of the Earth's surface. The SML has physicochemical and biological properties that are measurably distinct from underlying waters. Because of its unique position at the air-sea interface, the SML is central to a range of global biogeochemical and climate-related processes. Although known for the last six decades, the SML often has remained in a distinct research niche, primarily as it was not thought to exist under typical oceanic conditions. Recent studies now indicate that the SML covers the ocean to a significant extent (Wurl et al., 2011), highlighting its global relevance as the boundary layer linking two major components of the Earth system – the ocean and the atmosphere.

Three decades ago, Sieburth (1983) hypothesized that the SML was a hydrated gel-like layer formed by a complex mixture of carbohydrates, proteins, and lipids. In recent years, his hypothesis has been confirmed, and scientific evidence indicates that the SML is an aggregate-enriched biofilm environment with distinct microbial communities (Cunliffe et al., 2013). Ellison et al. (1999) estimated that 200 Tg C yr^{-1} accumulates in the SML, similar to sedimentation rates of carbon to the ocean's seabed, though the accumulated carbon in the SML probably has a very short residence time. Although the total volume of the microlayer is very small compared to the ocean's volume, Carlson (1993) suggested in his seminal paper that unique interfacial reactions may occur in the SML that may not occur in the underlying water or at a much slower rate there; he therefore hypothesized that the SML plays an important role in the diagenesis of carbon in the upper ocean. Biofilm-like properties and highest possible exposure to solar radiation leads to an intuitive assumption that the SML is a biochemical microreactor (**Figure 1**) as suggested by Bloug (2005). In this paper we discuss how such a vast microbial- and carbon-rich milieu covering 70% of the Earth's surface affects air-sea interactions, especially in times of a changing ocean.

Historically, the SML has been summarized as being a microhabitat comprised of several layers distinguished by their ecological, chemical and physical properties with an operational total thickness of between 1 and 1000 μm. Hunter (2005) defined the SML as "[…] microscopic portion of the surface ocean which is in contact with the atmosphere and which may have physical, chemical or biological properties that are measurably different from those of adjacent sub-surface waters". He avoids a definite range of thickness as it depends strongly on the feature of interest. A thickness of 60 μm has been measured based on sudden changes of the pH (Zhang et al., 2003), and could be meaningfully used for studying the physicochemical properties of the SML. At such thickness, the SML represents a laminar layer, free of turbulence, and greatly affecting the exchange of gases between the

* Carl von Ossietzky Universität Oldenburg, Institute for Chemistry and Biology of the Marine Environment, 26382 Wilhelmshaven, DE

† Leibniz Centre for Tropical Marine Research, 28359 Bremen, DE

‡ Florida State University, Department of Earth, Ocean, and Atmospheric Science, Tallahassee, FL, US

§ Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, 10964, US

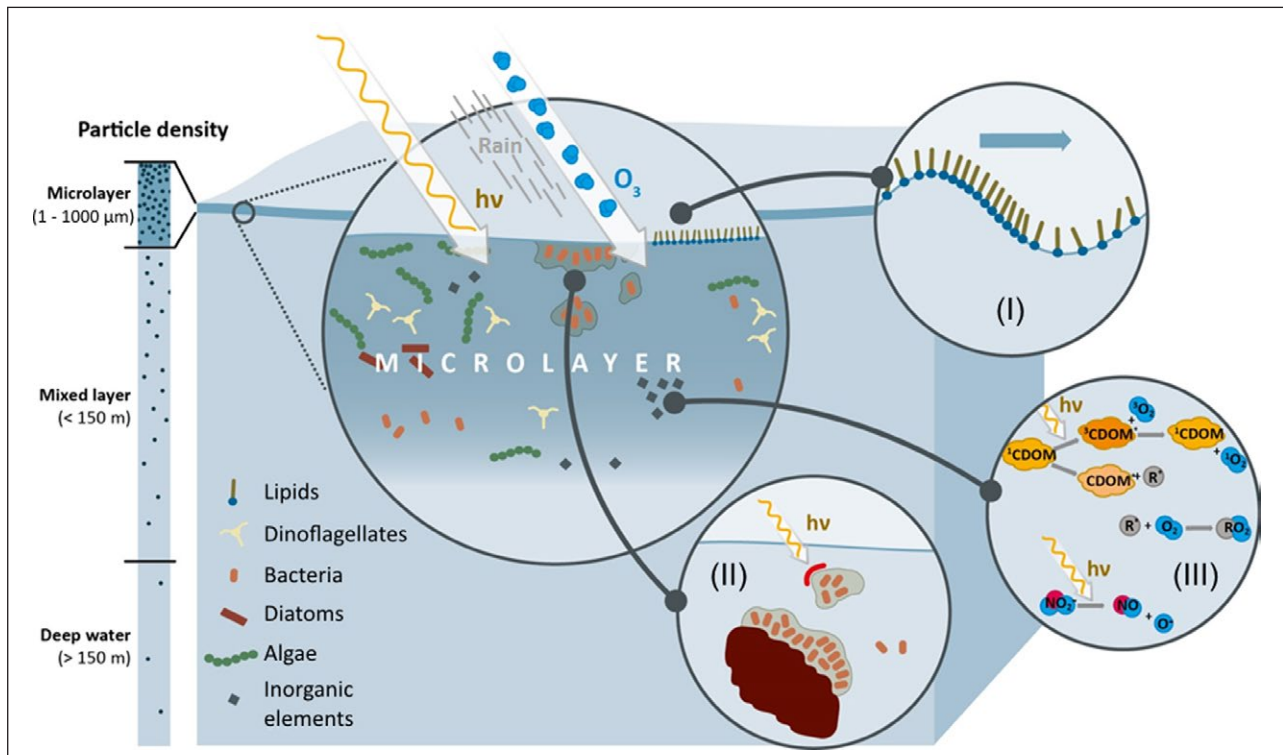Corresponding author: Oliver Wurl
(oliver.wurl@uni-oldenburg.de)

Figure 1: The sea surface microlayer (SML) as a biochemical microreactor. (I) Unique chemical orientation, reaction and aggregation (Carlson et al., 1993). **(II)** Distinct microbial communities processing dissolved and particulate organic matter (Sieburth et al., 1983). **(III)** Highest exposure of solar radiation drives photochemical reactions and formation of radicals (Zafiriou, 1986). DOI: https://doi.org/10.1525/elementa.228.f1

ocean and atmosphere. As a habitat for neuston (surface-dwelling organisms ranging from bacteria to larger siphonophores), the thickness of the SML in some ways depends on the organism or ecological feature of interest. Zaitsev (2005) describes the SML and associated near-surface layer (down to 5 cm) as an incubator or nursery for eggs and larvae for a wide range of aquatic organisms.

Hunter's definition includes all interlinked layers from the laminar layer to the nursery without explicit reference to defined depths (Hunter, 2005). With the recent research, we propose validation of Hunter's definition with a redeveloped SML paradigm that includes its global presence, biofilm-like properties and role as nursery. The new paradigm pushes the SML into a new and wider context that is relevant to many ocean and climate sciences. It is therefore timely to discuss its present and future role, as continuing anthropogenic forcing, including warming and rise of sea levels, ocean acidification and global distribution of man-made chemicals, pushes the ocean to change.

We believe that the SML can never be devoid of organics due to the abundance of surface-active substances (e.g., surfactants) in the upper ocean (Wurl et al., 2011) and the phenomenon of surface tension at air-liquid interfaces (Levich, 1962). The SML is analogous to the thermal boundary layer, and remote sensing of the sea surface temperature shows ubiquitous anomalies between the sea surface skin and bulk temperature (Schlüssel et al., 1990). Even so the differences in both are driven by different processes. Enrichment, defined as concentration ratios of an analyte in the SML to the underlying bulk water, has been used for decades as evidence for the existence of the SML. Consequently, depletions of organics in the SML are debatable; however, the question of enrichment or depletion is likely to be a function of the thickness of the SML (which varies with sea state; Carlson, 1982), including losses via sea spray, the concentrations of organics in the bulk water (Wurl et al., 2011), and the limitations of sampling techniques to collect thin layers (Cunliffe and Wurl, 2014). Enrichment of surfactants, and changes in the sea surface temperature and salinity, serve as universal indicators for the presence of the SML. Organisms are perhaps less suitable as indicators of the SML because they can actively avoid the SML and/or the harsh conditions in the SML may reduce their populations. However, the thickness of the SML remains "operational" in field experiments because the thickness of the collected layer is governed by the sampling method. Advances in SML sampling technology are needed to improve our understanding of how the SML influences air-sea interactions.

