Ocean Sciences Across the Solar System

FOREWORD

The 2016 Congressional Commercial Justice Science and Related Agencies appropriations bill tasked NASA in creating an Ocean Worlds Exploration Program. Their direction for this program was to seek out and discover extant life in Habitable Worlds within the Solar System. In support of these efforts, the Roadmaps to Ocean Worlds (ROW) group published a roadmap to identify and prioritize science objectives for ocean worlds over the next several decades (Hendrix et al. 2019). This roadmap has helped prioritize the exploration of ocean worlds.

In order for this to be effectuated, a framework of interdisciplinary experts in both Earth and Planetary science is needed. In 2019, NASA established a cross divisional research network to coordinate and enhance NASA funded researchers called the Network for Ocean Worlds. Ocean Sciences Across the Solar System (OASS) was cultivated as a result of this effort, building upon the ROW. OASS is a collaborative effort between Earth and Planetary scientists focusing on the advancement of research related to Ocean Worlds. The coordinated efforts of scientists that work in both Earth's ocean and oceans in other parts of the Solar System will allow knowledge gaps to be filled and opportunities to be identified for testable ideas based upon existing knowledge of the Earth's system. Synergistic research questions and collaborations between Earth and Planetary scientists will be developed to further our understanding of Ocean Worlds. An 'ocean world' can be defined as a body which plausibly can have or is known to have an existing liquid ocean. Several of these potential candidates have been identified in our own solar system, including Europa, Enceladus and Titan. However, the current trajectory requires considerable time to crystallize the data necessary for in depth assessments. Therefore, it's imperative that we utilize our own ocean world, Earth, as an analog. Bringing together Earth and Planetary science communities will allow for a comprehensive investigation and analysis. The two communities began as one, and this initiative will bring the two communities back together for a unified focus.

The overarching questions and topics included in this white paper were identified in a workshop held in late 2019, and five key areas of interest emerged as necessary in order to better understand and improve our knowledge of Ocean Worlds. These are:

I. Ocean Worlds as an Integrated System

II. Leveraging hydrosphere and cryosphere science to search for life in ocean worlds

III. Understanding the Properties of Environmental Change in Ocean Worlds

IV. Characterizing Habitable Environments in Ocean World Systems

V. Research in Analog Environments to Study of Ocean Worlds

VI. Necessary Broad Reaching Technology Requirements for in-situ and Remote Sensing exploration of Ocean Worlds

Research on Ocean Worlds will enhance scientific collaborations across disciplines, and catapult our understanding of Earth's ocean and life in our Solar System forward. It will lead to new technologies and bold ideas to guide the exploration and sustainable use of our own planet, and augment and expand existing approaches and efforts to study Ocean Worlds as complete systems.

SUMMARY

The discovery that there are major oceans beyond Earth is exciting for Earth oceanographers and planetary scientists alike. As life on Earth began in the ocean, these other worlds offer tantalizing possibilities of finding life beyond our own planet. They also offer the possibility of learning about conditions, including physical and chemical processes, that may be different from Earth, and that affect the ocean's surfaces and interiors and regulate how those systems function. The innate connection that exists between Earth's ocean and ocean worlds beyond Earth offers many possibilities, and demands the action, of strong research collaborations between Earth ocean scientists and extraterrestrial ocean scientists. This white paper summarizes six areas of priority where the study of Oceans Across the Solar System would benefit from a close collaboration between Earth and extraterrestrial oceanographers.

Ocean world research requires the study and understanding of Earth's ocean. The different sections herein outline some of the priority areas for ocean research across the solar system, identify existing gaps, and provide ideas for developing testable ideas based on the Earth System. It is important to acknowledge that there are no perfect analogs; however, the different sections highlight the strengths and weaknesses of using analogs for different types of research, such as improved understanding of ocean world processes, habitability, and where to search for life beyond Earth. For example, by identifying analogs for specific processes, rather than specific conditions, it may be possible to develop a mechanistic understanding that enables an extrapolation beyond Earthly points of reference. Observation and hypothesis testing in Terrestrial environments that most closely approximate the physical and chemical conditions thought to exist in ice covered oceans can refine our understanding of those in ice-covered oceans and within the ice, though the numerous differences between Earth and other ocean worlds will significantly impact the nature, abundance, and quality of evidence for any life that may exist, relative to what we observe on Earth. On Earth, life and biogenic materials are heterogeneously distributed according to the availability of resources, strength of stressors, and various physical transport processes; understanding the balance of factors that underlie such heterogeneity, and projecting that understanding into the context of environments beyond Earth, can maximize the potential of detecting biosignatures.

As the search for life in ocean worlds continues, technologies to detect such signatures will be critical, as will our understanding of the potential distribution of life in icy worlds. Large-scale synoptic views of ocean worlds can be afforded by active and passive remote sensing methods. Imaging spectrometers, spanning ultraviolet to infrared wavelengths, can assess the composition of inorganic and organic matter in the water or within snow and ice on the surface of an icy body. Active remote sensing technologies, such as radar and lidar, can measure backscattered light off of ocean particles, subsurface observation of ice, and provide information on the surface of worlds that have thick or obscuring atmospheres. *In situ* technologies for ocean worlds span systems and instruments that operate above, on, under, or within ice, slush, and fluids. These include technologies to determine biological, chemical, and physical properties, including biosignature detection methods.

There is much to be gained between a close collaboration between Earth and extraterrestrial ocean scientists for the study of Oceans Across the Solar System. The knowledge, tools, and different perspectives of the same discipline, applied across our solar system, provide complementary knowledge that will serve to advance the understanding of ocean world workings; this is critical for understanding Earth's oceans past and it's possible future under climate

change scenarios, and how life began on our planet. This will in turn further the search for life elsewhere and help us understand habitability beyond our Blue Marble.

Lastly, with the advent of space exploration, the protection of Earth's environment and other solar system bodies from harmful contamination have become an important principle of high priority. Consequently, the exploration of ocean worlds thought to be capable of harboring life (extinct or extant), or processes relevant to prebiotic chemistry, are of relevance to planetary protection initiatives. Both Earth and Planetary science communities, working together, can significantly contribute to the development of policies, procedures, and techniques to meet planetary protection requirements.

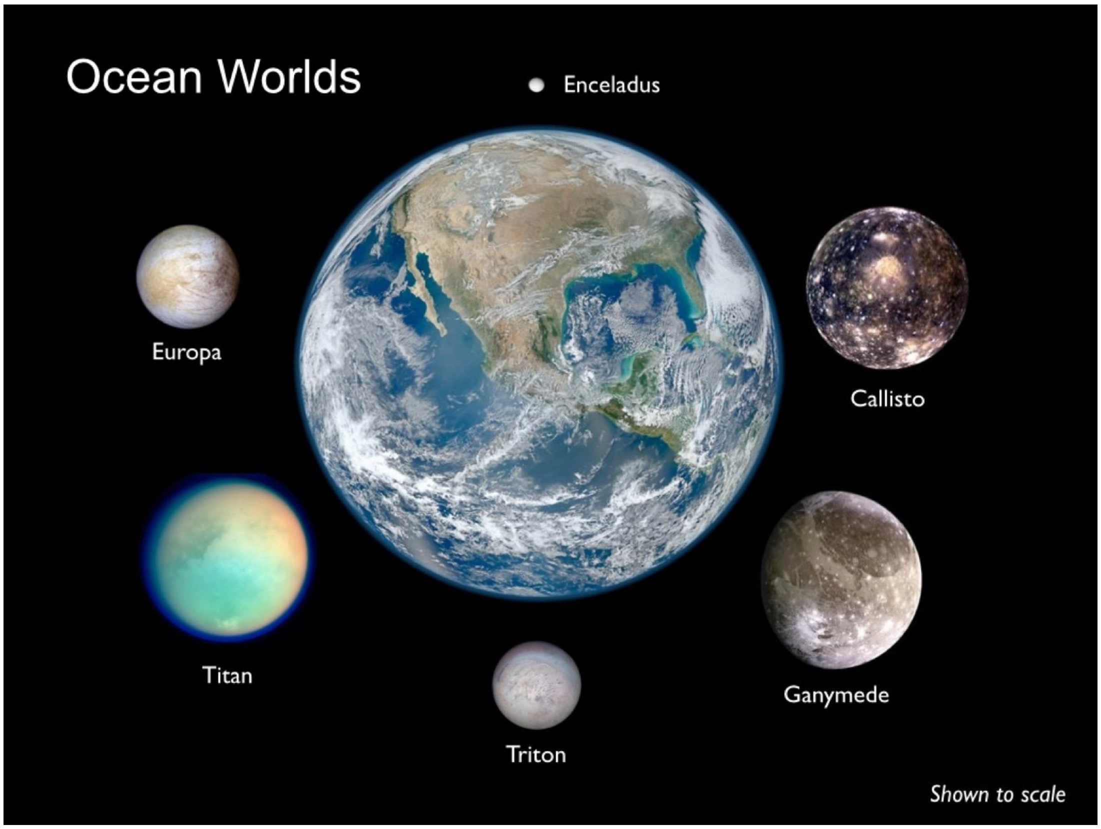

Fig.1 Ocean Worlds of the Solar System shown to scale. Jupiter's moons Europa, Callisto and Ganymede have all been confirmed to host large-volume salt-water oceans as have Saturn's moons Enceladus and Titan: all beneath thick ice-shells. Further out in the solar system, other candidate ocean worlds await further investigation, including Neptune's moon Triton. Image credit: K.P.Hand, NASA-JPL.

Planetary Oceanography: Leveraging Expertise Among Earth and Planetary Science

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1. Introduction

The study of planetary oceanography is a new and exciting field of research. While humanity's formal scientific studies of Earth's oceans date back more than a century and a half, the study of oceans beyond Earth is younger than the start of the current millennium. First confirmation of an extensive saltwater ocean anywhere beyond Earth only came relatively late within the lifetime of NASA's Galileo Mission (Kivelson et al., 2000) but continuing exploration has now revealed compelling evidence for large volume watery oceans on at least five ice-covered moons of our outer solar system (Fig.1) with perhaps as many as 10-20 when all candidate moons and dwarf planets are considered (Hendrix et al., 2019). Of the five confirmed ocean worlds (Jupiter's moons Europa, Callisto and Ganymede; Saturn's moons Enceladus and Titan) three have oceans so deep that they are underlain by a seafloor made of a high-pressure form of ice sitting on top of those planets' rocky interiors - so the water is trapped within what is effectively an ice sandwich (Nimmo & Papallardo, 2016). By contrast, the other two confirmed ocean worlds (Europa, Enceladus) have oceans that are in direct contact with a rocky interior.

While the discovery that there are major oceans beyond Earth, right here in our own Solar System, is already scientifically exciting for oceanographers and planetary scientists, the discovery that Europa, and subsequently Enceladus, have ocean worlds in contact with rocky seafloors represents an opportunity for a civilization-scale scientific revolution. It was only during the latter stages of the last Century that discovery was made of hot springs on the seafloor (Corliss et al., 1979). There, geothermal energy from Earth's interior drives subseafloor fluid convection that gives rise to the release of chemical energy at and near the seabed which, in turn, sustains oasis-like lush ecosystems populated by species previously unknown to science. In the intervening decades, hundreds of new species of megafauna have been discovered on the deep, dark seafloor, at an increasing number of vent-sites that have now been found in every ocean basin. Importantly, the physiology of vent-endemic multi-celled organisms have revealed a dependency on a relatively oxygenated ocean and, hence, should not be considered independent of sunlight – they require both photosynthesis to introduce oxygen into the upper layers of the ocean and overturning circulation to bring that oxygenated water to depth (Van Dover et al., 2002; Tyler et al., 2003). For the microbial populations that form the base of the chemosynthetic food-chain, however, such need not be the case. Guided, in part, by predictive studies targeting planetary exploration (Shock & Schulte, 1998) our continuing exploration on Earth has revealed an ever-expanding diversity of geologic settings where seafloor fluid flow can arise (German & Seyfried, 2014; German et al., 2016) including first definitive evidence for conditions under which abiotic organic synthesis of key prebiotic molecules can arise (McDermott et al., 2015).

