

Earth's Future

COMMENTARY

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Key Points:

- The coastal planetary boundary layer (PBL) is highly dynamic and poses challenges to accurately observe and model air quality (AQ), water quality, and ocean color
- Coastal AQ observations and simulations via field campaigns and networks have advanced our understanding of processes coupled by the PBL
- Extensive observations of the coastal PBL are needed to achieve interdisciplinary research goals at the land/water interface

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Surf, Turf, and Above the Earth: Unmet Needs for Coastal Air Quality Science in the Planetary Boundary Layer (PBL)

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Abstract Coastal areas are some of the most densely populated and economically important regions in the world. As such, protecting the health of the human population and ecosystems at the coastal interface and understanding the impacts of environmental stressors such as air pollutants provides wide-ranging benefits. Air quality (AQ) processes within coastal regions have been studied using ground and space-based platforms, with intensive field campaigns focused on addressing key science questions that are typically partitioned into either direct atmospheric effects (e.g., anthropogenic emissions creating air pollution) or indirect processes and feedback loops (e.g., terrestrial/marine biogenic processes modifying atmospheric properties). The atmospheric planetary boundary layer (PBL) and its depth (or height) connect land, air, and the water surface via many pathways, especially with transport and exchange processes tied to the complexities of the coastal interface. We still cannot accurately characterize—through field, aircraft, or space-based observations—the spatial and temporal PBL variability and processes within the PBL that couple together coastal dynamics and air quality. Several upcoming geostationary and polar-orbiting satellite missions are likely to make significant progress in characterizing these air/land/water interactions over the next decade. Here, we present a framework of the current understanding of the PBL's role in coastal regions, primarily regarding air quality and atmospheric deposition, to motivate future concerted efforts from ground- and space-based platforms to achieve a holistic understanding of the coastal interface.

Plain Language Summary Coastal areas are some of the most densely populated and economically important regions in the world. Protecting the health of the human population and ecosystems at the coastal interface and understanding the impacts of key environmental stressors, such as air pollution, provides wide-ranging benefits. The atmospheric planetary boundary layer (PBL) connects land, air, and the water surface, yet there are remaining challenges in accurately characterizing the role of the PBL in coastal areas and its variability. Here, we present a framework of the current understanding of the PBL's role in coastal regions, primarily regarding air pollution, to motivate future concerted efforts from ground- and space-based platforms to achieve a holistic understanding of the coastal interface.

1. Introduction

Most of the world's megacities are in the coastal zone (Brown et al., 2013), and nearly 50% of the US population lives in coastal counties (Crossett et al., 2004), facing urban environmental challenges that occur within the complex coastal atmospheric planetary boundary layer (PBL). While the definitions of the PBL and the PBL height/depth (PBLH) vary depending on scientific application (e.g., gradients in temperature/atmospheric stability, composition, or turbulence), we generally refer to the PBL as the lowest layer of the atmosphere that is directly affected by heat and moisture fluxes and friction from the Earth's surface (Medeiros et al., 2005). The interaction of both land and ocean surfaces with the PBL is a very active area of research, with distinct communities (land-atmosphere and ocean-atmosphere) and driving science questions (e.g., Santanello et al., 2018 and refs therein; Teixeira et al., 2021). Routine measurements of the PBLH are provided via high temporal and vertical resolution ground-based measurements, such as radiosonde soundings, commercial aircraft measurements (e.g., Aircraft Meteorological Data Relay (AMDAR), Y. Zhang et al., 2020), and lidar backscatter/ceilometer. For near global coverage, satellite estimates of PBLH can be derived from spaceborne lidar instruments, such as the

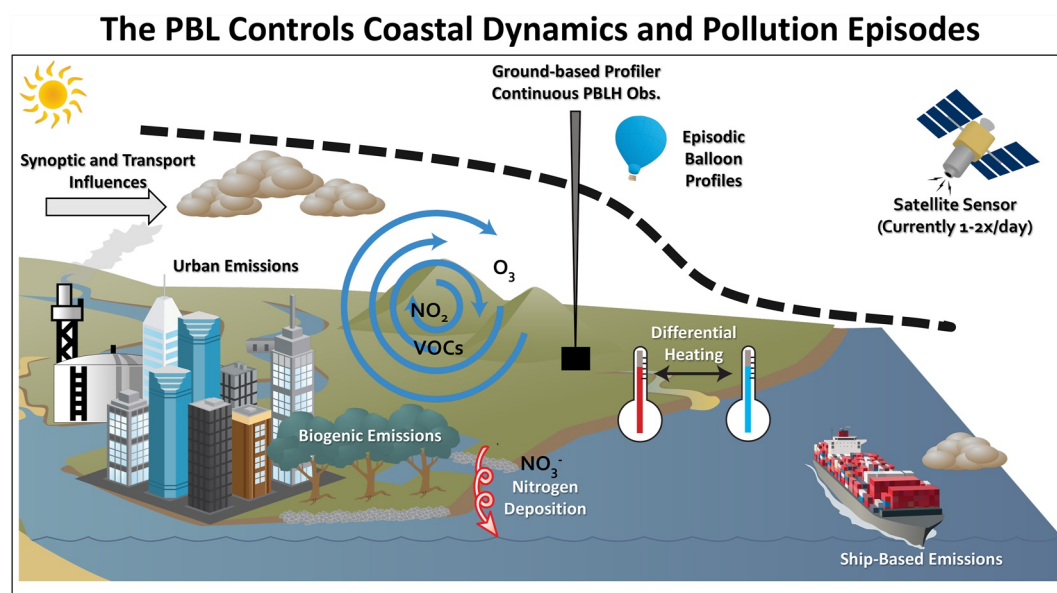


Figure 1. Conceptual model of the processes impacting the planetary boundary layer at the coastal interface.

Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), vertical sounders, such as the Atmospheric Infrared Sounder (AIRS), and GPS radio occultation, such as the GPS Occultation Analysis System (GOAS) and Global Navigation Satellite System (GNSS). Unfortunately, current spaceborne PBLH estimates have significant limitations with vertical or temporal coverage and generally only monthly/seasonally averaged products are considered reliable for scientific analysis. There is no single instrument that provides daily global coverage of accurate PBLH measurements, which requires these platforms and their retrievals to be used in conjunction with atmospheric model simulations and ground-based evaluation to achieve a better understanding of PBLH variability.

Current observational platforms have strengths and weaknesses related to spatial coverage and temporal frequency of observations and accuracy of the measurements. Spaceborne PBLH measurements are particularly challenging in coastal areas given the large horizontal gradients in terrain, surface albedo, and emissivity, along with the high likelihood that these gradients lie within a single satellite ground pixel. Ground-based measurements have high temporal and vertical resolution but are not able to provide a true global picture. In addition, the ability to “resolve” the PBL from satellite is inherently limited as the lower troposphere is the farthest from space and have reduced sensitivity to the PBL which can be confounded by clouds and aerosols.

These observational limitations in the PBL present a challenge to the scientific community who are trying to better understand its sub-hourly chemical and dynamical traits. The PBL and its depth are directly responsible for the temporal, vertical, and spatial scales on which many environmental interactions take place (Figure 1). In situations where a shallow PBL depth is formed, atmospheric pollutants emitted from the surface are trapped within this shallow layer. In contrast, as the PBL depth grows convectively during daytime, pollutants are diluted through vertical transport and mixing. Convective mixing of the PBL can also entrain pollutants transported at higher altitudes from upwind regions, adding to the budget of boundary layer pollutants. Therefore, to better understand coastal AQ science, it is imperative to better understand the controlling factors (e.g., meteorology, atmospheric composition and transformation, terrain, emissions, wet and dry deposition) of the coastal environment and how they influence and are influenced by changes in the PBL (Crosman & Horel, 2010).

Changes in environmental conditions often occur at varying time scales, ranging from quickly evolving pollution events (e.g., J. Zhang et al., 2020) to decadal changes in de/nitrification of bodies of water (e.g., Clune et al., 2021). Therefore, many researchers have naturally focused on a specific coastal environmental issue addressed through a disciplinary perspective and assumptions. However, the multifaceted impacts of PBL on coastal processes demand that current and future observations, simulations/assimilations, and funding opportunities for the Earth System shift focus beyond one discipline toward understanding PBL evolution as an integrated and interconnected system.

Table 1

A Summary of Various Collaboratively Supported Field Campaigns, Primarily in the U.S. and North America, Examining Air and Water Quality Near the Coastal Interface

	Campaign	Time period	Focus region	Reference(S)
1	CBODAQ/DISCOVER-AQ ^a	July 2011	Mid-Atlantic US	Goldberg et al. (2014)
2	GoMex/DISCOVER-AQ ^b	September 2013	Gulf of Mexico	Kowalewski and Janz (2014)
3	DANCE ^c	July–August 2014	Mid-Atlantic US	D. K. Martins et al. (2016)
4	NAAMES ^d	2015–2018	North Atlantic/Canada	Behrenfeld et al. (2019)
5	KORUS-AQ/OC ^e	May–June 2016	Korean Peninsula	C. E. Jordan et al. (2021a, 2021b), Tzortziou et al. (2018)
6	OWLETS 1–2 ^f	June–July 2017–2018	Mid-Atlantic US	Sullivan et al. (2019), Dreessen et al. (2023),
7	LMOS ^g	May–June 2017	Lake Michigan	Stanier et al. (2021)
8	LISTOS ^h	June–September 2018	NYC/Long Island Sound	Karambelas (2020)
9	SCOAPE ⁱ	May 2019	Louisiana/GOM	Thompson et al. (2020, 2023)
10	TRACER-AQ ^j	September 2021	Houston/GOM	Jensen et al. (2022), Judd et al. (2021)

^aGEO-CAPE Chesapeake Bay Oceanographic campaign with DISCOVER-AQ (Baltimore, MD/Washington D.C. 2011 Deployment); <https://earth.gsfc.nasa.gov/ocean/campaigns/geo-cape-chesapeake-bay-oceanographic-campaign-discover-aq-cbodaq>. ^bGulf of Mexico field campaign/Deriving Information on Surface conditions from Column and Vertically Resolved Observations Relevant to Air Quality (Houston, TX 2013 Deployment); <https://www-air.larc.nasa.gov/missions/discover-aq/discover-aq.html>. ^cDeposition of Atmospheric Nitrogen to Coastal Ecosystems experiment; <https://sites.psu.edu/dance2014/>. ^dNorth Atlantic Aerosol and Marine Ecosystem Study; <https://science.larc.nasa.gov/NAAMES/>. ^eKorea–United States Ocean Color experiment; <https://www-air.larc.nasa.gov/missions/korus-aq/>. ^fOzone Water-Land Environmental Transition Study; <https://www-air.larc.nasa.gov/missions/owlets/>. ^gLake Michigan Ozone Study; <https://www-air.larc.nasa.gov/missions/lmos/>. ^hLong Island Sound Tropospheric Ozone Study; <https://www-air.larc.nasa.gov/missions/listos/index.html>. ⁱSatellite Coastal and Oceanic Atmospheric Pollution Experiment; <https://www-air.larc.nasa.gov/missions/scoape/index.html>. ^jTracking Aerosol Convection Interactions Experiment—Air Quality; <https://www-air.larc.nasa.gov/missions/tracer-aq/>.