Air-Sea momentum transfer and ocean waves

Accurate evaluation and prediction of the momentum flux at the surface of the ocean is critical to a large range of problems that include evaluating air-sea drag as well as heat, moisture, and gas exchange, because turbulent diffusivity generally dominates its molecular counterpart by orders of magnitude and, thus, is the

primary mechanism for transport. Unfortunately, the range of scales involved renders direct numerical simulation inadequate for models of these air-sea processes. Furthermore, high resolution data are sparse. Therefore, most applications require that the surface momentum flux be derived from readily obtained and resolved variables such as wind speed and wave variables. For flow over a smooth, flat plane, upon which boundary layer turbulence theory is derived, this approach is quite successful because the stress in the vicinity of the surface can be considered to be constant, resulting in the well-known "law of the wall." Succinctly, the law of the wall, close to the surface, identifies two distinct layers: the viscous sublayer, where molecular stresses dominate, and the log layer, where the turbulent stresses dominate. The constant stress layer assumption leads to self-similar functions for the velocity profile in the form of the classical log-linear profiles.

Unlike air-flow over flat surfaces, individual stress components for the marine boundary layer are not well resolved, and their interactions are even less well determined. The complicating factor for the oceanic case is the presence of a free surface at the boundary. As the wind blows over the ocean, waves form, grow, interact with each other, and eventually break. In addition to the stress from the viscous boundary effects and turbulence, there is also stress due to the form of the waves (e.g., Janssen, 1989; Belcher and Hunt, 1993; Makin et al., 1995; Hare et al., 1997; Edson and Fairall, 1998). Recent work (Veron et al., 2008) at low to moderate wind speeds has also shown that that there are wave-modulated sensible and latent heat fluxes. In the marine atmospheric boundary layer, the partition between viscous, turbulent, and wave stresses, is poorly understood. The consensus seems to be that in low winds, the viscous stress dominates, whereas the role of the surface waves and breaking wave decreases. Therefore, the classical wall-layer approach needs to be modified to incorporate a sea-state dependence which is usually parameterized by the wave age. Furthermore, modeling shows that the momentum flux is strongly linked to breaking wave and near-surface wind properties rather than just wind speed (Sullivan and McWilliams, 2010). Thus, the role of surface waves, and breaking waves in particular, needs to be better understood.

In the constant stress boundary layer near the sea surface, the total stress can be decomposed into different constituents: viscous, turbulent, wave-induced (form drag) and separation-induced (from the breaking waves). Because each individual stress component depends on and alters the sea state, a linear addition of all stress components is too simplistic. Modeling of the air-sea surface fluxes must incorporate air-flow separation from surface breaking and its effects on the other stress components, such as a reduction of the surface viscous stress in the separated region as suggested by recent measurements (Veron et al., 2007). Naturally, the inclusion of these effects leads to a nonlinear stress formulation and reproduces the observed features of the drag coefficient from low to high wind speed. In addition,

the air-sea flux model of Mueller and Veron (2009; 2010) agrees remarkably well with recent measurements (Figure 18 in Romero et al., 2012) as well as large historical data aggregates (Figure 9 in Andreas et al., 2012). Understanding how these stresses are partitioned and interact is therefore critical to our ability to determine and predict air-sea fluxes on a global scale, especially in a changing climate where changes in long-term, ocean wave climate variability are projected and large-scale spatial distributions of wave heights are influenced by various teleconnection patterns (Shimura et al., 2013). Decreased significant wave height for more than 25% of the global oceans has been suggested (Hemer et al., 2013) and will lead to a greater importance for viscous stress transfer and therefore for the SML. In order to improve our understanding of air-sea momentum, heat and gas fluxes, it is clear that high resolution understanding of the wave field effects on the SML are necessary.