Thus, it is entirely plausible that ocean worlds in the outer solar system could sustain water-rock interactions giving rise to chemical energy that can sustain requisite metabolisms for primitive forms of microbial life. We can anticipate that Ocean Worlds are habitable and, potentially, inhabited. How, then, should we explore?

2. Shared Interdisciplinary Values

In the study of Earth processes, it is well recognized – both in ocean and polar research - that theoretical studies can be comparatively inexpensive, laboratory experiments less so, but that launching field campaigns to collect the inestimable rewards of direct observations provides a unique set of challenges – both to conduct expeditions to extreme environments and to secure the resources required to conduct them. For space-based research, whether for Earth observations via remote-sensing or for Planetary Exploration, the same maxims hold true. Lived experiences show that from conception of missions to implementation in the field can span timescales of decades, in oceanography and in space - but for missions involving launch-pads, the implementation costs are far more extreme.

In the study of ocean worlds beyond Earth, therefore, it seems obvious that benefits should accrue if the planetary science community seeks to take advantage of the >150 year head-start that humanity has in the study of oceanographic processes on Earth and the corresponding ~100 year head start in the study of Earth's cryosphere. Simultaneously, from the sparse data already obtained from other ocean worlds, collaboration with planetary scientists offers the Earth-facing research community the opportunity to expand their data base beyond (n=1) for the study of integrated ocean system science.

While these two scientific communities, until very recently, have remained rather insulated from one another, there are good cultural grounds upon which to build future collaboration. Each field – of necessity – has already evolved to be both multi-disciplinary and inter-disciplinary in nature: physical, chemical and geological processes are already known to interact with one another on other planetary bodies, with multiple feedback loops. On Earth the same is true but there is also an increasing consciousness of the role that life plays in interacting with and even regulating the whole. Might the same be true in space? Soberingly, life may already be present, awaiting discovery, on planetary bodies that Earth-launched spacecraft have already passed by.

3. A Plan for Action

Below, we lay out the basis for developing a new cross-disciplinary research theme in the study of ocean worlds: one that harnesses community-level engagement across the Earth and Planetary Sciences and works toward pooling of resources and expertise across those diverse communities. We close by identifying key next steps toward implementing such a vision.

3.1 Community-level engagement

Both the study of planetary sciences and the study of Earth's oceans and cryospheres are already extraordinarily diverse. But there are multiple areas of expertise within the Earth and Ocean community, extending spatially from (sub-)seafloor geology at the deepest, up through the oceanic water column to ice-ocean interactions where expertise relevant to the study of ocean worlds most certainly exists. Of course, there are other aspects of oceans and cryospheres on Earth that may not map so directly to Ocean Worlds. As one illustration: the external temperatures of cryospheres on Europa and Enceladus may be order ~100°C colder than at Earth's ice-caps – but while that significant offset may appear to close a simple route for comparative studies among cryospheres, it may open several more. Ice in the outer shell of Europa or Enceladus may not exhibit the exact same properties as ice at the exterior of Earth's cryosphere, but mutual benefit could accrue from considering both how the study of rock mechanics on Earth can inform the mechanics of brittle-ice behavior at the exterior of an ocean world and how the study of cryosphere processes across the temperature ranges that are found on Earth might inform the predicted behavior of deeper, warmer ice on any ocean world that must approach 273K/0°C at their ice-ocean interface.

This simple example reveals a wider truth – there is untapped potential that could be released by bringing together communities to share individuals' science questions, outline their objectives and provide a broader platform where previously unlooked-for opportunities for collaboration can be identified and stimulated. Research communities are stronger when they pool individual resources and talent. Shared expertise can be brought to bear on mutually complementary interests, with or without exactly the same scientific goals. Areas of expertise in one field might be unknown, yet of extraordinary value for another team of researchers. Together, new teams of scientists might be able to develop new hypotheses that neither, in isolation, could previously have been able to articulate. And within this crucible of cutting-edge research, a new generation of interdisciplinary scientists, equally conversant in ocean and planetary sciences can be forged.

3.2 Pooling Resources & Expertise

From an ocean/cryosphere perspective, one of the most obvious contributions that can be made to the advancement of ocean world studies is in terms of accessibility. Whatever the complexities in organizing and scheduling field expeditions, at least the cadence and transit times to the field area are much less. For example, Europa is the nearest known ocean world to Earth but when NASA's next flagship mission, Europa Clipper, launches in 2024 (Howell & Papallardo, 2020) it will face a 6-year transit to reach Jupiter and by the time it starts to return data, a decade hence, it will be thirty years since that body was first revealed to host a salt-water ocean in contact with a rocky seafloor (Kivelson et al., 2000). With ever expanding computing power, theoretical forward modelling represents an opportunity to make predictions of what might be expected on other ocean worlds – and laboratory experiments can be designed to mimic such processes, just as can be done on Earth. But where field-access may have a particularly intriguing role to play is where those approaches reveal particularly intriguing possibilities, not least (although not exclusively) in terms of the opportunity to find extreme life in settings that have never yet been explored on Earth but have the potential to exist. Most of Earth's extreme environments remain unvisited – both in polar regions and throughout most of the deep ocean, even though the latter represents the largest contiguous habitable environment for life yet known – anywhere in the Universe (German et al, 2011).

Of course, access to Earth's oceans and cryosphere offers more than just an opportunity to explore extreme environments. It also provides opportunities to extend mechanisms by which such investigations can be conducted. Historically, oceanography has been conducted by teams of individuals mounting ship-based expeditions limited by the endurance of the vessel used and the finite resources that can be loaded aboard ship. Such an approach has not changed fundamentally from the first purposely-commissioned studies of the oceans, such as the Challenger Expedition of the 1870s to the present day. In contrast, future exploration of Ocean Worlds will – at least for the foreseeable decades – be conducted by robotic missions equipped with in situ sensors and, with much longer communication times from Earth than arise for past and present-day missions to the Moon and Mars, will require an increased reliance on autonomous platforms and autonomous data analysis, value extraction and reduction prior to transmission. All of these technological developments – while essential for the study of ocean worlds beyond Earth, could also be transformative for the study of Earth's oceans and cryosphere.

The recent successes of the ARGO floats program for physical oceanography and its expansion into the Global Ocean – Biogeochemistry Array, starting in Spring 2021, reveal the potential of such a technological revolution for ocean sciences - one that has already begun. When one factors in what more could be done through the long-term deployment of more capable platforms, collaborative robotics and exploitation of satellite-enabled teleconnections to shore the value in bringing together the technological as well as the scientific expertise of both communities becomes even more clear. For systems to be approved for space flight there is a need to advance along a very clear path of Technology Readiness Levels (TRLs, Banke, 2017): a mission that takes years to reach its destination requires robust technologies that can be relied upon to be effective when they arrive. Access to Earth's oceans and cryosphere provide excellent opportunities to develop such technologies. From the end of a pier to the most caustic deep ocean vents or the coldest polar terrains, instruments, algorithms and platforms can all be tested – individually and as integrated systems.

Importantly, because such technologies are not routinely available to Earth-based scientists, such testing need not be restricted to engineering trials. Ocean and cryosphere scientists will undoubtedly seize the opportunity to exploit these new technologies to advance their own research, providing value-added user-based authentication and feedback.

While this section has focused, thus far, upon a discussion of field campaigns and technology developments as areas of mutual benefit within the realm of Ocean Worlds research, it is important to recognize the new opportunities that a collaborative approach might also present for both laboratory-based experimental approaches and theoretical modelling. Laboratory experimentation can be particularly valuable, for example, in simulating conditions that theory predicts should arise in hard-to-access locations, both in space and here on Earth. But such experimental apparatus can be expensive to establish and maintain, while the experiments that they are used to conduct can be extremely time consuming and labor-intensive. This can lead to limitations in terms of access for contrasting reasons – either because of insufficient capacity across a community to conduct all the experiments that might be desired, or because of a lack of awareness across our communities results in capabilities being under-resourced and under-utilized through lack of demand. Improved communication of what capabilities exist, where, and with what capacities has great potential to stimulate new experiment-based collaborations.

Similarly, predictive modelling can be extremely valuable on Earth to provide simulations that faithfully reproduce myriad observations. Models that can adequately represent the modern day system can then form the basis for investigating how changes of various parameters, for example within the bounds of predicted future climate change, might become manifest at the global scale. Traditionally, however, such modelling has been informed by the cumulative acquisition of decades (more than a century) of direct observations from a single ocean system: Earth. Now, however, the discovery of new planetary-scale oceans has the potential to expand our parameter space: from the importance of planetary-scale rotation on ocean circulation through the impact of diverse tidal-forcings on heat dissipation to the nature of a planet's interior geophysics as a driver of water-rock interactions at the seafloor (both physical and geochemical). Two extreme outcomes can be anticipated. At the most conservative, established models derived from the study of Earth may prove directly applicable to other ocean worlds, in which case expansion of the modelled parameter space to encompass other planetary systems may still help point up particular areas of interest on Earth that remain to be investigated. This case study discussed in the Introduction provides reassurance that this concept is based in reality and is more than just an abstract intellectual construct. Perhaps most exciting, however, is the possibility that the (however sparse) data-sets obtained for other ocean worlds are so different from Earth that they will reveal a need to revisit the received wisdom upon which Earth-based modelling is currently based. The study of Ocean Worlds could provide a unique and novel lens on what remains to be explored, with what priority, here on Earth, lead to significant scientific advances in our understanding of our own home planet.

3.3 Priority Next Steps

Looking ahead, we can identify the following priorities toward growing and nurturing the field of planetary oceanography. First, it will be important to build an inter-community working group on this theme. The recently constituted Network for Ocean Worlds (*oceanworlds.space*) represents a valuable first step in that direction but will need to expand its reach and influence beyond its initial, relatively narrowly-defined, domain within NASA's Astrobiology program.

As it expands, the field of planetary oceanography should be able to meet the following goals:

- to develop a family of thematic sessions at established meetings, stand-alone meetings and workshops, and virtual spaces for researchers to interact, share ideas and develop new collaborations.
- to develop an infrastructure within which to share information about expertise, laboratories, and facilities, and career opportunities.
- to champion the support across multiple federal agencies for collaborative proposals that address scientific objectives pertinent to oceanographic objectives on Earth and beyond.

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Leveraging Earth Hydrosphere Science in the Search for Life on Ocean Worlds

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Introduction: Ocean World Observations from Remote to In Situ

Planetary exploration takes place through campaigns of targeted observations and missions, each of which builds upon previous findings. The methods of data acquisition, and often the scales of observation, evolve through successive campaigns as enabling technologies and the understanding of the target environment advance. For example, the exploration of Mars has evolved from the hand-drawn telescope images of Schiaparelli, through increasingly powerful telescopic observations and spacecraft-based remote sensing, to landers and rovers performing in situ imaging and analysis at landscape to microscopic scales. These observations will, in turn, inform the careful selection and return to Earth of samples that can then be prepared and analyzed with a broad range of methods that are not presently viable to conduct in situ. This progression, from remote to in situ, and from telescopic to microscopic scales of analysis, reflects an opportunity inherent in any exploration strategy: to optimize the potential for scientific advancement by leveraging observations made at one scale to formulate new objectives, drive new enabling technology, and inform the targeting, implementation, and measurement strategies that are deployed in successive observing campaigns. Such optimization will be essential as we begin to pursue the bold objective of detecting evidence of life beyond Earth.