To better meet these interdisciplinary challenges occurring within the PBL, many regional sub-orbital (i.e., ground-based, ship-based, and airborne) intensive experiments have been carried out jointly with state and federal agencies geared toward improving the lives of their stakeholders (see Table 1). As the AQ community enters the era of geostationary satellite observations, coordination of additional campaigns and enhancement of existing observing networks (e.g., NASA's Tropospheric Ozone Lidar Network (TOLNet), the Unified Ceilometer Network, NASA's/ESA's Pandora Global Network (PGN), NASA MicroPulse Lidar NETwork (MPLNET), and routine radiosonde/ozonesonde launches) offers an opportunity to quantify PBL dynamics and improve the representativeness of spaceborne measurements of PBL processes.

The 2017 National Academies Decadal Survey (*Thriving On Our Changing Planet*, NASEM, 2018), specifically proposed a combination of geostationary and polar orbiting satellites, airborne platforms, and ground-based networks to characterize the strong diurnal cycles of PBL processes. Cross-discipline studies and working groups have been established to aid in PBL characterization, such as through NASA's PBL Incubation Study Report (Teixeira et al., 2021; https://science.nasa.gov/science-pink/s3fs-public/atoms/files/NASA_PBL_Incubation_Final_Report_2.pdf). While NASA's Decadal Survey Incubation activities are heavily focused on spaceborne applications, a necessary component is incorporating findings and methods from prior sub-orbital campaigns, illustrating their advances in PBL science in coastal areas. Here, we synthesize findings from previous ground-based/airborne campaign measurements to address the interdisciplinary nature of existing research questions relevant to PBL processes and requirements of future measurement strategies. Specific questions addressed are:

- What have we collectively learned from coastal AQ observations and simulations (through field campaign efforts or observation networks) that advance our understanding of processes coupled by the PBL? (Section 2)
- How representative are current and future measurements from space of PBL characteristics and the feedback/exchange processes impacting AQ? (Section 3)
- More generally: How are research goals surrounding the land/water interface prime examples of the need to increase the interdisciplinary nature of atmospheric scientific research? (Section 4)

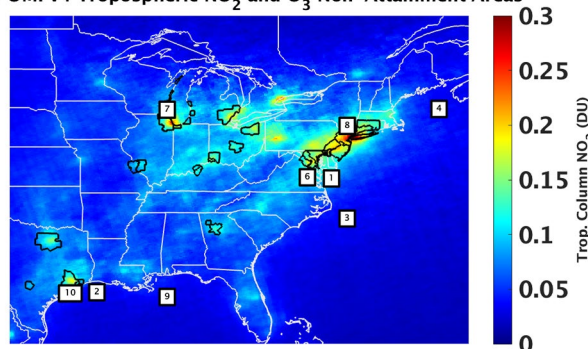
2019 OMI v4 Tropospheric NO₂ and O₃ Non-Attainment Areas


Figure 2. OMI version 4 tropospheric column NO₂ average in Dobson Units (DU) for 2019 (https://avdc.gsfc.nasa.gov/pub/data/satellite/Aura/OMI/V03/L3/OMNO2d_HR/OMNO2d_HRM/). Locations of campaigns listed in Table 1 (except KORUS-OC; 5) are shown. Black outlined regions indicate current U.S. EPA-designated Ozone Non-Attainment Areas based on the 2015 National Ambient Air Quality Standards (NAAQS; <https://www.epa.gov/green-book/green-book-gis-download>; Last Updated 1 February 2022).

In this paper, our primary focus is on the complexities of the coastal PBL and the impact they have on AQ, deposition of pollutants, and coastal ecological processes. Our goals are to provide more context and insight on the above questions. This is accomplished by defining important land/water feedback processes in the PBL, discussing measurement strategies employed to better understand these processes, and identifying critical measurement gaps of PBL characteristics that must be addressed to answer important interdisciplinary science questions.

2. Lessons From Recent Coastal Field Campaigns

2.1. Summary of Recent Campaigns

The coastal PBL facilitates interactions between anthropogenic and biogenic pollutants (both their sources and sinks) that contribute to poor AQ (as illustrated in Figure 1). We draw from past NASA and partnering organization supported field campaigns (listed in Table 1 and shown on Figure 2) that sought to address some of the scientific questions listed above. These campaigns took place generally in summertime in and near various bodies of water within the United States since 2011. An exception is the KORUS-OC (Korea-U.S. Ocean Color experiment) that occurred in coastal waters

surrounding the Korean peninsula in 2016 (C. E. Jordan et al., 2021a, 2021b; Thompson et al., 2019; Tzortziou et al., 2018). KORUS-OC is instructive because it combined air and water quality measurements from research vessels in conjunction with the comprehensive KORUS-AQ (Korea-U.S. Air quality) campaign that used observations from aircraft, ground sites, and satellites (Crawford et al., 2021). Measurements during KORUS OC/AQ were used to examine transport of atmospheric pollutants, including urban nitrogen pollution, over the coastal ocean and their impacts on atmospheric correction of satellite ocean color and retrievals of coastal ecological processes. The coordinated KORUS OC/AQ fieldwork program is an excellent model for future interdisciplinary land/water interface science. For example, Tzortziou et al. (2018) measured total column NO₂ (TCNO₂) and O₃ (TCO₃) over coastal waters around the Korean peninsula using shipborne Pandora instruments as part of KORUS-OC. These observations were integrated with KORUS-AQ observations and data products such as ground-based observations at coastal land sites, synoptic satellite imagery, and air mass trajectory simulations. They reported that variability in TCO₃ over the coastal ocean was relatively small (20%) and mostly exhibited a quasi bi-weekly oscillation driven primarily by larger scale meteorological processes and synoptic weather fronts that were captured successfully by AURA-OMI. TCNO₂, however, exhibited small-scale and short-term variability by more than an order of magnitude, linked to urban nitrogen pollution. If not properly accounted for in atmospheric correction retrievals of coastal ocean color, such variability in coastal atmospheric composition will result in a false spatial or temporal variability in ocean biogeochemical properties and ecological processes.