Air-Sea gas and heat exchange

The processes controlling carbon transport and transformations in the ocean represent large sources of uncertainty in regional and global budgets of carbon and climate-relevant gases (e.g., CO_2, CH_4, N_2O). In order to accurately quantify these processes, studies require accurate estimates of the air-sea gas flux. Currently, these efforts are seriously undermined by an inability to satisfactorily model the factors governing the air-water gas transfer velocity, k, in physically complex ocean systems including the SML.

Wind forcing has long been known to exert a major control on gas transfer as well as on near-surface turbulence, and many wind-forced processes have been suggested as mechanisms for the enhancement of both (Garbe et al., 2014). Small-scale waves have been suggested as a dominant controlling factor for k (Bock et al., 1999), because wave slope is strongly linked with gas transfer. Microbreaking, or the breakdown of small-scale waves that do not entrain air, may explain the link between k and surface roughness and has been shown to directly enhance gas transfer at low to moderate wind speeds (Zappa et al., 2001, 2004). In the presence of an enriched SML near-surface turbulence is suppressed and k may be significantly reduced at a given wind speed or wind stress (Jähne et al., 1987). Surface contamination by thin organic films measured in the field has also been shown to dampen high frequency waves and lead to reduced gas exchange (Frew et al., 2004). Less dependence of k on wind speed is observed under conditions when buoyancy may dominate the production of turbulence in the near-surface layer (McGillis et al., 2004; Rutgersson and Smedman, 2010; Rutgersson et al., 2011) or when rain directly affects the turbulence at the interface and causes variability in k (Ho et al., 2004; Zappa et al., 2009). Dilution due to rain also has a significant effect on the CO_2 uptake by the ocean (Turk et al., 2010) and any future shifts in precipitation patterns (Trenberth, 2011) will affect uptake rates.

The turbulence-mediated transfer across the ocean surface mass boundary layer (i.e., within the SML) has

been related explicitly to the turbulent kinetic energy dissipation rate, ε, for a variety of processes (Banerjee et al., 1968; Lamont and Scott, 1970; Kitaigorodskii, 1984; Melville, 1996). Zappa et al. (2007) demonstrated that turbulent kinetic energy dissipation is a good predictor for gas transfer at low to moderate winds. Although to first order gas transfer can be thought to be dictated by wind speed, which is a primary driver of turbulence in the upper ocean, a large variety of environmental forces and processes (wind, currents, rain, waves, microscale wave breaking, surfactants, fetch, stability of both the atmospheric and ocean boundary layer) actually influence k. Therefore, variations in wind speed alone cannot capture the variability of air-water gas exchange rates. Understanding the physical processes controlling air-sea gas transfer through the SML, including their potential change in the future, will allow us to evaluate the importance of the SML on air-sea gas exchange under a wider range of low to moderate wind speed regimes.