The early characterization of the outer solar system through remote sensing methods has revealed a range of ocean worlds with intriguing potential to host extant life. As the objectives for further characterizing these worlds begin to focus on habitability and life detection, the mode of study is shifting in parallel, to orbital/flyby and landed in situ observing campaigns. For technological reasons, the first generation of missions to explore the surfaces of contemporary ocean worlds will likely not be mobile (see, e.g., Hand et al., 2017), and sample acquisition systems may be limited to depths of about tens of centimeters. These constraints will require that we optimize our potential to detect evidence of life through well-informed selection of a few-square-meter-sized patch on which to land, and well-informed choices of how best to select, acquire, and analyze samples. Prior observations made at these worlds inform our understanding of physical and chemical processes at planetary to regional scales. To leverage this information in choosing where to land, how to sample, and what observations to make, we must combine it with an understanding of how the distribution of life and its products relates to underlying physical and chemical controls across a range of scales.

Our understanding of Earth's biosphere – in particular, its hydrobiosphere -- is an invaluable resource to inform the search for life on ocean worlds. We understand the distribution of life on Earth as a system-level phenomenon – one governed by interacting physical and chemical processes – across scales ranging from microscopic to global. We have been able to study all hydrosphere surface environments using the full range of methods that could be applied in the search for life on ocean worlds, from remote hyperspectral satellite imaging and radar sounding to in situ chemical analysis and microscopy. Complementary numerical modeling and laboratory analyses have informed us as to the possibilities for life's origin on Earth, how certain environments became and remain habitable, and how surface features reflect underlying processes that influence not only the physical and chemical landscape, but also the distribution of life across it. "Ground truth" datasets, which correlate remote, space- or aerial-based data with chemical and biological characterization of surface materials, are especially critical. Leveraging these datasets, the methodology developed to obtain them, and the understanding built upon them will help to place spacecraft observations within an interpretive framework that links biological processes to physical and chemical ones. Doing so will inform the selection of landing sites based upon remote observation and also help to identify optimal sampling and measurement strategies. Here, we explore the synergies between ocean system science on Earth and the pursuit of life detection objectives on other ocean worlds.

The Distribution of Biology and Biogenic Materials on Earth

On Earth, life and biogenic materials are heterogeneously distributed according to the availability of resources, strength of stressors, and various physical transport processes. A useful framework for understanding the distribution of potential biomass in any ecosystem is the balance between metabolic opportunities and environmental stressors. Higher stress incurs an increasing cost on cellular physiology, which can only be met if there is sufficient free energy in the system. The excess energy that remains after basic cellular maintenance is met (i.e. repairing damage caused by environmental stress) is available for growth. The availability of nutrients and carbon substrates (organic for heterotrophic life, inorganic for autotrophic life) further controls biomass, as does grazing. The varying balance of these factors results in a heterogeneous distribution of life and biogenic materials at multiple spatial scales (Fig. 2).

The distribution of biology in sea ice, which is frequently referenced as a proxy for certain ice types on ice-covered ocean worlds, exemplifies the influence of physical and chemical processes on biological heterogeneity across scales (Fig. 2 D-F). Although sea ice differs from these environments in the basal energy source for life (sunlight), how life is organized in that system is not fundamentally different from any ice environment with an exogenous energy source. Within the sea ice system, life is partitioned at sub-millimeter scales into brine pockets that form as salt and particles are excluded from ice crystals during sea ice growth (Krembs et al, 2002). A microscale evaluation of a mature sea ice crystal would report a feature nearly devoid of life, while a similar evaluation of an adjacent brine channel would find a rich microbial habitat. Even within the brine channels, life is distributed non-uniformly over both vertical and horizontal scales. Further toward the ice surface, for example, the temperature is colder, the in situ salinity is higher, stressors, such as ultraviolet light, are more severe, and connectivity with the external environment is reduced. As a result, despite a considerably greater supply of energy (sunlight), there is no accumulation of biomass. The importance of physical transport is exemplified in the exclusion of brine as ice crystals form, and its subsequent deposition on the ice surface. The moisture evaporates and quickly super-saturates in a cold atmosphere, freezing out on available nucleation sites. Once a crystal is nucleated, it encourages further nucleation, leading to patches of fragile ice features known as frost flowers. Through a process still not fully understood, these features accumulate additional salt and bacteria, leading to a several-fold accumulation of biomass over nearby ice surfaces (Bowman and Deming, 2010).

The distribution of life in sea ice serves to exemplify the myriad ways in which physical processes can create heterogeneity across multiple spatial scales. Understanding the balance of factors that underlie such heterogeneity, and projecting that understanding into the context of environments beyond Earth, can serve to minimize the chance of a false negative results – i.e. failure to detect evidence of life that is actually present. Heterogeneity at meter and larger scales determines where a lander should be placed. At smaller scales, it determines the dilution of signal that occurs when a scoop, rasp, saw, or other collection device integrates over the volume of a sample.

It's important to recognize that the distribution of biological materials may differ from the distribution of biomass. Again, Earth's ocean provides useful examples of how biological molecules - including biomarkers - are organized. Biological molecules are not distributed homogeneously and are at their highest concentration near their source (this is what drives the distribution of heterotrophic biomass in Fig. 2A). This principle accounts for the phycosphere, or zone of chemical influence, around autotrophic cells in aqueous environments (Amin et al., 2012). To the extent that these molecules are more persistent in the environment than the organisms that created them, and more easily transported, they are more uniformly spread. This represents both a challenge and an opportunity for life detection efforts: biological molecules are more dilute than biomass, but also more widely distributed.

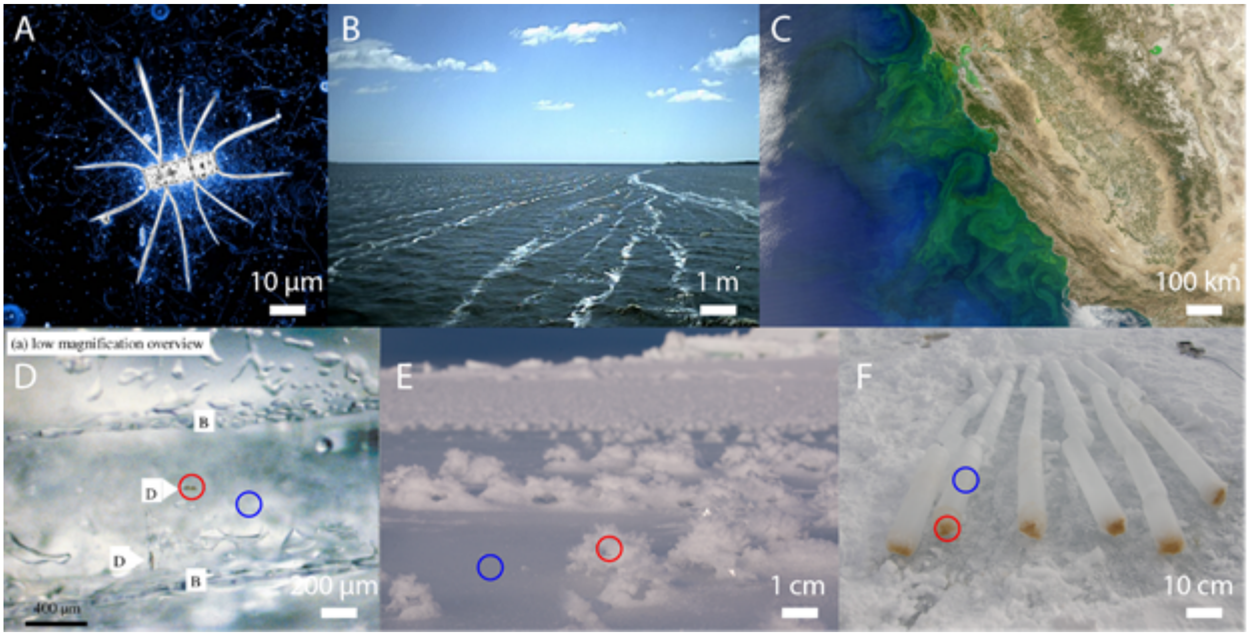

Fig. 2. Distributions of biomass at different spatial scales in ocean ecosystems. A) Gradients of carbon around autotrophic cells create strong spatial patterns among heterotrophic bacteria (https://ki-galleries.mit.edu/2015/diatom). B) Langmuir circulation creates zones of high and low biomass on the surface (https://www.ldeo.columbia.edu/~ant/Langmuir.html). C) Nutrient concentrations lead to strong gradients in biomass between onshore and offshore locations (https://oceancolor.gsfc.nasa.gov/gallery/658/). Panels D, E, F illustrate the distribution of biomass within the sea ice system at different scales. Zones of high biomass (red circles) can be found adjacent to zones of low biomass (blue circles). D) Single ice algal cells are partitioned into brine pockets within sea ice, leaving the ice crystals with relatively low biomass (Krembs et al., 2002). E) Frost flowers are nearly ubiquitous on the surface of newly forming sea ice and contain an order of magnitude more bacteria than adjacent sea ice surfaces (Bowman and Deming, 2010). F) In a classic example of the stress vs. resource trade-off, sea ice algae concentrate at the base of sea ice cores collected from McMurdo.

Key Differences between Earth and the Ice-Covered Ocean Worlds

Understanding the balance of factors that underlie the heterogeneous distribution of life and its products across Earth's hydrosphere provides a conceptual framework to guide the search for evidence of life on other ocean worlds. At the same time, it is important to acknowledge that Earth differs from these other worlds in ways that significantly impact this balance, and therefore the nature and abundance of evidence for life that our world presents to the observer.

a. *Resource availability*. Synthesis of new biomass (productivity) can be limited by availability of energy, nutrients or, in the case of autotrophs, the reducing power needed to 'fix' inorganic carbon into organic compounds, while maintenance of existing biomass depends on energy availability. On Earth, the flux of light directly into liquid water habitats provides such an abundant energy source that the oceanic biosphere overall is limited by nutrient fluxes rather than energy. As an ocean-wide average, only about 7% of incident, biologically usable light energy is harnessed into photosynthesis (Field et al., 1998). Deeply ice-covered ocean worlds would lack this large flux of energy, and any life therein would depend instead on chemical energy fluxes supplied by geochemical and/or radiolytic processes. Estimates of such flux for Europa and Enceladus (e.g., Vance et al., 2016), per unit volume of their respective oceans, are at least seven orders of magnitude lower than the flux of solar energy entrained into photosynthesis per unit volume of Earth's oceans (Hand et al., 2017). Beyond energy, vigorous continental weathering on Earth drives riverine and aeolian fluxes of limiting nutrients, such as phosphorus and iron, that may also be orders of magnitude higher than could occur on ice-covered ocean worlds (Lingham and Loeb, 2018). The implication of these potentially large differences in resource fluxes is that, on a global basis, both the magnitude of productivity and the standing biomass that can be supported may be greatly diminished on the other ocean worlds relative to that on Earth. It is essential that our measurement strategies factor in this diminished potential.