The U.S.-based campaigns have focused on the Mid-Atlantic and North Atlantic Ocean (see Table 1 for acronyms; DISCOVER-AQ, CBODAQ, DANCE, NAAMES, OWLETS, LISTOS), Gulf of Mexico (DISCOVER-AQ, GoMex, SCOAPE, TRACER-AQ), and Lake Michigan (LMOS). These areas were targeted primarily because of their proximity to non-attainment regions for the U.S. EPA's National Ambient Air Quality Standard (NAAQS) for ozone (<https://www.epa.gov/green-book>), and the abundance of local anthropogenic emissions (NO₂ and ozone non-attainment areas shown on Figure 2). Our focus is primarily on the U.S. and North America given that there are several upcoming polar-orbiting and geostationary satellite missions targeting this region that will aid our understanding of the coastal PBL.

2.2. Characterizing Processes Driving PBLH Evolution

Most recent coastal AQ-focused campaigns (Table 1) highlighted examples of differential heating between the land and water, which impacts the PBL in specific ways that are more complex than traditional continental regions. This gradient affects the height or mixing depth of the PBL and causes winds to stagnate or reverse flow directions during the daytime or transitional periods, such as sunrise or sunset. Differential surface heating and cooling between land and water can also lead to a gradient in PBL depth at the coastline resulting in large

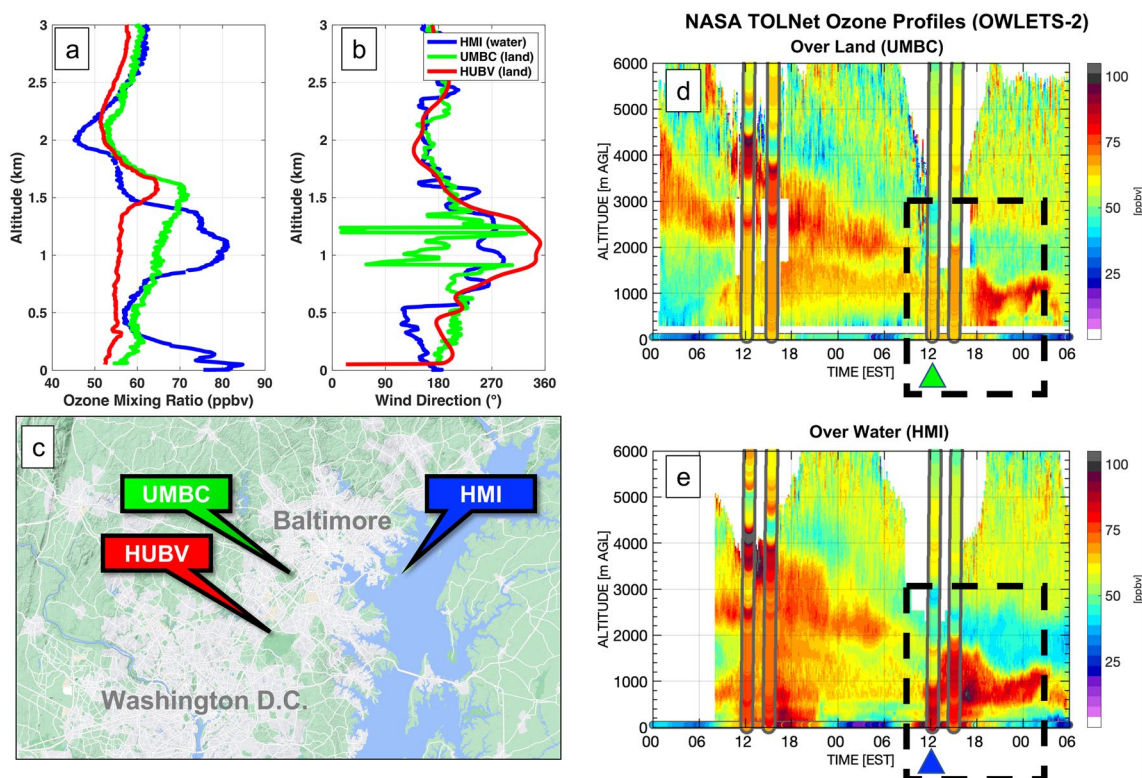


Figure 3. Coincident ozonesonde profiles from 1 July 2018 during the OWLETS-2 campaign in the northern Chesapeake Bay region. (a) Ozone mixing ratio (thick, solid lines) and (b) Wind direction profiles up to 3 km AMSL. The three ozonesondes were launched within minutes of each other (1715 UTC; 1215 LST). The map (c) shows the locations of the three ozonesonde launch locations using the same color scheme as the vertical profiles. Note HMI is 30 km due east of UMBC and HUBV is 26 km SW of UMBC. Time series of ozone lidar profiles at (d) UMBC and (e) HMI are also shown with an overlay of ozonesonde profiles (blue/green triangles) and surface ozone analyzer data (bottom).

gradients in cloud coverage, air pollution concentrations, and dry deposition (Dreessen et al., 2023; Goldberg et al., 2014; Loughner et al., 2016; Mazzuca et al., 2019; Stauffer & Thompson, 2015; Sullivan et al., 2019).