Despite the potential relevance of the SML to ocean-atmosphere interactions, still little is known about its structural characteristics and sensitivity to a changing environment such as higher CO_2 levels and increased oceanic uptake of anthropogenic CO_2. Higher CO_2 levels might be encouraging growth of phytoplankton. For example, a long-term basin-scale increase in coccolithophores suggests that increasing CO_2 and temperature have accelerated the growth of a phytoplankton group that is important for carbon cycling (Rivero-Calle et al., 2015). As a result, the production of surface-active phytoplankton exudates that suppress gas transfer is likely to increase (Riebesell, 2004). Enhanced primary production in a high CO_2 ocean provides a positive feedback on the ocean uptake of CO_2 (Riebesell et al., 2007), but also may lead to a suppression of air-sea gas transfer by increased surfactants that provides a negative feedback on the ocean uptake of CO_2. The SML has long been known to have elevated levels of phytoneuston, total chlorophyll, particulate carbon fixation, and dissolved organic matter relative to the subsurface waters (Hardy and Apts, 1989). Increasing oceanic uptake of atmospheric CO_2 is also known to stimulate carbon fixation by autotrophic cells (Engel et al., 2013), and their release of organic polymers may increase as a result of their elevated metabolism (Riebesell et al., 2007). These organic exudates can aggregate to form "gel particles" in the eutrophic zone, where rising air bubble plumes (Zhou et al., 1998) and positive buoyancy (Azetsu-Scott and Passow, 2004) are important transport mechanisms towards the SML. Higher production of gel particles in the future ocean will potentially lead to a thicker and more widely distributed SML, which can reduce air-sea CO_2 fluxes by up to 15% (Wurl et al., 2016). On the other hand, the SML is a highly heterotrophic system (Piontek et al., 2010), and enhanced organic matter accumulation under future ocean scenarios may further drive heterotrophic processes in the SML, possibly pushing the SML to become a net source of CO_2. Indeed, Galgani et al. (2014) showed in mesocosm studies that ocean acidification may induce a change in the nature of the organic matter in the SML, e.g., higher concentrations of hydrolyzable amino acids, indicative of higher bacterial biomass, and lower concentrations of carbohydrates, probably due to enhanced bacterial degradation processes. Rahlff et al. (2017) showed a statistically significant and positive interaction between pCO_2 and wind speed on the enrichment of bacteria in the SML. Acidification (i.e., high pCO_2) of the bulk water and diffusional gas transport across the SML at low wind speed could have provided a slightly less acidified "sanctuary" for the bacteria in the SML.

Such biological processes and their feedbacks are dependent on the sea surface temperature. The sea surface skin temperature is a fundamental feature of the SML, and satellite maps of the skin temperature are used for understanding climate (Kennedy et al., 2012), weather (Donlon et al., 2012) and prediction of the ocean's warming (Lee et al., 2013). For example, global-average sea surface temperature warming trends are calculated to be $0.124 \pm 0.030°C$ decade^{-1} when computed from the gridded sea surface temperature data sets between 1979 and 2012 (Hartmann et al., 2013). As sea surface temperature is computed from the skin temperature, it can be assumed that the SML is warming at a similar rate. This warming is of particular concern in polar regions, as continuing low sea ice coverage in the Arctic will increase the area of open ocean for gas exchange (Feltham, 2015). However, the capacity of the Arctic Ocean for uptake of atmospheric CO_2 is probably weaker than intuitively assumed, mainly due to warming of the shallow mixed layer (Steele et al., 2008), increased ventilation of the surface mixed layer (Else et al., 2013) and broader presence of the SML in polar regions forcing gas exchange to be limited by diffusion (Wurl et al., 2011). Incomplete understanding of how sea ice modulates the SML, and therefore gas fluxes, renders it difficult to estimate the carbon budget in possible future climate scenarios of an ice-free Arctic.

Effects of aerosol deposition on biogeochemical processes in the SML

Although 100% of the atmospheric fluxes of biologically-essential trace elements (TEs) must enter the surface ocean through the SML by wet or dry deposition, very little is known about the enrichment of these essential TEs and their interactions with particles, organics, and microbes in the SML (recent summarized by Cunliffe et al., 2013). Hunter (1980) described the enrichment of particulate TEs in the SML from atmospheric deposition, and subsequent studies have shown consistent enrichment in the SML for particulate trace elements (Hardy et al., 1990; Brügmann et al., 1992; Cuong et al., 2008). Unfortunately, we have very little understanding of how these aerosol inputs are impacted by, or have an impact on, the active microbial communities within the SML. We lack multidisciplinary data sets that link the microbial community structure and function in the SML with biogeochemical processes such as solubilization of aerosol trace elements, dissolved/particulate conversions for trace elements, and the production and consumption of dissolved organic compounds.