b. *Stressors and attrition*. Because organisms and their biochemical remains are, themselves, sources of energy and nutrients for other organisms, biological consumption of these resources is a key control on the abundance and distribution of life and organic compounds in Earth's oceans. For example, while the net productivity (rate of new biomass synthesis) of land-based and oceanic photosynthesis is approximately equal (Field et al., 1998), the standing photosynthetic biomass in the oceans is estimated to be about 500-fold smaller than that on land (Bar-on et al., 2018) - a difference attributable primarily to rapid grazing in the oceanic case. One consequence of rapid biological cycling (production/consumption) is that associated biomass and dissolved biomolecules have short lifetimes. For example, the residence time (Box 1) of both phytoplankton (Field et al., 1998; Falkowski and Raven, 2007) and biologically produced compounds such as amino-acids (Moran et al., 2016) can be as short as hours to days in the productive regions of Earth's oceans. Systems characterized by orders-of-magnitude lower productivity, as is likely the case for ice-covered ocean worlds, will differ markedly. There, lower productivity would necessarily translate to correspondingly longer residence times or lower concentrations of biomass/biomolecules, or a combination of the two (see Box 1). The implication of much longer residence times is that abiotic degradation and transport processes that are negligible in an Earthly context may be more important as controls on the nature and abundance of evidence for life on other ocean worlds. For example, racemization – the abiotic interconversion of the D and L forms of amino acids, occurs over timescales of tens to hundreds of thousands of years at temperatures characteristic of Earth's oceans. Such a process is inconsequential in affecting the ratio of D and L forms, a potential indicator of life, when the residence time of amino acids is in the range of centuries or less but would severely degrade such evidence when residence times are orders of magnitude longer.

c. *Physical transport*. Earth's oceans are potentially subject to more vigorous transport and mixing than might occur on ice-covered ocean worlds. Wind-driven circulation in the surface ocean can occur with velocities up to the meter per second range (e.g., in the Gulf Stream and Kuroshio currents) and associated turbulence serves to mix these surface waters both laterally and vertically on relatively short time scales. Moreover, evaporation and/or cooling of surface fluids leads to density-driven (thermohaline) circulation that serves to cycle water through the deep oceans on a time scale of about 1500-2000 years. These processes exert an important control on the flux of resources to life in Earth's oceans. For example, wind-driven circulation causes upwelling of nutrient rich deep waters that sustain the high levels of productivity and abundant biomass observed in Earth's richest fisheries (Fig 2c). Ice-covered worlds lack the potential for wind driven circulation and, while crystallization/melting of ice and hydrothermal flow can impart density differences, the much lower gravity of these worlds will lead to correspondingly lower density-driven flow rates. Our sampling and analysis strategies should be informed by improved understanding of the potential for physical processes to both (re)distribute resources and transport evidence of life from sites of production to sites of sampling.

Box 1: Residence Time

$$\tau = C/J$$

Residence time (τ), the average length of time during which a substance or object is in a given system or condition, is determined by the ratio of the concentration (C) of that substance to its flux (J) through (into and out of) the system. The consequence of a diminished flux of biologically derived materials – for example, due to a scarcity of resources to fuel biological productivity – is a combination of lower concentration and/or longer residence time. Lower concentrations require sensitive detection capabilities, while longer residence times increase the relatative importance of transport and abiotic degradation. Both are important considerations in designing effective sampling and measurement strategies.

These and numerous other differences will significantly impact the nature, abundance, and quality of evidence for any life that may exist on other ocean worlds, relative to what we observe in the world around us. It is critical to be mindful of these important differences as we develop strategies to seek evidence of life beyond Earth.

Leveraging the Science and Technology of Ocean System Research

The exploration of ocean worlds elsewhere in our solar system can leverage not only our understanding of Earth's ocean system, but also the methodology used to develop that understanding, and the diversity of environments and processes from which it derives.

Earth's hydrosphere comprises a range of environments that can serve as natural laboratories to inform the search for life on other ocean worlds. Models developed for worlds such as Enceladus and Europa can focus our attention on the Terrestrial environments that most closely approximate the physical and chemical conditions thought to exist in ice covered oceans. Observation and hypothesis testing in these Terrestrial environments can, in turn, refine our understanding of those in ice-covered oceans and within the ice, including the factors that govern biological processes. For example, the exploration of Terrestrial lakes beneath thousands of meters of glacial ice guides our understanding of sub-ice oceans and perched water bodies theorized to form in the outer solar system (e.g. Michaut and Manga, 2014; Dombard et al., 2013), and the objectives and measurement approaches that may be used to study them. Recent exploration of two lakes beneath roughly a kilometer of ice in West Antarctica reveals inhabited environments that differ greatly in their geochemistry, including dissolved oxygen levels (Skidmore et al., 2019; Davis et al., 2019). Understanding how organisms 'make a living' under these differing conditions can inform what we search for in prospective low oxygen oceans (perhaps Enceladus (Glein et al., 2015)) and higher oxygen oceans (perhaps Europa (Hand et al., 2007; Russell et al., 2017)) in the outer solar system. More broadly, the ~400 known subglacial lakes beneath several kilometers of ice in East Antarctica provide a diverse array of natural laboratories, with various geochemical and geothermal inputs, for investigating the diverse ways that life may function in cold, non-photosynthetic, but variously oxygenated environments (Siegert et al., 2016).

Even as we seek Terrestrial environments that approximate the conditions of icy ocean worlds, it is important to acknowledge that there are no perfect analogs. In using these environments as observational points of reference, we must also recognize key differences and account for how they may propagate through multiple levels of the system. For example, the development of models to understand fracturing and fluid transport within the ice shells of the ocean worlds can build on observations of ice dynamics in Terrestrial settings (e.g. Craft et al., 2016; Walker and Schmidt, 2015), but must also account for the differing dynamics of colder and potentially much thicker ice. Similarly, we must recognize and account for differences at the physical or chemical level that, as described above, may propagate into the abundance and distribution of life. For example, the habitable niches observed at the ocean-ice interface on Earth receive trace amounts of sunlight that fuel the biology there, and the physical and chemical dynamics that drive distinctive patterns in the distribution of life play out in specific regimes of temperature and pressure. We must expect and account for differences that may arise when the fluid-ice interface lacks the input of light energy, or when ice crystals form dissimilarly under the differing physical and chemical conditions that are likely present in ocean world ice shells. Even here, Terrestrial environments can provide an important resource. By identifying analogs for specific processes, rather than specific conditions, we can develop a mechanistic understanding that, potentially, enables an extrapolation beyond Earthly points of reference. For example, accessing deep ocean sediments enables us to study the dynamics of biological populations supported by extremely low fluxes of chemical energy (Hoehler and Jørgensen, 2013), such as may prevail on ice covered ocean worlds, rather than the orders-of-magnitude greater energy that drives the distribution of biology in many other environments of our hydrosphere. Our exploration of ocean worlds will benefit most extensively when it leverages such process analogs in addition to the range of physical analogs that Earth offers.

Fig. 3. Artist concept for a cryobot probe to an ocean world (Oleson et al., 2019)

The methods and technology that have been developed to explore Earth's hydrosphere also serve as a valuable design reference point for the exploration of worlds beyond Earth (Fig. 3). For example, the development of technology for exploring subglacial lakes and under ice shelves currently informs, and provides crucial test opportunities for, high technological readiness level (TRL) systems that can access and sample oceans in the outer solar system. The WISSARD drill team that sampled West Antarctic lakes has pioneered rigorous, quantified control of forward contamination (Rack, 2016), which can now inform planetary protection approaches for ice-penetrating systems. The NASA Concepts for Ocean worlds Life Detection Technology (COLDTech) and Scientific Exploration Subsurface Access Mechanism for Europa (SESAME) programs have supported the adaptation of terrestrial ice-drilling and melt probe technologies to potential ocean world applications, the development of communication technologies and navigation systems, and modeling of tectonic hazards and ice shell characteristics to reduce risks in flight hardware development. Similarly, the Planetary Science and Technology from Analog Research (PSTAR) program sponsored adaptation of deep-UV fluorescence and Raman-scattering methods to organic detection and characterization, as demonstrated on the Greenland ice sheet (Malaska et al., 2020). Beyond technology development, PSTAR also supports studies that develop mission “concept of operations” (ConOps) and explore specific observing strategies. As an example, the SUBSEA (Systematic Underwater Biogeochemical Science and Exploration Analog) PSTAR project (D. Lim, PI) brought together ocean and space scientists and operations experts in an effort to assess the best ways to conduct a remote science mission in an underwater ocean world environment.

Summary

The ocean worlds of our solar system offer the intriguing potential to host extant life that, if present, would almost certainly have emerged independently of life on Earth. Advancement in exploration and measurement technologies leave us poised, as never before, to search for evidence of life on these worlds. Relative to Earth, the potential scarcity of resources implies that such evidence may be overall less abundant, but we also know that the distribution of life and its products may vary by orders of magnitude across the landscape -- leading to concentrations far above the global average. To optimize our chances of detecting evidence of life on ocean worlds thus requires careful selection of targets, landing sites, sampling and measurement strategies. This selection should be informed not only by existing observations of these worlds but also by an understanding of the processes that govern the distribution of life and its products across a landscape. Our understanding of Earth’s hydrosphere, and the methods by which that understanding was built, offer an invaluable resource in this regard. We understand life on Earth as part of a broader system of processes that play out on a range of spatial and temporal scales. This system is amenable to characterization at scales ranging from microscopic to global, with methods that encompass and combine modeling, in situ analysis, and remote sensing. The result is not just a concrete point of reference, but an intellectual framework that can be applied to existing spacecraft observations in understanding where and how to search for evidence of life on the ocean worlds of our solar system.

Understanding the properties of environmental change in ocean worlds

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Introduction and Overview

The polar regions on Earth are undergoing rapid change, with declining sea ice cover, ice shelf breakup, warming seawater and changing ecosystem dynamics (Thorman et al. 2020). In the search for biological life in icy worlds, both on earth and in planetary scope, there are key properties of environmental change on Earth that might provide a better understanding of key processes and mechanisms for future exploration. In this white paper we evaluate questions of climate change through the use of earth's polar and deep ocean systems as analogs to understand key processes in icy ocean worlds. The need to access and explore subsurface oceans is essential for the search for life in the solar system. There are strong synergies between icy moon exploration and the studies of polar oceans and sea ice conditions on Earth that can expand our capabilities for investigating and understanding such environments throughout the Solar System. Antarctica is an important site for such studies due to its existing support infrastructure, specifically at sites which provide access to a subglacial lakes that are overlain by multiple kilometers of ice. However, there is also an opportunity to access other polar ice shelves underlain by a sub-surface ocean, specifically to study sea-ice interface conditions in polar oceans that have key processes that may be active even at extreme depths in off Earth ice ocean worlds. Hydrothermal vents are also key areas for cross-linked Earth and Planetary studies relevant to deep oceans dynamics as the biological components use reduced compounds as energy sources at vent systems by microbes that are then consumed by multicellular life forms (e.g., tube works and clams).