Under weak synoptic scale forcings, differential surface heating or cooling between the land and water can lead to localized circulation patterns, such as sea, bay, or lake breezes (Miller et al., 2003). Stagnation in the wind and a flow reversal associated with localized onshore or offshore breezes confines fresh emissions (Dacic et al., 2020; Kotsakis et al., 2022; Loughner et al., 2011, 2014; Stauffer et al., 2015) and the accumulation of pollutants that would otherwise be transported beyond the urban region. These conditions contribute to ozone non-attainment (see Figure 2) designations, whether in populated U.S. coastal areas, such as the Gulf Coast (e.g., Houston, New Orleans), the Chesapeake Bay, Lake Michigan, and Long Island Sound regions (Goldberg et al., 2014; Loughner et al., 2014; Nauth, 2021; Stauffer et al., 2015), or in coastal megacities worldwide, such as Seoul (Peterson et al., 2019). Such meteorological conditions near New York City were characterized by particularly low-speed southerly/westerly winds and were previously shown to drive high NO_2 pollution episodes even under extreme reductions in emissions from the transportation sector during the COVID-19 pandemic (Tzortziou et al., 2022). Furthermore, in many occurrences a stable PBL leads to fair weather cumulus clouds at the top of the PBL over land but not over water causing contrasting chemical processing regimes (i.e., increased ozone production efficiency over water) that may occur directly in the shallow PBL (often 20–60 m AGL) within the marine environment versus those in a traditional land environment that have much deeper PBL depths (illustrated in Figure 1).

2.3. Campaign Example in the Chesapeake Bay (OWLETS-2)

Figure 3 illustrates the complexity of land/water PBL gradients that lead to differing vertical distributions of pollutants. During the Chesapeake Bay region 2018 OWLETS-2 campaign (Table 1), three ozonesondes were launched within minutes of each other at three locations: within the Chesapeake Bay (Hart Miller Island; HMI), near Baltimore (University of Maryland Baltimore County; UMBC), and farther inland (Howard University

Beltsville Campus; HUBV). Time series of ozone lidar profiles at (d) UMBC and (e) HMI are shown with an overlay of ozonesonde profiles (blue/green triangles corresponding to the ozonesonde color) and surface ozone analyzer data.

The ozone sonde profiles represent a “local snapshot” of the gradients in near-surface ozone pollution, vertical stability, and vertical wind profiles that are often present in coastal regions during the summer (Thompson and Herman, 2019). Ozone lidar observations (Sullivan et al., 2014) (Figure 3d/3e, dashed black box) further illustrate the challenges of coastal AQ as it relates to the PBLH conceptual model in Figure 1. Both sites observe synoptic subsidence of long-range transport of increased ozone concentrations above 2 km AGL and have deep nocturnal residual layers that are entrained into the next day's PBL (sunrise is near 0600 LT and sunset is near 2030 LT on these days). Both ozonesondes and lidar profiles indicate the aloft ozone peak over HMI at ~1 km AGL is from the return flow of the bay breeze, which was also observed during the DISCOVER-AQ field campaign occurring in the same region (Loughner et al., 2014; Stauffer et al., 2015). Vertical stability was much greater over HMI, limiting the vertical mixing of the ozone pollution near the surface and the elevated layer at ~1 km. Lack of vertical mixing over water, or capping surface emissions in the lowest ~200 m AGL, indicates a critical need for understanding emissions over the water that are contributing to coastal AQ issues.

Figure 3 is representative of a real-world example illustrating the difficulties of quantifying land/water atmospheric gradients close to the surface. Accurate measurements from satellite instruments are challenging on this scale, if not impossible, due to the coarse satellite spatial resolution that results in mixed land-water pixels and significant land-water adjacency effects. Surface ozone (Figure 3a) is nearly 30 ppbv greater over the water site (HMI) compared to the land-based locations during the ozonesonde launch, indicating a different photochemical regime than over land (where the surface values of ozone generally appear to be representative of the PBL estimate). However, these enhanced measurements make it possible to understand the pollution aloft more fully and evaluate transport patterns that would not have been measured in a traditional routine monitoring capacity. Ground-based networks of observing platforms, particularly during intensive campaign-based operations, are requisite to the understanding and evaluating the coastal PBLH and its exchange processes.

3. Representativeness of Satellite Measurements in Coastal Regions

Noting the ozone NAAQS non-attainment areas on Figure 2, we cannot currently measure PBL ozone from space at desired accuracy or precision from low Earth orbit satellites. However, commonly retrieved satellite quantities (below) serve as proxies for the spatial extent of coastal pollution. They illustrate successes and challenges for coastal measurements and are expected to benefit from upcoming geostationary satellite products.

