

# Marine aerosol-cloud-climate interactions

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## Introduction

Projections of future climate remain an important scientific goal for much of the Earth science community. A large fraction of the uncertainty in predicting 21<sup>st</sup>-century climate change lies in the uncertainties associated with anthropogenic aerosol forcing and feedbacks that result from land-atmosphere-ocean interactions and interactions between natural and anthropogenic emissions [IPCC, 2013]. As aerosol effects on climate are estimated from the differences between model simulations with present-day and with preindustrial aerosol and precursor emissions, accurate representation of marine aerosols is critical for assessment of anthropogenic aerosol effects in Earth System Science models [Ramanathan *et al.*, 2001; Andreae, 2007; Hoose *et al.*, 2009; Ghan *et al.*, 2013; Carslaw *et al.*, 2013]. Changes in marine ecosystems in response to a wide range of stress factors caused by human activities can further incite complex feedbacks between ocean and atmosphere. Reduction in sea ice cover and changes in physical (temperature, salinity, circulation), chemical (nutrient availability, pH) and biological (bacterial and phytoplankton abundance) properties of seawater can strongly influence production rate and physicochemical properties of marine aerosols. These changes in seawater properties can, in turn, affect the sources, sinks, and properties of marine aerosol, influence concentrations of cloud condensation nuclei (CCN) and ice nucleating particles (INP) in the atmosphere. Participants in recent sea spray aerosol workshop suggested that ***there is a great need for comprehensive observational data on marine aerosols that can be used for improvement/evaluations of climate models*** [Meskhidze *et al.*, 2013]. The collection of such data requires multiscale measurements (from in situ to remote sensing) **through a coordinated and multidisciplinary response, with involvement and expertise from a broad range of scientific communities (including atmospheric sciences, physical and biological oceanography).**

## Responses to the NRC call questions

### **1. What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?**

Current Earth System Science models exhibit a large diversity in their representations of marine aerosol sources and sinks, as well as the processes by which these aerosols impact cloud water and ice formation. This diversity is due in part to the lack of measurements to constrain the models. Measurements of marine aerosols are challenging because of their vast spatiotemporal variability and low concentration. Key questions remain unanswered regarding the impacts of marine aerosols on clouds and climate, limiting our ability to

quantitatively predict how the future climate will respond to continued and increasing greenhouse-gas and fine-particle emissions.

- 1. How much do major classes of marine particles contribute to the CCN and INP number of the marine boundary layer in different regions and seasons?*
- 2. How do environmental parameters (surface wind speed ( $U_{10}$ ), atmospheric stability), ocean physicochemical properties (sea surface temperature (SST), salinity, whitecap fraction, Chlorophyll *a* ([Chl-*a*]), dissolved and particulate organic carbon concentration, surface film coverage), biological indicators (organism type and abundance, physiological stress), and sea ice extent modify the CCN and INP number over the ocean?*
- 3. How do changes in ocean-derived CCN and INP abundances affect cloud microphysical properties and phase?*
- 4. What are the feedbacks between oceanic emissions, marine aerosols and clouds, aerosol deposition, and ocean ecosystems? How is humankind changing these feedbacks?*

These questions can be addressed by the development of improved remote sensing products in combination with recent advances in modeling, remote surface monitoring and in situ field and laboratory measurements.

## **2. Why are these challenges/questions timely to address now especially with respect to readiness?**

**This is a timely challenge.** The scientific community is currently poised to make significant advances in understanding marine aerosols, by utilizing recent improvements in space-based earth observing systems, in combination with current and planned ground-breaking measurements from field campaigns and laboratory studies. Many of the parameters crucial for improved characterization of marine aerosols can be retrieved by sampling the top of the atmosphere radiance spectra and polarized radiance spectra for selected UV, visible and SWIR bands. Moreover, current global climate models have reached the point where improved assessments of the human impact on climate change require small changes in model parameters and processes. Because the response of cloud properties to changes in aerosols is most sensitive when total aerosol and cloud droplet concentrations are low, remote marine sites that are not heavily influenced by anthropogenic or continental sources of aerosols can help approximate the pre-industrial atmosphere and are ideal natural laboratories for understanding marine aerosol-cloud-climate interactions at a fundamental level.