At present, the oceans of Europa (moon of Jupiter), Enceladus and Titan (moons of Saturn) are key targets in the planetary search for biological life forms in the solar system, with Titan having too thick an icy shell for robotic exploration. However, the icy outer shells of Europa and Enceladus, with a few to tens of kilometers thickness, provide potentially explorable environments. Enceladus, and likely Europa, have deep global oceans in direct contact with rocky interiors at their deepest depth, thus providing the potential for water-rock reactions for chemical exchange that could provide the chemicals (e.g., silica) to support life as occurs in reducing deep sea environments, such as hydrothermal vents (Van Dover and Trask 2000). Notably there is ongoing geologic activity, including gravitational interactions with their host planets, that could allow for surface-interior material transports within the fluid ocean with the potential to produce chemical components at both the ice-ocean and rock-ocean interfaces. Such situations occur in Earth oceans, and it

is the connection of oceanographic and planetary scientist that could find common ground for enhanced collaboration within the context of climate change studies on Earth.
The subsurface conditions of Ocean Worlds (Enceladus, Calisto, Ganymede, Triton, Titan, Europa) vary significantly. As one example of an icy world for investigation Europa provides a strong potential of liquid water, with an ice shell potentially ranging from 10 to 40 kilometers thick, overlying an ocean up to 130 kilometers in depth, and covering a rocky core. The ice shell (and potentially the rocky interior) tidally flexes in response to the gravitational interactions with Jupiter, thus generating heat (Thomson and Delaney 2001) to support the mechanisms necessary for the producing a liquid ocean with chemical components and facilitating variable mechanisms for circulation.

In December 2019 NASA held a workshop in California, with a goal to develop collaborative topics for joint Earth and Planetary science investigations. Three questions related to climate change and summary statements are highlighted below:

1. How can studies focused on climate change on Earth provide a better understanding of the evolution of an ocean world?

Climate change has planet-wide impacts to large-scale world climate and regional weather patterns, ocean dynamics, and geological history as well as understanding external planetary system dynamics. Ocean world ice shells are composed of cold, near-surface ice, that sustains fracturing and faulting, and warm interior ice that relaxes to prevent fracturing and may be convecting, thus providing a mechanism for variable ice-ocean conditions at their interface. The Earth and other ocean worlds can be evaluated for past, current and future understanding of climate change impacts that may enable forecasting of future system change. Earth system scientists (e.g., oceanography, geology, volcanology) can provide past earth history and current process understanding of key climate physical forcing factors on the earth system relevant to better understanding of other planetary worlds, especially those having an ice cover over liquid water as occurs in polar regions of Earth. Looking at both temporal and spatial environmental impacts are important to this topic. Support for research activities that provide cross-fertilization opportunities of earth and planetary science initiatives relevant to better understanding of ocean worlds, including planet earth, are recommended. A key question is how conditions at Earth's ice-ocean interface might compare to those beneath the ice shells of ocean worlds (specifically related to pressure, temperature, and composition), thus looking at earth's analogs may hold the key. Future work by the planetary and sea-ice communities should include understanding the terrestrial processes that can be extrapolated to icy worlds. Since temperature at the ice-ocean interface is governed by pressure, it is the mechanisms at interfaces of ice-ocean and ocean-rock that hold the best potential for evaluating change at variable time scales on Earth and other ocean worlds.

2. How can remote sensing and in situ measurements inform our understanding of planetary change, especially via polar systems and in the deep sea?

On planet Earth autonomous remote sensing by satellites and other sensors as well as in situ sensing platform are necessary for studies of the under-ice environment, liquid water (oceans, deep lakes), and sediment/geological interface (bottom oceans, hydrothermal vent systems). Earth system scientists can provide past and current day earth measurements (oceans, land) from Polar Systems (Arctic, Antarctic, Greenland) and deep ocean systems relevant to planetary exploration in ocean worlds. Similarly, planetary science requires autonomous capabilities for investigations into extreme environments (low and high temperature, ice cover/liquid subsurface systems, high pressure) that have technological development that would benefit current earth system analyses on earth (see section VI-technology section of this white paper for further details).

3. How does environmental change impact biological processes and what are the feedbacks?

Human populations depend on biological processes for our oxygen environment and food production, thus environmental security and food security are key components to human existence. The search for biological life beyond earth is one of goals of human interest in planetary science and understanding our own roll in the overall planetary system. Thus, understanding impacts on biological processes, from organic molecular development to single and multi-cellular growth (and destruction), is an important goal for earth and planetary scientists. Both earth and planetary scientists can benefit from interactions relevant to understanding key drivers and environmental change impacts on biological processes relevant to planetary life over multiple scales.

Earth's frozen regions, specifically in Earth polar regions that are most relevant to planetary topics, are undergoing rapid change under a warming climate that has a direct impact on the Earth's climate and biological growth and destruction. Processes at the ice-ocean interface during sea ice production and melt influence large-scale ocean circulation patterns and connection to the climate system. Melting freshwater glaciers and ice sheets under climate change can provide chemical components and organic material to the ocean that are then available for biological life.

Analogs on Earth to Icy Worlds that are Influenced by Climate Change

Terrestrial environments on Earth are key analogs to the physical and chemical conditions thought to exist in ice covered oceans of planetary bodies as mentioned in the habitability chapter. Such terrestrial lakes found beneath thousands of meters of glacial ice in Antarctica and ice covered regions around Greenland in the Arctic are relevant to investigating mechanisms for influencing deep circulation patterns and associated processes that could influence chemical and biological components in icy world oceans. Studies of subglacial lakes under kilometers of ice in West Antarctica indicates subsurface systems that have variable geochemistry, including oxygen and biological life (Murray et al. 2016, Skidmore et al., 2019; Davis et al., 2019). These investigates are pertinent to icy world oceans that may include deep low oxygen oceans, such as on Enceladus (Glein et al., 2015) to deep, higher oxygen oceans on Europa (Russell et al., 2017). The many subglacial lakes in Eastern Antarctica under km thick ice cover have both variable geochemical, heat components, and life forms not supported by photosynthesic carbon (Siegert et al., 2016).

In addition, polynyas (open areas in ice covered seas), especially those that form in winter, could provide an analog of ice-ocean interactions and frazil ice development that may be useful for joint studies to evaluate key processes at this important interface. Ito et al. (2019) found favorable conditions in winter during brine formation and rejection of salt into the ocean that allowed the resuspension and freeze up of sediment components within frazil ice, a mechanism that could entrain chemical and molecular components at the ice-ocean interface or produce a subsurface pool of material (chemical and heat components) in the upper ocean region and allow for potential sites for chemosynthetic life.

By comparison, mineral rich water at depth in both the high Arctic and around Antarctica, specifically at the ice-ocean interface either near the surface or under floating ice shelves, along with deep-sea environments, provide sites for the processes that influence the development of microbial life and multicellular organisms. Variable temperature and pressure regimes influence single and multi-cellular forms of life under low or no light conditions. The processes influencing this variability are key components to investigate to find analogs for life away from Earth. Climate change is influencing the declining sea ice in polar regions, especially the Arctic (Perovich et al. 2020) and warming seawater temperatures (Timmermans 2020, Timmermans and Labe 2020), such that sea ice-ocean processes can be a valuable analog for joint earth-planetary studies, both through field studies and technological advancements for both science fields. Deep ocean sediments and hydrothermal vents on Earth maintain life through variable fluxes of chemical energy to support life (Hoehler and Jørgensen 2013, van Dover and Task 2000). The fundamental properties of the ocean water (temperature, pressure, pH, reduction potential, salinity), key nutrient elements (C, N, P, S, Fe, etc.), and the availability of chemical energy are all processes in this analog environment worthy of study. Colored dissolved organic matter (CDOM), humic substances, and clathrate deposits in polar regions are all important for microbial life and are susceptible to climate change.

Recent laboratory studies of organic molecules released from destructive stress to extremophile bacteria at high temperatures resulted in small fragments of carbohydrates, proteins, and lipids, potentially providing insight on the origin of organic matter in icy planets. Salter et al. (2020). This study undertook pyrolysis of organic material to simulate organic molecules from planetary plumes as occur from the icy shells of Saturn's moon Enceladus and Jupiter's moon Europa after collision with a spacecraft. It would be valuable to actually investigate analogs of this process at earth systems under high temperature and pressure, such as hydrothermal vents in the deep sea spreading centers. Specific studies of mantle-heat-ocean interactions in relation to organic molecule production is important to study. Investigations into the plumes being ejected from some icy planets from subsurface liquid pools of water or the internal oceans themselves are candidates for NASA missions, but testing the process of organic matter fragmentation under extreme stress on Earth, both in the lab and field, could provide valuable information for planetary studies. Studies of basic molecular organic structure of organism living in high radiation environments on earth may also be worth investigating on earth.

Conclusion

The consensus of the participants at a NASA workshop in late 2019 was the need to develop synergistic research questions and collaborations between Planetary scientists and Earth's terrestrial and ocean sciences community to move forward research related to studies off Earth ocean worlds, especially with icy shells that could harbor subsurface oceans and potentially biological components indicative of life. A recommendation from that workshop was the need to initiate a coordinated joint working group of scientists from both communities that would facilitate discussion of joint knowledge of status and gaps of understanding related to key processes pertinent to life, identify opportunities for testable ideas based on the Earth System for planetary studies, and to allow development of a strategy to advance our knowledge of Ocean Words in our solar system.

Defining and characterizing habitable environments in ocean world systems

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Habitability is broadly defined as an environmental state with liquid water, chemical disequilibria, and the molecules (elemental and organic) needed for life as we know it. In addition to having the basic ingredients for life, habitable environments must also exist within the pressure, temperature, pH, and water activity boundaries that allow cells to persist (Dartnell 2011). Could life as we know it survive in liquid water environments that exist elsewhere in the solar system? A practical strategy to assess habitability quantitatively is to determine the physiochemical conditions that would drive the operation of possible life on extraterrestrial ocean worlds. These conditions include fundamental properties of the water (temperature, pressure, pH, reduction potential, salinity), the forms and abundances of key nutrient elements (C, N, P, S, Fe, etc.), and the availability of energy that could be used by life. In most cases, these properties are completely unconstrained by present observational data because it is difficult to access subsurface liquid water environments beyond Earth. However, as exploration of icy ocean worlds matures from initial reconnaissance to more in-depth characterization, opportunities will arise to obtain some of the critical information. The near-term opportunities can involve serendipity, such as plume eruptions from the ocean of Enceladus, or less direct sources of information that may be contained in the compositions of planetary surfaces or atmospheres (see Glein and Zolotov (2020) for an overview).

What do we know about ocean habitability of the "Three E's": Earth, Europa, and Enceladus?

I. **Earth**: Every drop of water in the Earth's ocean is habitable and inhabited by a diverse array of life, and – of course – Earth is the only planetary body in the universe that we know for certain is inhabited. Earth's oceans are habitable due to multiple factors: recycling of critical nutrients through ocean circulation, pH buffering by the Earth's carbonate system, and maintenance of clement temperatures and pressures largely due to Earth's atmosphere, to name a few. Ocean circulation is a fundamental control on Earth's ocean habitability at a variety of spatial scales and is critical for transferring heat and dissolved gases throughout the ocean, as well as nutrients needed for life. Ultimately, habitability of Earth's ocean also depends on large and long-scale tectonics and the weathering and release of critical nutrients like phosphorus that would otherwise limit growth of marine life. Ocean circulation is a fundamental control on Earth's ocean habitability at a variety of spatial scales and is critical for transferring heat and dissolved gases throughout the ocean. Ultimately, habitability of Earth's ocean also depends on large and long-scale tectonics, which brings fresh rock above sea level, which is subsequently weathered, releasing critical nutrients like phosphorus that would otherwise limit growth of marine life.