3.1. Satellite Measurements of PBLH

Estimates of the PBLH have been obtained directly from space and select detection methods are briefly summarized below for active sensing using elastic lidar and passive infrared sounding. In the literature there are many examples of estimates of PBLH from space-based systems that are used to better understand the seasonality of PBLH (e.g., McGrath-Spangler & Denning, 2012; Su et al., 2017) and evaluate regional and global model simulations of PBL (Hegarty et al., 2018; N. S. Jordan et al., 2010). GPS Radio Occultation (Ao et al., 2012; Kalmus et al., 2022) and passive infrared sounders, such as AIRS (Ding et al., 2021; J. P. A. Martins et al., 2010), are able to retrieve coarse PBLH estimates with horizontal ($\sim 2^\circ \times 2^\circ$ –50 km \times 50 km) and vertical (1–2 km) resolution based on atmospheric (e.g., temperature, moisture, or refractivity) gradients near the PBLH (Gettelman et al., 2004; Thrastarson et al., 2020) in coastal or other complex domains.

Under well-mixed (e.g., convective) PBL conditions, spaceborne lidars, such as the Cloud-Aerosol Transport System (CATS; Yorks et al., 2016), ICESat-2 (Markus et al., 2017), and CALIPSO (W. Zhang et al., 2016) are able to quantify daytime and nighttime PBLH with high vertical (30–100 m) precision using gradients in total (L1) or aerosol (L2) attenuated backscatter within a certain threshold as proxy for the PBLH. This retrieval is based on the assumption that the PBLH is located at the transition from the polluted PBL to the relatively less aerosol-laden air above the PBL. However, in less idealized conditions (especially when stable stratification has developed below and above the thermodynamic PBLH), using attenuated backscatter presents a challenge to correctly interpret and algorithmically quantify (such as the wavelet covariance technique employed in Compton et al., 2013) an accurate PBLH. Furthermore, spaceborne lidars such as CALIPSO only visit within 10 km of

a specific ground pixel on average twice every 16 days (and one of these overpasses is in the nighttime hours), making the data set challenging to evaluate diurnal PBLH cycles in the coastal environment.

In summary, current spaceborne PBLH measurements provide *either* high-resolution vertical sampling with poor horizontal/temporal coverage, or near-once-daily global afternoon coverage with lower spatial resolution and accuracy. Although space-based datasets provide context for seasonality of the PBLH, which is important for global modeling and understanding long term climate trends, there are currently no spaceborne platforms that provide temporal or spatial PBL coverage beyond twice per day, much less at the horizontal spatial scales of a few km and vertical scales of ~30–100 m necessary for coastal areas. Furthermore, many of these platforms rely on the assumption of a strong gradient in a signal only at the top of the PBL and are likely unable to resolve mixed layering at multiple heights, especially layering that is above or within the PBL. Note that several groups are employing machine learning to identify where the PBL top is most likely located and to resolve the PBLH in areas of atmospheric stratification (Palm et al., 2021; Sleeman et al., 2020). Other investigations are using current and future low Earth orbit and geostationary passive sensors geared toward understanding the underlying atmospheric chemistry and dynamics of that impact PBLH retrievals in coastal regions (Loría-Salazar et al., 2021; Turner & Ulrich, 2021; Wang et al., 2021). Current research supported by NASA's PBL Decadal Survey Incubation program includes multi-sensor retrieval (passive and active) to take advantage of the combined capabilities and to integrate ground and spaceborne PBLH profiles into regional/global modeling data assimilation systems. There are challenges in validating novel retrievals; for example, high spatial and temporal resolution AQ models show sharp gradients in air pollution concentrations and nitrogen deposition near coastlines, but there is a lack of observations to evaluate these findings (Abdi-Oskouei et al., 2020; Loughner et al., 2016). Field data from US ozone NAAQS non-attainment areas (Figure 2), are still relatively sporadic, of limited duration (1–2 months); coastal PBL information is particularly lacking on deployments.

3.2. Satellite Measurements of PBL Air Quality

Satellite measurements of tropospheric and total column amounts of nitrogen dioxide (NO₂, Figure 2) have become increasingly accurate over the past two decades with improvements to retrieval algorithms from instruments like the GOME (Global Ozone Monitoring Experiment) series, Ozone Monitoring Instrument (OMI) and the higher spatial resolution TROPospheric Monitoring Instrument (TROPOMI). However, relating the column amounts of pollutants to “nose-level” or PBL concentrations, especially in coastal regions, remains a challenge due to the complexities of vertical distribution and often strong spatial and temporal variability in surface (land or ocean) reflectivity (Knepp et al., 2015; Kollonige et al., 2018; Szykman et al., 2019; Thompson et al., 2019, 2023; Tzortziou et al., 2015, 2018). However, continued work is moving toward evaluating and utilizing these satellite derived NO₂ products to the neighborhood scale (Demetillo et al., 2021; Dressel et al., 2022; Goldberg et al., 2021; Johnson et al., 2022; Judd et al., 2020) to better evaluate urban pollution and human health (Anenberg et al., 2022).

Wet and dry atmospheric nitrogen deposition are major contributors of excess nitrogen (N) to coastal waters and ecosystems (Cornell et al., 2003; Kanakidou et al., 2016). Excessive reactive Nitrogen deposition (both wet and dry) can cause a series of negative effects on ecosystem health, biodiversity, soil, and water and has been summarized in a recent review by Liu et al., 2020. Methods have been established to estimate global NO₂ dry deposition fluxes at high spatial resolution using the combination of satellite measurements and high resolution chemical transport models (Geddes and Martin., 2017; Nowlan et al., 2014), but continue to be particularly challenging to correctly measure near coastal urban megacities or in instances of aged pollution transport (Kharol et al., 2018). In polluted coastal urban regions, excess N inputs from the atmosphere or land to adjacent aquatic systems may lead to eutrophication, recurrent algal blooms, and subsequent development of oxygen-depleted dead zones, such as those found almost every year in many heavily urbanized coasts and estuaries, for example, Gulf of Mexico, Chesapeake Bay, and Long Island Sound (Anderson & Taylor, 2001; Loughner et al., 2016; Murphy et al., 2011; Rabalais et al., 2001). Incorporated into vegetation directly through the leaves and indirectly through the soil, N deposition is also an important nutrient source for terrestrial plants and can affect biogeochemical and ecological processes across the continuum of terrestrial-aquatic ecosystems from upland forests to coastal wetlands (Morris, 1991).