TEs in the ocean can act as nutrients or pollutants as well as tracers of oceanic cycling processes. For example, the lack of dissolved Fe, an essential micronutrient for all organisms, is believed to limit, or co-limit, phytoplankton productivity in high-nutrient low-chlorophyll regions of the ocean (e.g., Martin et al., 1990) and may also affect nitrogen fixation in some areas (Falkowski, 1997). For the highly insoluble micronutrient Fe, and possibly for other micronutrients such as Mn, Co, and Zn, the deposition of mineral dust to the SML can be the dominant pathway for supplying these essential trace elements to surface waters of the open ocean. While current global ocean models for Fe biogeochemistry (e.g., Orr et al., 2016) do not include any aerosol cycling processes in the SML, if significant solubilization of bio-active aerosol trace elements does occur in the SML, and if that solubilization varies in space and time (very likely), then representing the SML explicitly in Fe biogeochemistry models should be considered because of the known ubiquitous SML coverage of the ocean (Wurl et al., 2011).

In addition to mineral dust from arid regions, aerosols are also produced by biomass burning, coal and oil combustion, and industrial processes such as cement manufacturing and metal smelting. Based on incubation experiments, Paytan et al. (2009) concluded that soluble aerosol Cu from industrial emissions can affect the phytoplankton community structure in surface waters. Many of these aerosol sources are likely to persist into the future (e.g., Wang et al., 2013), and atmospheric transport and deposition will continue to deliver these pollutant aerosols to the open ocean (Duce et al., 1983). Furthermore, aerosols produced by different mechanisms have characteristic chemical properties that influence their solubility in seawater (e.g., Sholkovitz et al., 2012). Predicted future shifts in precipitation patterns (Trenberth, 2011) and atmospheric circulation (England et al., 2014; Bony et al., 2015) should therefore result in changes in the supply of both essential and pollutant trace elements to the SML, and subsequent changes in the biological response in the SML and the upper ocean.

Changing patterns of UV flux to the ocean (Williamson et al., 2014) suggest that photochemical processing in the SML will also change. This change could have a significant impact on TE processing in the SML, especially for redox-active TEs and TEs in complexes with dissolved organic ligands. Understanding how aerosol material is altered by biotic and abiotic processes in the SML, and how photochemistry is involved, is essential for quantifying the impact of these processes on the biogeochemistry of the upper ocean. In summary, one can argue that quantifying the rates and mechanisms for biogeochemical cycling of TEs in the SML is extremely important for understanding ocean ecosystems and the global carbon cycle (and thus climate change).

Habitat for a distinct planktonic community

The steep gradient of physicochemical properties across the atmosphere-water boundary concentrates a high amount of organic material in the SML, which attracts a variety of organisms of different sizes. Various microorganisms use this organic matter directly, resulting in planktonic communities in the upper 5 cm of the water column that are significantly different from those in the layers below, both in composition and abundance (Hardy, 2005). To survive in this extreme environment and access this rich food source, organisms had to adapt to high irradiation and temperature variability. In halfbeak (Hemirhamphidae) larvae, intensive pigmentation is found in the very early stages as a defense against light penetration. Some surface-dwelling copepods show a blue color (pontellid and arcatiid species) for the same reason, indicating that they are using the SML as a habitat. Higher abundances of copepods in the SML compared to the subsurface layer underline the preference of organisms for this layer (Zaitsev, 1971). The spectral composition and intensity of light in the SML are similar to direct sunlight, and inputs of nutrients and micronutrients, such as iron from aerosols, can quickly enhance primary production. Nutrients from the atmosphere that peak during dust events can also trigger pulses in productivity in the SML (Rubin et al., 2011). This phenomena can be observed in oceanic areas of the North and South Atlantic that are under the sphere of influence of the Sahara and Namib dust plumes. This effect can lead to extreme enrichment ratios (SML: bulk water abundances) of 2,444, 380, 12, and 40 for bacteria, microalgae, chlorophyll pigments, and photosynthesis, respectively (Hardy and Apts, 1984).

Processes within the planktonic community in the SML, interspecies relationships, and responses to variability in the physicochemical conditions of the SML have been investigated rarely and are thus poorly understood. Wang et al. (2014) showed that the changes in phytoneuston, both in density and composition, were mainly due to changes in nutrient input. Increasing temperature (Schmidtko et al., 2017) combined with likely increasing nutrient input from both the land (river runoff) and the atmosphere (e.g., dust) will alter the community composition within the different size fractions of the neuston. Many fish larvae that are normally found in the neuston close to the SML and that feed on either the phytoneuston or microzooplankton may be outcompeted by species that are better adapted to these new conditions.