II. **Europa:** The availability of chemical disequilibria for energy sources for a putative biosphere on ice-capped ocean worlds with limited sunlight is likely dependent on movement of reduced chemicals upward from the silicate interior to the ocean via water-rock reactions at the seafloor (Vance et al. 2016), and movement of oxidants (e.g. H2O2; Carlson et al. 1999) downward via the ice shell into the liquid ocean from the irradiated surface (see Schmidt 2020 for a review). On Europa, this exchange is highly likely and could provide energy to support a dark biosphere (Chyba 2000; Chyba and Phillips 2001; Hand et al. 2009). Russell et al. (2017) argue that areas of relatively high oxidant fluxes at the lid of a Europan ocean should be expected to be highly biologically productive. The details of how this occurs are currently unknown, but evidence for global tectonism (Doggett et al. 2009; Kattenhorn and Prockter 2014; Pappalardo et al. 1998) and recent activity (Jia et al. 2018; Roth et al. 2014; Schmidt et al. 2011; Sparks et al. 2017) suggests that current ice-ocean exchange is possible via ice shell processes on Europa. With tidal activity over at least the last two billion years providing global energy to Europa, it is possible that the conditions to support life have existed on Europa over the history of the solar system. Exchange processes may work differently on other ocean worlds with less active ice shells.

III. **Enceladus**: Exploration of Enceladus by the Cassini mission provided important lessons on how we can investigate the habitability of an extraterrestrial ocean world. As an example, Cassini found hydrogen gas (H2) in the plume, likely sourced from water-rock reactions below Enceladus' seafloor (Waite et al. 2017). Using a combination of mass spectrometry measurements in the plume and geochemical modeling of carbonate equilibria, researchers were able to constrain the pH of Enceladus' ocean to ~9 (Glein et al. 2015; Glein and Waite 2020). Enceladus also taught us that hydrothermal processes (Hsu et al. 2015) can be a critical component of energy generation on ocean worlds beyond Earth (Choblet et al. 2017). The abundance of H_2 was found to be sufficiently high so that methanogenesis is energetically feasible (Taubner et al. 2018; Waite et al. 2017).

To what extent can Earth's ecosystems serve as analogs for other ocean worlds?

Unlike all other ocean worlds in our solar system today, most of Earth's surface ocean is in direct contact with the atmosphere and bathed in light from the sun. Although some organisms live off the heat and reduced chemicals of oceanic hydrothermal vents, Earth's ocean productivity is largely driven by photosynthesis in the surface layer, the euphotic zone, where sunlight penetrates. On ice-capped ocean worlds, sunlight may not penetrate to the liquid ocean and wind-driven ocean mixing would be absent. More relevant Earth analogs for habitable environments on other ocean worlds are interfaces, such as ice-water and seafloor-water boundaries (e.g. hydrothermal systems). Other analogs include habitats inside of ice and gas clathrates.

Interfaces. Some of the most productive and diverse aquatic habitats on Earth are found along boundaries and interfaces where biomass is concentrated. Examples include the seabed (whether sedimentary or igneous) and the underside of floating ice. Large-scale ocean processes deliver energy, chemicals, and organisms to these boundaries, which obstruct further transport, thereby concentrating life and life's necessities, and enabling biology to proceed more vigorously than in more dilute seawater. Elemental cycles are often controlled by interactions at the interfaces that control atmospheric deposition, exchanges across the coastal zone, and ice dynamics. On Earth, these interfaces are areas where marked changes in the physical, chemical, or geological structure of marine, brackish, and freshwater environments take place continuously. Growth rates of organisms in these habitats often change rapidly, from day to day, and over these short distances.

Some of the most relevant Earth analogs to other ocean worlds are the unique habitats formed at the boundary between ice and water. Sea ice plays a dual role in the control of high-latitude phytoplankton blooms by influencing both light shading and stratification (Arrigo et al. 2012; Kauko et al. 2017). Melting ice in the spring can stabilize the water column, supporting large phytoplankton blooms. The timing, size, and type of ice edge algal blooms can define the success of a growth season and control food web dynamics (Ducklow et al. 2013). New research has shown that phytoplankton blooms can occur with limited light under several meter-thick layers of ice and snow (Boles et al. 2020). but limits to growth of phytoplankton under thicker ice layers are not well known. Certainly heterotrophic microbial life can also be important along boundary habitats given nutrient availability in the form of dissolved organic matter. Even without penetration of sunlight directly, physiological adaptations of microorganisms to the ocean/ice dynamics could serve as analogs to adaptations of both autotrophic and heterotrophic life in other icy ocean worlds. The undersides of floating Antarctic ice shelves vividly illustrate the importance and roles of interfaces. Murray et al. (2016) discovered a vibrant, diverse ecosystem, including abundant sea anemones, at the undersurface of the floating Ross Ice Shelf. A similar community observed under Thwaites Glacier (Schmidt 2020) shows the possibility for dense, complex, and energy-intensive biological activity in an unexpected and astrobiologically highly relevant location. Since the icy shells of these bodies also form and evolve from cyclic freezing and melting, analogous processes to ocean-derived ices on Earth are helping to constrain the active cycles within the ice and at its interfaces (Buffo et al. 2018; Buffo et al. 2019) as well as cycles of water within the ice shell (Chivers et al. in review; Kalousová et al. 2014).

Life is abundant at the seafloor-ocean interface where unusual microbial and invertebrate populations exist on organic material from CO_2 reduction by chemotrophic bacteria that oxidize inorganic compounds released by hydrothermal vents (Van Dover and Trask 2000). This interface is also where photosynthesis is postulated to have begun under low-intensity, long-wavelength geothermal light (Martin et al. 2018). Anaerobic green sulfur bacteria, for example, are capable of photosynthetic growth at extremely low light intensities. Temporally variable light has also been observed in visible wavelengths (400–600 nm) at deep-sea vents that is orders of magnitude greater than predicted for a thermal source likely caused by mechanisms associated with turbulence, mixing and precipitation, such as vapor bubble luminescence, chemiluminescence, crystalloluminescence and triboluminescence (White et al. 2002). Studies on marine microalgae in the polar night can also contribute to our understanding of low light photosynthesis and serve as an analog to the light climate of the deep sea (Cohen et al. 2020; Johnsen et al. 2020) and potentially icy ocean worlds.

Earth analogs for habitable regions on ocean worlds may also exist on land, particularly at Earth's polar regions. One fascinating example is found at the upper interfaces, or "lids", of Antarctic subglacial lakes, where overlying glacial ice meets subglacial lake waters. Molecular oxygen is supplied to the lids of some subglacial lakes during melting of air-clathrate-bearing ice. Air is trapped by progressive burial under new snow at ice sheet surfaces. At depth, the air is forced into cage-like structures in the ice crystal lattice under high pressure; the ice flow then carries such clathrates over subglacial lakes. Although oxygen in this case is photosynthetically derived, it would seem likely to play a similar role in dark, chemosynthetic environments to subducted oxidants in the Europan ice shell (Hand et al. 2006). Spatial variation in oxygen delivery (Winebrenner et al. 2019) may provide a natural laboratory for investigating analogous geobiological processes on ocean worlds. While important cycling within some lakes provides a habitable niche based primarily on the rock cycle (Mikucki et al. 2016; Mikucki et al. 2009), the ice accreting above these lakes is also among the lowest energy niches on Earth, which provides an important lower limit on both energy required to sustain and technology needed to detect life in ocean worlds (Hand 2017).

Life inside ice. On Earth, there are active habitats within ice, as well as at its outer boundaries. It is presumably the case that a habitable ocean world would also have habitable niches within the ice shell. On Earth, this means that research into the processes that occur within ocean-formed ice—marine and sea ice—and the cycling and processes that define their ecology, are relevant to ocean worlds and their processes as well (Buffo et al. 2018; Buffo et al. 2019; Schmidt 2020). On the biological side, snow packs serve as habitats and nutrient reservoirs for microbes across the global cryosphere on all continents (Hodson et al. 2017; Lutz et al. 2016). Snow or glacial algae survive in a liquid water film between melting snow and ice crystal and may color snow green, golden-brown, red, pink, orange, or purple-grey (Hoham and Remias 2020). Formation of snow algae blooms is related to light availability, liquid water content, and temperature (Hoham and Remias 2020). Algal pigments can be photoprotective and shield snow algae from harsh light conditions (Bidigare et al. 1993) and they can also play a functional role in melting snow and ice creating more liquid water required for their growth (Dial et al. 2018). With some exceptions, snow algae are usually found in snow with acidic pH. Snow and ice algae can be ephemeral, on the order of weeks during spring and summer when air temperatures remain above freezing, and on small spatial scales often bordering ice and land margins. Nutrient cycling can be locally diverse and include volcanic sources, leaching from underlying rock, marine fauna (e.g., penguin and seal excreta), as well as intense cycling within glacial microbial communities.

Also known as clathrates, gas hydrates may be the most accessible habitats on which to find life on other planetary bodies in our solar system. Gas clathrates are cages of (typically) methane gas molecules trapped inside solid water cages. Under Earth's continental margin seafloor, methane clathrates host unique microbial assemblages (Inagaki et al. 2006). Gas hydrates are likely present on other planetary bodies in our solar system (Mousis et al. 2015) and may play a role in creating and sustaining liquid oceans, especially on ocean worlds without actively maintained sources of tidal heat (Kamata et al. 2019; Tobie et al. 2006). At the Martian poles, methane clathrates could be as shallow as only half of a meter deep, and extend down several dozen kilometers (Gloesener et al. 2020). These habitats have the potential for serving as pockets of liquid water for microbial refugia in the deep subsurface and may be accessible to future drilling missions. On the seafloor above gas hydrates, methane escaping from the seafloor serves as an energy source for extensive communities of microbes and the tubeworms and clams that feed on them at cold seeps (Levin et al. 2016).

What technology and integrative scientific approaches can enable us to probe the habitability of currently inaccessible oceans?

Below we describe some key future directions in this field.

I. **Organics:** The next addition to our toolbox for quantifying habitability may be organic molecules. Conventionally, organic molecules are targeted as potential biosignatures (Neveu et al. 2018) or precursors to life. However, observations of outer solar system bodies suggest that abiotic organic compounds may be abundant planetary materials, possibly of comparable importance to water and rocks (Néri et al. 2020). This means that organic compounds could have major involvement in planetary evolutionary processes, such as hydrothermal alteration. Geochemical experiments show that many groups of organic compounds behave predictably in hydrothermal systems, where the abundances of organic compounds are driven toward states of metastable equilibrium, which are defined by the physiochemical conditions of the system (Robinson et al. 2020; Seewald 1994; Shock et al. 2019). These relationships provide the potential to derive properties (e.g., temperature, oxidation state, pH) of the host hydrothermal system from measurements of organic compounds. However, fully realizing the power of this approach and understanding its limitations will require (1) improvements in our ability to quantify the thermodynamic properties of organic compounds at high temperatures and pressures, (2) additional experiments to determine the mechanisms and corresponding rates of organic reactions under icy ocean world conditions, (3) development of models that track the coupled evolution of diverse water-rock-organic compositions during hydrothermal circulation and other transport processes, and (4) ground-truth field tests of the prevalence of metastable equilibria among different compound classes at organic-rich hydrothermal systems such as Guaymas Basin.

II. **Interfaces:** Interfaces are critical areas where physical, chemical, and biological processes act on a variety of spatial and temporal scales. Intense biological activity, accumulation of organic and inorganic substances, unique interactions that deviate from general conditions occur at these locations and can form an environment that may be unique for life. Understanding exchange and movement at interfaces of nutrients, gases, heat, and redox potential and quantifying light production and availability in low light environments such as deep-sea vents and the polar night are essential to quantifying habitability of oceans and to guiding searches toward the most habitable environments. Environmental processes along interfaces typically have shorter time scales (hourly) and space scales (meters to kilometers) and often require different methods to assess change compared to other ocean habitats.