3.3. Satellite Measurements of Ocean Color

Remotely-sensed ocean color observations suggest that coastal PBL dynamics and AQ have profound effects on coastal water quality, aquatic ecosystems, and productivity. Over the past 20+ years, continuous measurements of

ocean color from polar orbiting satellites in low Earth orbit have quantified ocean biogeochemical cycles, ecological processes and their responses to climatic disturbances on a global scale (Werdell et al., 2018). Measurements are supplied by multi- and hyperspectral ocean color instruments, such as the NASA Sea-viewing Wide Field of View Sensor (SeaWiFS; 1997–2010), NASA's Moderate Resolution Imaging Spectroradiometers on Terra (MODIS; 1999–present) and Aqua (MODISA; 2002–present), ESA's Medium Resolution Imaging Spectrometer (MERIS; 2002–2012), the NASA-NOAA Suomi National Polar-orbiting Partnership Visible Infrared Imaging Radiometer Suite (VIIRS; 2012–present), ESA's Ocean and Land Color Instrument (OLCI; 2016–present), the Hyperspectral Imager for the Coastal Ocean (HICO; 2009–2014) and are expected from the upcoming Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission. Measurements from regional geostationary sensors, such as the Geostationary Ocean Color Imager (GOCI mission, 2010–present, covering East Asia) provide unique information on highly dynamic physical processes and biogeochemical exchanges occurring in coastal waters. Note that reducing uncertainties for ocean properties through atmospheric correction of polar-orbiting and geostationary satellite data relies on knowing vertical and column amounts of aerosols and trace gases like ozone and NO₂ that may vary considerably across the land-water interface (Ahmad et al., 2007; Tzortziou et al., 2014).

A multi-satellite approach (for simultaneous retrievals of spatiotemporal variability in coastal atmospheric composition and ocean color) is thus required to obtain highest quality measurements of ocean biogeochemical properties. This fusion of multi-sensor data in turn will aid atmospheric retrievals because accurate aerosol and trace gas measurements are based on accurate knowledge of ocean surface reflectivity. Future measurements from upcoming ocean color hyperspectral (e.g., 2-nm to 5-nm spectral resolution) imagers, such as PACE and Geostationary Littoral Imaging and Monitoring Radiometer (GLIMR) may provide an opportunity to directly retrieve NO₂ over the ocean for both aquatic and atmospheric applications (Joiner et al., 2022). At present with only polar-orbiting satellites observing most of the globe (GOCI and GEMS over east Asia are exceptions) the inability to capture diurnal changes in atmospheric composition leads to uncertainties in non-coincident ocean color data. It is expected that being able to combine geostationary atmospheric and ocean color sensors TEMPO (Tropospheric Emissions: Monitoring of Pollution) and GLIMR over North America will provide an unprecedented opportunity to monitor the highly dynamic atmospheric and ocean processes along coastlines and to resolve important issues about PBL dynamics.

4. Summarizing Community Needs to Improve Coastal Air Quality Science

Recent coastal field campaign efforts listed in Table 1 have been funded and carried out in different ways depending on specific mission goals. However, several questions—of direct interest to coastal resource managers as well as scientists—remain in our understanding of the PBL and AQ in coastal environments. In summarizing the campaign efforts listed in Table 1 and satellite limitations, we recognize three areas of interdisciplinary research that are urgently needed to better understand the coupled PBL interactions.

1. Improve fundamental understanding of the diurnal PBL cycle as it relates to recirculation and entrainment of nocturnal residual and long-range transport layers as they enter the coastal urban region. The campaigns broadly indicate that episodes where aloft layers or recirculation patterns persisted were the days generally driving exceedances of the ozone NAAQS. These features have occurred in several coastal regions (Table 1) as described for Long Island Sound (Rogers et al., 2020; Torres-Vazquez et al., 2022; Wu et al., 2021) and the Chesapeake Bay (Bernier et al., 2022; Dreessen et al., 2016; Kotsakis et al., 2022; Sullivan et al., 2017, 2019; Tao et al., 2022; Yang, Demoz, Delgado, Sullivan, et al., 2022; Yang, Demoz, Delgado, Tangborn, et al., 2022).
2. Quantify chemical perturbations from offshore transport of urban emissions, ships, boats (both commercial and personal/recreational) and offshore oil and gas drill sites, as they interact with the onset of a bay/sea breeze in the shallow marine boundary layer. Without accurate over/near water emissions, chemical transport models are not capable of simulating current and future regulatory scenarios (Sorte et al., 2020). Understanding these non-traditional emission sources will require the combination of satellite estimates and evaluations from sub-orbital campaign data sets. Preliminary studies reaching similar conclusions were documented in the Chesapeake Bay region (Caicedo et al., 2021; Gronoff et al., 2019; Ring et al., 2018), the South Korean coast waters (Thompson et al., 2019; Tzortziou et al., 2018), the Gulf of Mexico (Thompson et al., 2023), the Lake Michigan region (Vermeuel et al., 2019) and along the New York City coast (Nauth et al., 2023; Tzortziou et al., 2022).
3. Identify novel and viable pathways derived from the interaction of the land-ocean-atmosphere that can drive PBL content and structure in coastal communities. For example, describes aquatic vegetation contributing

to biogenic emissions that can produce pollution. Qin et al., 2019 demonstrates the importance of including a full inventory of biogenic emissions in modeling of coastal regions along the Great Lakes during LMOS (Table 1, 7). A recent review of how aquatic emissions can travel long distances to degrade AQ downstream appears in Lee et al. (2020).