Marine pollutants

Due to its unique physicochemical properties and position between the ocean and the atmosphere, the SML acts as both a sink and a source for many pollutants, including flame retardants, pesticides, antifouling agents, heavy metals, and petroleum and polycyclic aromatic hydrocarbons (PAH). Hydrophobicity is a key property of many man-made chemicals, such as pesticides, that are used to achieve desired properties; however, hydrophobicity forces those pollutants to accumulate in the SML by up to 500 times relative to concentrations occurring in the underlying bulk water column (Wurl and Obbard, 2004). Increasing oil exploration and associated risks of oil spills (Liu et al., 2015) threaten the SML as a

sensitive habitat through direct impacts and weathering of oil and concentrated by-products of semi-volatile PAHs (Faksness et al., 2015).

Other emerging pollutants have a direct impact on the SML and its inhabitants, including the deposition of soot particles (X Mari, personal communication) from land-based sources and increasing ship traffic. Coal combustion remains a dominate energy source in Asia, with projected peak use not expected before 2024 (Wang et al., 2013). In addition, increasing ship traffic (Tournadre, 2014) indicates that the deposition of soot particles on the SML could become an increasing problem in the future. Changing precipitation patterns occur with climate change (Trenberth, 2011) and rain washes pollutants out of the atmosphere and deposits them on the SML (Lim et al., 2007), leading to the concern that the SML will increasingly become a refuse site. One class of emerging pollutants includes pharmaceutical compounds, personal care products, and endocrine-disrupting compounds. These pollutants historically have had loose disposal policies and are now increasingly detected in the marine environment (Gaw et al., 2014). However, only rare attempts have been made to measure their presence or impacts in oceanic surface water (e.g., Peele et al., 1981) and none have been made for the SML to our knowledge. With an increasing world population, improved medical care, and increasing standards of hygiene, the threat to the marine environment, including the SML, from these pollutants cannot be excluded if proper disposal and treatment in waste water are not addressed in the near future (Gómez et al., 2007).

Since the 1970s, the sea surface has contained floating plastic material estimated at 250,000 tons (Eriksen et al., 2014), which has become a critical environmental issue. In addition to toxic by-products from photochemical and microbial transformations, the direct ingestion of micro-to macro-plastics by larvae and surface-feeding animals is of concern. Micro-plastics and polymers are enriched in the SML by factors of up to 200 compared to the underlying bulk water (Song et al., 2015). The 620% increase in the production of plastic resin that occurred from 1975 to 2012 (Jambeck et al., 2015) is likely to continue, sending more plastic debris into the ocean, which ends up floating in the SML.

Through the potential of the SML to act as a biochemical microreactor, the question remains about the fate of pollutants, including the transformation and toxicity of by-products within the SML. The fate of emerging pollutants is especially unknown, and due to the unique position of the SML, photochemical transformations are of particular concern.

Concluding remarks

Due to its unique position between the ocean and atmosphere, all material and energy being exchanged between these realms has to pass through the SML. Transport through the SML is dominated by molecular diffusion and conduction, and its biofilm-like character further transforms material and absorbs energy. Air-sea interactions cannot be completely understood without taking interfacial processes in the SML into account. However, with future changes in climate, the SML will be modified by changes in atmospheric circulation and meteorological forces, including UV radiation, precipitation and warming. Changes in the upper ocean, especially increases in primary production, will supply more surface-active organic material to the SML, potentially affecting transport by molecular diffusion and conduction across the interface in the future. The growing threat to the SML habitat from man-made pollutants may have adverse effects on the food web and fisheries, given the role of the SML as nursery to eggs and larvae. With new technology and guidance on best practices for investigating the SML (Cunliffe and Wurl, 2014), a wide range of research topics can and need to be integrated into future studies of air-sea interaction. Overall, we suggest that, due to its unique position, the SML will respond sensitively to climate change, but that understanding the influences of the SML on air-sea interactions in a future ocean requires holistic approaches in research that include studies of the physics, chemistry, and biology of the SML.

Competing interests
The authors have no competing interests to declare.

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