    Ice-ocean interactions is an expanding area in the research into ocean worlds, which is growing in fidelity. Fundamental controls on the circulation of oceans under the ice is an area of active research in the climate and polar community from which the ocean world community can benefit and interact (Dinniman et al. 2016; Holland and Jenkins 1999; Holland et al. 2020). Such understanding hinges on ocean modeling on large- and meso-scales, as well as coordinated, focused observations of fluxes and processes near the interfaces. Already, some modeling of ocean world circulation exists (see Soderlund et al. 2020 for a review). However, the details of salinity, nutrient, and putative biomass distribution by ocean circulation is currently not included, since fundamental processes are still being resolved, such as overturning circulation, ice pumping, or double diffusion. Laboratory research in cyclic freezing and melting should also be expanded, to study the effects of freezing as a means of changing the composition of reservoirs and the ice, as well as to understand the fundamental sources of chemical energy possible in these environments.

    Technology development is essential both for accessing interfaces in challenging places (e.g., on the deep seafloor, beneath ice shelves, or at the lids of subglacial lakes) and for measurements to diagnose poorly known processes going on there (e.g., heat, salt, light, and nutrient fluxes beneath ice shelves). New in-water autonomous platforms with a variety of sensors are being deployed to investigate the biodiversity and phenology of under-ice blooms. This is especially important to understand the dynamics of life associated with the underside of ice during winter and spring, which is challenging to assess with many remote sensing techniques. New technology (Rack et al. 2012), can motivate a variety of new scientific questions, e.g., on interface processes, as well as further technology development to explore this habitat more extensively. Synergy between Earth's ocean-ice interactions (with important implications for geochemical cycling and climate response of ice shelves) with those that likely also operate on ocean worlds means that exploring these physical processes on Earth also provides feed-forward context for exploring other ocean worlds. Exploring these regions with ice penetrating radar, seismic and underwater vehicles is often (but not always) technologically synergistic with needed developments for exploring ocean worlds. The upcoming Europa Clipper mission will provide in situ measurements of the geochemical nature and detailed local context of ice-ocean exchange processes, which was not possible with earlier missions. How these types of interactions operate on bodies like Enceladus with more regional scale geologic processes is an area of active work (Běhounková et al. 2017; Kang and Flierl 2020; Nimmo et al. 2018; Walker and Schmidt 2015; Weller et al. 2019).

III. **Modeling:** Resolving the phenology of diverse life forms is crucial for understanding responses to environmental perturbations and is impossible to capture with a single snapshot. Investigations require careful time series of measurements and modeling across relevant time scales. To achieve this, it will be critical to measure and model the patterns and dynamics (spatial and temporal) of ice and oceans. It will be necessary to determine the essential model parameters necessary to improve ocean, ice and crustal models, and evaluate new and existing technologies and models relevant to studying ocean, ice, and crustal dynamics.

Biogeochemical and ecosystem models are advancing our ability to characterize the complexity of life in Earth's ocean world. For example, marine biogeochemical and ecosystem models include parameters for the physical environment (temperature, light, salinity, and circulation of the ocean), the cycling of inorganic and detrital matter (biogeochemistry), and the explicit representation of some portion of the living component of the ocean (e.g., phytoplankton, zooplankton) (IOCCG 2020). Such integrated modeling tools could be adapted for assessing the parameters and potential for life in other ocean worlds. Advances are being made in measuring and modeling mesoscale and sub-mesoscale circulation patterns (e.g., eddies, streamers, and fronts) and their roles in transporting heat and nutrients into and out of the euphotic zone (McGillicuddy Jr 2016).

The general approach of using modeling to help fill in the gaps where data are incomplete provides a tool for extracting maximal information on extraterrestrial ocean properties. This type of tool was not developed until late in the Cassini mission. Future ocean worlds missions should plan integrative approaches from the start, during the development/testing of instruments and planning of mission operations, and these integrative approaches should include full traceability that links primary mission data to ocean properties for a broad range of models. More generally, a key science lesson is that ocean habitability involves other parts of the planetary body dynamically interacting with the ocean. This echoes our understanding of the Earth system and suggests that coordinated geophysical and geochemical studies are needed to better understand how exchange processes can create habitable conditions on ocean worlds. Modeling seawater chemistry and water-rock interactions based on analogous processes on Earth, extended to hypersaline lakes and deep anoxic hypersaline basins with more exotic chemistries (Brown et al. 2020), would benefit both the Earth and astrobiology communities.

To better understand the habitability of gas hydrates, it will be necessary to measure and model the patterns and dynamics (spatial and temporal) of methane clathrates, determine the essential model parameters necessary to improve gas hydrate models, evaluate new and existing technologies and models relevant to studying hydrate dynamics, and pursue more microbiological characterization of microbes in their native hydrate habitats on Earth.

IV. **Interdisciplinary efforts:** Coordination between the Earth/ocean sciences and planetary science communities will be critical for next generation studies of ocean world habitability, and – ultimately – life detection. Earth/ocean scientists have a deep base of experience on how life can be linked to environmental conditions and processes, while planetary scientists are able to translate the underlying concepts to alien environments and indirect spacecraft measurements. Synergy between thinking about how the various layers of the planet affect our observations is important, because the ice shell and atmosphere are the window through which we will, for now observe ocean world systems. How does the ice reflect or hide the ocean? How does seafloor heating and rotation drive ocean currents, and how do these distribute biosignatures, heat, salt, and other components? Is the ice-ocean interface the first habitable niche, or are there locations in the ice or along the seafloor to search? Synergy between studies of ice, ocean and geothermal processes on Earth, in targeted ways, and models of how these processes may manifest on ocean worlds benefits both communities. Moreover, the technological needs for exploring, especially at the poles, is often synergistic. Terrestrial and extraterrestrial ocean scientists must work collaboratively to measure and model spatial and temporal dynamics, determine essential parameters that govern interface processes, and evaluate new and existing technologies to access and study dynamics of habitable worlds.

Research in analog environments to enable studies of ocean worlds

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Are there Earth analog environments that capture the physics, chemistry and biology of ocean words?

Interest in the physics, chemistry, and potential for life on other planets has been widespread among the general scientific community and this interest has been increasing in recent years. A number of missions have either been completed (e.g. Galileo, Voyager, Cassini-Huygens) or are in the planning phases (e.g., Europa Clipper, Europa Lander) to characterize the conditions of some of the outer planets and their moons and determine whether they harbor conditions that could be suitable for life. The most promising of these are ocean worlds within our own solar system, such as the moons of Saturn (Enceladus and Titan) and Jupiter (Europa), that are covered in liquid water beneath a thick layer of ice. Internal heat sources prevent this liquid water on the lunar surfaces from freezing, possibly providing the conditions necessary for the evolution and sustenance of microbial life (Lobo et al., 2021).

However, the cost and longtime horizons needed to plan and mount missions to study these ocean worlds means that very few such missions are possible. To maximize the probability of detecting life on these ocean worlds, it is therefore necessary to first understand the suite of conditions required to support life on Earth and use this information to search for similar or analogous habitats on other ocean worlds. To do so, scientists seek out extreme environments on Earth where the physical and chemical conditions may result in an environment that is a reasonably close analog to habitats on other worlds. The most likely analog environments are found either near the poles, where kilometers thick ice sheets, isolated saline lakes, and seasonally forming sea ice provide unique but extreme habitats for microbial communities here on Earth (Garcia-Lopez and Cid 2017), or in the deep sea where tectonic activity produces energy-rich hydrothermal plumes that support and entirely chemosynthetic food web (Michalski et al. 2017).

These analog environments on Earth enable scientists to begin to answer research questions about extraterrestrial ocean worlds that would be otherwise inaccessible to them. In addition, because of their relative ease of sampling and much closer proximity to research facilities (compared to lunar landing missions), utilization of analog environments allows scientists to undertake many investigations for the cost of a single planetary mission. This ability for rapid testing of sampling techniques and experimentation on analog environments would provide an effective test bed for the kind of operations required for future ocean world missions and increase the likelihood of mission success. For example, before we can drill through and sample the ocean beneath the icy moon Europa, we need to demonstrate an ability to remotely drill through the ice sheets of Antarctica or Greenland.

The study of analog environments on Earth requires collaboration among different scientific communities, each with their own specific disciplinary expertise. Members of the planetary science community need to identify those physical, chemical, and biological processes on extraterrestrial ocean worlds that remain poorly understood and require further study. For example, the thickness of the ice shells on moon such as Europa and Enceladus and the composition of the water below are not well known and require the identification of technologies and approaches that would be most efficacious for their accurate characterization. Using what information is available for specific ocean worlds, members of the earth science community would then be well positioned to identify analogous environments on Earth where these technologies and approaches can be rigorously tested at a reasonably low investment of time and money. These analog environments would also provide technologists with the requisite information needed to develop suitable sensors and sampling platforms that would allow the measurement and observation of the identified physical, chemical, and biological processes.

The essential first step in developing plans and processes for sampling remote ocean worlds, using analog environments on Earth as a test bed, is to form a number of disciplinary working groups consisting of scientists and technologists. These working groups would essentially be “fact-finders” tasked with compiling the latest data on specific issues related to the study of ocean worlds. For example, a series of three working groups could focus on physical, chemical, and potential biological processes on other planets or moons that need to be understood in order to frame and answer relevant ocean world questions. Other sets of working groups could help identify specific tractable analog environments on Earth and the resources required to conduct research in those environments. The information gathered by these working groups would then be used as a framework for developing the sampling strategies and the technologies required to study each of the identified analog environments on Earth.

How can we use models to inform scalability, sampling and operations for analog environments?

In addition to direct in situ sampling, different modeling approaches can be useful and cost-effective tools both for determining whether a moon or planet is indeed a suitable Earth analog and for designing strategies to sample extraterrestrial analog environments. While even the most sophisticated earth system models are gross oversimplifications of reality, they can still provide useful information. For example, reconfigured earth system models like ROCKE-3-D that runs on NASA’s Discover supercomputer (Aleinov et al. 2019) can be used to determine if conditions on other ocean worlds are suitable to support life. Additionally, the Virtual Planetary Laboratory at the University of Washington develops and combines a variety of scientific models from many disciplines and with varying degrees of complexity to constrain habitability for newly discovered worlds. These models could be used to study exoplanets or other ocean worlds within our own solar system.

Slightly more complex hierarchical modeling frameworks allow the user to model a planetary system at different levels of complexity, based on the underlying knowledge of the system under investigation. One such model (Isca) has been used to model planets such as Earth, Mars, and Jupiter at different resolutions and with a different suite of processes (Thomson and Vallis 2019). More targeted models, such as the Titan Community Atmosphere Model (CAM), have been used to better understand highly specific processes such as the dune-forming wind fields on this large moon and how they are impacted by topography and torque (Larsen 2019).

Once models provide sufficient support that a particular ocean world has conditions suitable to support life, they can be used to test our understanding of the underlying physics, which will allow us to design better sampling strategies for analog environments, both here on Earth and on extraterrestrial ocean worlds. For example, ice sheet models (Farinotti et al. 2021) developed for Greenland and Antarctica can help target the most suitable location for drilling and subsequent sampling. All ice sheets flow, albeit slowly - and in some instances very slowly, and this motion together with any associated horizontal shear, needs to be accounted for when designing a sampling strategy, particularly for portions of the ice sheet that has not yet reached the ocean. Ice sheet models can provide valuable information about vertical stress gradients (due to differences in horizontal flow speeds at different depths within the ice) as well as temperature gradients (which control ice deformation) for an ice sheet of interest, aiding in the determination of appropriate sampling sites.