Today, remote sensing technology has matured enough to be at Technology Readiness Levels (TRL) 4 to 6, providing an increased number of aerosol and ocean ecosystem parameters with sufficient accuracy to yield meaningful insight into physical processes involving marine aerosols. The planned Pre-Aerosol, Cloud, ocean Ecosystem (PACE) mission will provide ocean biological parameters, including phytoplankton functional type and pigment absorption spectra, colored dissolved organic matter (CDOM) absorption, total and phytoplankton carbon concentration, ocean particle size distribution, and others. However, in order to better characterize forcings and feedbacks between the ocean biogeochemical cycling and ecosystem function, and aerosols and clouds in response to anthropogenic change and natural environmental variability, ocean

measurements must be supplemented by simultaneous high-resolution, vertically-resolved retrievals of aerosols and ocean sub-surface properties. Such vertically-resolved information is essential for distinguishing sea spray aerosol from wind-borne terrestrial aerosols and exploring quantitative links between ocean parameters and marine aerosol properties. The multi-wavelength high spectral resolution lidar (HSRL) with the capability to measure aerosol backscatter at 3 wavelengths, extinction at 2 wavelengths, and depolarization at 2 wavelengths and the multi-angle, multi-wavelength polarimeter planned for the Aerosol-Cloud-Ecosystem (ACE) mission can provide vertical profiles of aerosol type (sea spray, dust, smoke, etc.), extinction, optical thickness, complex index of refraction, concentration and size, simultaneously with ocean surface wind speed and sub-surface data products such as the subsurface particulate backscatter coefficient and depolarization ratio.

### **3. Why are space-based observations essential to addressing these challenges/questions?**

Satellites are, and will likely remain, the dominant means for improved characterization of marine aerosols and aerosol-cloud-climate interactions in a changing climate because they provide global, long-term information on the spatiotemporal variability of many properties affecting marine aerosol production (i.e., surface wind speed, wave parameters, surface Chlorophyll *a* ([Chl-*a*]), dissolved and particulate organic carbon concentration, whitecap fraction, SST, and salinity) and removal. There is **a number of past, existing and planned remote sensing instruments supported through U.S. and international programs** that can be used for characterization of marine aerosols, as well as ground-based systems including the MAN, a ship-borne data acquisition initiative complementing island-based AERONET measurements, and satellites such as MODIS, MISR, AATSR, PARASOL, MERIS, SeaWiFS, CALIPSO, GPM, SAGE-III/ISS, CATS, and PACE. However, none of these sensors can achieve coincident (in time and space) retrievals of vertically-resolved aerosol information, ocean sub-surface properties, and ocean biological parameters, i.e., parameters essential for quantitative characterization of marine aerosol-cloud-climate interactions. Moreover, current satellite sensors either do not provide the data or provide at signal-to-noise ratio that is not high enough for retrieval of many ocean ecosystem processes and aerosol speciation and loadings over the oceans. Existing satellites also provide limited data in the Arctic and Southern Ocean regions characterized by high cloudiness and low solar zenith angles. Therefore, only the combination of instrumentation planned for future PACE and ACE missions can provide the data on global ocean ecology, biogeochemistry, aerosols and clouds, accurate enough to lead to advances in our understanding of the coupled ocean-aerosol-cloud system.

**Additional investments are needed to link space-based observations with other observations.** The supporting satellite measurements are needed to assess environmental conditions affecting marine aerosols including SST,  $U_{10}$ , ice cover, humidity and temperature profiles and precipitation rates. In particular, measurements of drizzle and precipitation rates coincident with the lidar and polarimeter observations are required to better constrain aerosol sinks over the oceans. In addition to the ocean's physical state, the chemical composition of the ocean and the sea surface can influence sea spray production, so direct measurements of surface film coverage (e.g., via synthetic aperture radar) and biogeochemical variables that have *causal* links to sea spray production are

needed. Improvements in sensor technology can advance the field past using proxies like [Chl-*a*] to derive marine chemical state and its impact on aerosol composition.

The detailed mechanisms and the radiative impact of marine aerosols in the Earth's climate system are best understood through the combination of **satellite remote sensing, in situ observations, and modeling**. For example, controlled lab work can provide detailed insight and help exploring the relevant parameter space with greater clarity and specificity. Such lab experiments can be used as a tool to illuminate causal relationships that may lead to better field observations. Dedicated field measurements can range from in-water physical, chemical, biological, and optical properties, to number size distribution, chemical characterization, hygroscopicity and CCN and INP properties of aerosols and precursor trace gas concentration measurements. In addition, field campaigns will contribute valuable data for calibration and validation of satellite sensors, as well as provide required data to answer the key challenges and questions for Earth System Sciences raised in Part 1 of this document.

**Improved marine aerosol characterization will have broad societal implications.** By expanding available satellite-borne sensors to encompass retrievals of marine aerosols and ocean physicochemical/biological systems, it will be possible to capture some potentially important feedbacks with implications for atmospheric radiative effects and climate. An improved understanding of these processes means that models will be better equipped to represent the current state of climate as well as better capture the changes that have occurred over the past century and predict the changes to climate that would result from different future emission strategies. The current acidification of the ocean and its biological adaptation are a response to climate change, which in addition to causing climate feedbacks through impacts on the CO<sub>2</sub> cycle and aerosol emissions, may affect future fisheries and coastal ecosystem responses. Yet, our current estimations of future climate effects are based on model approaches where many of the feedback processes are not included or poorly described. Achieving a high confidence in Earth System Science models critically depends upon more realistic simulations of the ocean ecosystem-aerosol interactions with forcings and feedbacks operating on multiple spatiotemporal scales.

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