The KORUS-OC/AQ campaign (see Crawford et al., 2021; C. E. Jordan et al., 2021a, 2021b; Thompson et al., 2019; Tzortziou et al., 2018) provides a model for future campaigns to examine both air and water quality issues at the coastal interface. Coincident intensive measurements of air pollution and water properties will advance our understanding of the feedbacks noted above that govern air/water exchange processes. Details on interdisciplinary topics needing more exploration are described in the NASA's Geostationary Coastal and Air Pollution Events report (GEOCAPE, https://geo-cape.larc.nasa.gov/wp-content/uploads/sites/142/2020/12/GEO-CAPE_2018_Final_Report.pdf), with further details in the GEO-CAPE Interdisciplinary Science White Paper (https://geo-cape.larc.nasa.gov/wp-content/uploads/sites/142/2022/08/2022-08-29-Integrating-Coastal-Earth-System-Science-across-Marine_19Jan.pdf).

The GEO-CAPE science team prioritized several interdisciplinary foci areas, with the most relevant being to form a better understanding of influences of meteorology on coastal waters and vice versa with the (a) role of coastal waters in land/sea breeze dynamics affecting transport and processing of atmospheric constituents and (b) changes in PBLH over estuarine and coastal waters with respect to that over their adjacent land masses and the subsequent effects on vertical distribution, transport, processing, and deposition of atmospheric constituents. Further examples of these that have not been explored or previously discussed include quantifying oil slicks in bodies of water and investigating the development and impacts of red tides and other algal blooms.

The 2017 Decadal Survey (NASEM, 2018) explicitly requested a satellite platform that could adequately resolve the large spatial variation of aerosol and trace gas concentrations (partly due to surface heterogeneities, such as urban-rural or land-water contrast), at a horizontal resolution of 5 km and a temporal resolution of every 2–3 hr. Therefore, the next generation of satellites needs to adopt new multi-sensor constellations with innovative deployment of small instruments or cubesats that can nimbly measure AQ in coastal environments along with ground-based systems used in prior field campaigns. Ground-based remote sensing and balloon-borne observations will continue to be vital to both evaluate the geo-stationary a priori models (Johnson et al., 2018) and to observe the fine spatial and temporal scales needed to understand coastal AQ within the PBL.

Launched over the next decade, geostationary sensors from the U.S. (TEMPO, GLIMR, and NOAA's Geostationary Extended Observations (GeoXO)), Europe (Sentinel 4), and SE Asia (GEMS and GOCI-II already in orbit) can form a northern hemisphere GEO constellation for studies of processes and exchanges across the land, ocean and atmosphere in complex coastal systems. Since these platforms will not have a dedicated PBL measurement onboard, the required approaches to improve our coastal PBL and AQ understanding remain: a dedicated sub-orbital airborne measurement suite to consistently resolve coastal PBL heights in a regional coastal domain where high resolution (<1 km) chemical transport model output can be confidently simulated. This is further enhanced with ground-based lidar/ceilometer, spectrometer/spectroradiometer, sun photometer, balloon, and in-situ measurements, particularly during intensive campaign-based operations. The combination of these suborbital observations (which are a fraction of the cost of any satellite program) can then continually validate existing satellite measurements and provide feedback to algorithm teams working on novel techniques, such as machine learning-based and multi-sensor (e.g., active + passive) PBL retrievals.

5. Conclusions

We described important land/water feedback processes in the PBL, discussed measurement strategies to better understand these processes, and identified critical measurement gaps of PBL characteristics that must be addressed to fully characterize the interaction of AQ, physical and biological processes along the coast. For the first time, we have summarized scientific consensus from analyses during coastal AQ campaigns (Table 1) and these results have been used to highlight the complexities of real-world PBL measurements over the water (Figure 3).

Continental air pollution emission sources are generally well-known (e.g., transportation, industry, and biogenic) but characterizing their downstream effects on water quality where PBL dynamics are complex remains a challenge. Most coastal areas observe large differences in model projections of air pollution compared to observations, which prevents policymakers from designing sound implementation plans for improving coastal air and

water quality. A community driven design for future generations of spaceborne measurements, model simulations, and Earth System science will produce effective regulatory mitigation efforts, enhance environmental justice, and improve public health. However, this will only be accomplished with the combination of interdisciplinary research support and consistent/routine suborbital observations.

Data Availability Statement

OMI version 4 tropospheric NO₂ averages can be downloaded from the NASA Goddard Space Flight Center Aura Validation Data Center (Krotkov et al., 2019). Data for US EPA Non-Attainment Areas for criteria pollutants can be accessed at <https://www.epa.gov/green-book/green-book-gis-download> (US Environmental Protection Agency, 2023). The tropospheric ozone lidar used from NASA's Tropospheric Ozone Lidar Network (TOLNet) and are publicly available (<https://www-air.larc.nasa.gov/cgi-bin/ArcView.1/TOLNet?NASA-GSFC=1>, Newchurch et al., 2016). The ozonesonde data used in this publication were obtained as part of the OWLETS-2 campaign and are publicly available (<https://www-air.larc.nasa.gov/missions/owlets>, following procedures documented in Thompson et al., 2019).

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