Models can also be used to scale field observations and site-specific measurements to those spatial scales that most are relevant for the space-based explorations that rely on either satellite-based or lander-based measurements (Schinder et al. 2011). In situ sampling of extreme environments on Earth is often a logistically difficult and expensive endeavor, resulting in collection of relatively few samples over fairly restricted time horizons. The use of 3D models allows us to synthesize these measurements into an appropriate geophysical framework, and to scale them up with respect to both space and time, so that we can gain a broader perspective of the analog environment of interest. Using models in this way allows us to convert static point measurements into time-dependent processes in multiple physical dimensions, resulting in a fuller understanding of the underlying physical processes.

Both earth and planetary scientists are critical to the development of appropriate analog models. Planetary models of chemistry and physics are based on models developed first for use in simulating processes on the Earth. Models of atmospheric dynamics, hydrothermal vent systems, ice sheet dynamics and thermodynamics, and sub-ice ocean interiors developed by earth scientists are being used by planetary scientists as a basis for developing analogous models for extraterrestrial ocean worlds. This is possible because many of the equations governing the fundamental physical and chemical processes here on Earth are the same as, or very similar to, those on other ocean worlds, so the models often only require simple adjustments to a few key parameters. For example, general circulation models (GCM) developed to describe atmospheric dynamics on Earth have been modified for use on other bodies in the solar system such as Mars (Wilson and Hamilton 1996, Forget et al. 1999, Rafkin et al. 2001, Richardson et al. 2007), Venus (Richardson et al. 2007), and Titan (Richardson et al. 2007, Lora et al. 2019). One such model that has proven especially useful for this purpose is the Weather Research and Forecasting (WRF) model, which was developed collaboratively by National Center for Atmospheric Research, the National Oceanographic and Atmospheric Administration, the US Department of Defense, and a number of research universities (Michalakes et al. 2004, Skamarock et al. 2005). This model, and others like it, can be run in 1, 2, or 3 dimensions and at resolutions ranging from meters to kilometers. Thus, earth scientists have an important role to play in providing many of the basic model frameworks for describing processes such as ocean and ice thermodynamics, fluid flow, and key chemical processes that can be modified for use on other ocean worlds. Earth scientists will also be required to identify those analog environments on Earth that are amenable to modeling and where lessons learned there can provide critical information and insights for developing analogous models for extraterrestrial ocean worlds.

In turn, the planetary science community can contribute the theoretical frameworks needed to translate earth system models to models of extraterrestrial ocean worlds, as well as critical observational data from missions such as Cassini-Huygens to constrain those models (Tokano 2009, 2013, 2019). Atmospheric dynamics such as cloud formation and precipitation can be detected using the suite of sensors like those on Cassini-Huygens (Turtle et al. 2018), as can surface topography (e.g., mountains, canyons, lake beds, channels, and dunes). This greater data quantity and quality from Titan has inspired planetary scientists to develop numerous GCMs of the Titan's climate system. These models allow planetary scientists to infer atmospheric processes such superrotation, circulation and chemistry of the middle atmosphere, tropospheric methane cycling, interactions of surface and atmosphere, and even Titan's paleoclimate (Lora et al. 2019). Because many of these modeling studies are largely independent, the planetary modeling community has increasingly relied on multi-model results and model intercomparison projects (Lora et al. 2019) to understand and account for potential model biases and structural differences to ensure that results are not model-dependent.

Utilizing analog environments on Earth can be an effective way to further conceptualize, develop, and parameterize models that may be suitable for extraterrestrial ocean worlds. The first step will be for earth and planetary scientists to agree on which environments on our planet represent suitable analogs for extraterrestrial environments. Once that decision is made, models of those environments can either be developed, or if possible, existing models refined, to simulate the critical processes driving that environment. Initial development and testing of these models for earth environments is necessary because if models are unable to simulate the critical processes driving analog environments here on Earth, they are unlikely to be effective tools to understand other ocean worlds. Once a model works well for a particular earth environment, the next step would be for earth and planetary scientists to determine what modifications need to be made to the model to make it suitable for simulation of other ocean worlds. After these modifications have been implemented and the model rigorously tested against available observational data from an extraterrestrial ocean world, the model can be used to for a variety of purposes on other ocean worlds, including testing our understanding of critical processes, identifying appropriate sampling strategies and locations, and determining which geophysical parameters may be the most important to design sensors to measure.

How can work at analog environments inform planetary protection strategies/needs?

The advent of space exploration has made the protection of Earth's environment and other solar system bodies from harmful contamination an important principle of high priority. Consequently, the development and implementation of planetary protection policies has taken place at both the national and international levels. Scientific advances have permitted the targeting of these policies to those few bodies thought to be capable of harboring life (extinct or extant), or processes relevant to prebiotic chemistry. This trend in increasingly targeted planetary protection is expected to continue as the exploration of ocean worlds of the outer solar system progresses, which is important given that planetary protection accounts for approximately 10% of the cost of a typical mission (Bearden and Mahr 2017).

Generally speaking, planetary protection policies address robotic missions to and from all types of solar system bodies (planets, moons, comets, and asteroids) and places these bodies into categories based on mission type, the likelihood of that body harboring life, and the probability that either organisms brought from Earth would survive on that body (forward contamination) or that material returned to Earth would pose a risk here (back contamination). However, based on existing knowledge and capabilities, only three objects are currently of serious planetary protection concerns: Mars, Europa, and Enceladus (National Academies 2018). Of course this may change as we learn more about the moons of the outer planets in our solar system.

Recent biological discoveries in analog environments on Earth related to extremophiles, biofilms, prions, and genomics are likely to be relevant to planetary protection science. Metagenomic analyses of organisms living in extreme environments on Earth (e.g., dry polar or desert environments, ice sheets, hydrothermal vents, frozen oceans) generate lists of archaeal and bacterial species and specific genes that are necessary to thrive in environments that are the closest analogues to other ocean worlds in our solar system. This type or research will facilitate a more targeted approach to planetary protection. Rather than treating all microbial species as a potential pathogen for extraterrestrial ocean worlds, it might be possible to target those microbes that are found in analog Earth environments that are most like the landing sites on icy ocean worlds, and to survey spacecraft assembly rooms for those organisms (Shtarkman et al. 2013, Abreu et al. 2016). In this way, information about the abundances of specific microbes with known environmental tolerances would increase our ability to implement a probabilistic approach to planetary protection for missions to the outer planets and their icy moons (DiNicola et al. 2018).

Currently, the icy body contamination requirement is that the probability of inadvertent contamination of an ocean or other liquid water body must be less than 1×10^{-4} per mission (NRC 2000, 2011, Sherwood et al. 2017, Lamy et al. 2018). Icy body contamination is defined as “the introduction of a single viable terrestrial microorganism into a liquid-water environment.” The instruments to be used on robotic missions to ocean worlds are decontaminated using a variety of methods (Meltzer 2011), including treatment by radiation (e.g., gamma radiation), chemicals (e.g., hydrogen peroxide), high temperature sterilization (e.g., autoclaving and dry heat), and lower temperature sterilization (e.g., hydrogen peroxide plasma). It must be noted, however, that these methods may not be completely effective. For example, hydrogen peroxide vapor sterilization does not impact organisms within enclosed volumes on spacecraft or enclosed within other materials. In addition, some extremophiles have been shown to exhibit radiation hardiness to the levels used for decontamination (5.5 Mrad) (National Academies 2018). Thus, the study of organisms from analog environments on Earth could provide for more robust testing of decontamination procedures, thereby increasing their effectiveness.

The development of planetary protection policy in the US is based on the Outer Space Treaty (OST), which states that all parties “shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination, and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter.” As of 2018, the OST had been ratified by 105 countries (and signed by 25 others), including all of the spacefaring nations. Technical aspects of planetary protection have been developed internationally by the Committee on Space Research (COSPAR), which is part of the International Council for Science (ICSU) that consults with the United Nations. COSPAR is a scientific organization whose purpose is to “provide the world scientific community with the means whereby it may exploit the possibilities of satellites and space probes of all kinds for scientific purposes, and exchange the resulting data on a co-operative basis.” It has been an effective forum for the development of international consensus on planetary protection guidance for science exploration missions (National Academies 2018).

Government organizations such as NASA formulate and implement planetary protection policies and procedures to be consistent with COSPAR planetary protection policy. To do so, NASA gathers scientific input from the Space Studies Board (SSB) of the National Academies of Sciences, Engineering, and Medicine, internal agency advisory groups, and consultants to the Office of Planetary Protection (OPP). To date, rules for planetary protection do not apply to the private sector. Given the increasing activity of the private sector in developing and launching space missions in recent years, it will be necessary to find ways to regulate and monitor their plans for implementing effective planetary protection protocols (National Academies 2018).

Planetary protection depends on identification of the thresholds for the survivability of microbes and development of methodologies to eliminate them. Therefore, both space science and earth science communities can contribute to the development of policies, procedures, and techniques to meet planetary protection requirements, and both communities can contribute to testing possible solutions in analog field sites.

In recent years, NASA's planetary exploration priorities have evolved in two directions: to place special emphasis on robotic exploration of ocean worlds (relevant to ocean worlds), and to develop a plan for sample return missions classified as "restricted Earth return" (not relevant to ocean worlds), notwithstanding the human exploration of Mars. In light of these priorities, modern biology, specifically the ability to sequence the genomes of hundreds of thousands of organisms, offers a scientific pathway to the future for development of planetary protection policy that would benefit from the participation of both earth and planetary scientists.

Unfortunately, to date, scientists affiliated with the NASA Astrobiology Institute, which have been active in studies relating to extremophile microbes on Earth and what sorts of biochemistry they use and on origin of life, have not been substantially involved in the planetary protection process. Hopefully, this will change after the recent recommendations by National Academies that studies, workshops, and brainstorming sessions that are organized by NASA and other space agencies (e.g., ESA and JAXA), as well as the SSB and COSPAR, and are intended to advise planetary protection policy makers, need to include a sufficiently broad range of microbiologists (National Academies 2018). This will require the development and implementation of mechanisms for creating partnerships between earth scientists and planetary scientists to test planetary protection solutions at field analog sites.

Technologies for In Situ and Remote Sensing Exploration of Ocean Worlds

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Exploration of Ocean Worlds across the solar system will be enabled by technological developments across a range of sensing methodologies. We review some of the state-of-the-art techniques from oceanography and planetary science that may inform sensing of the biological, geophysical, and chemical properties of Ocean Worlds (Fig. 4). This summary encompasses both large-scale synoptic views afforded by active and passive remote sensing to in situ autonomous sampling and biosignature detection methods, but is by no means exhaustive.

Orbital Technologies

Passive Optical Remote Sensing

Next-generation remote sensing instruments require advances in both passive and active sensing technologies to compare to some of the most sensitive oceanographic sensors that already exist (Tyack 2000; Madsen et al. 2005). These remote sensing techniques from air and space primarily use passive broad-spectrum illumination provided by the Sun coupled with sensitive push broom-style line array photodetectors fitted with narrowband filters to produce multispectral images (Irons et al. 2012). Hyperspectral remote sensing extends this concept further by using photodetectors and scanning spectrometers to resolve hundreds or even thousands of spectral bands (Eismann 2012). However, atmospheric conditions and the Sun's radiation distribution limit the frequencies of light and attainable signal-to-noise ratios (SNR) for multispectral imaging on Earth and other planets within our solar system.

Airborne and spaceborne sensor technology have advanced rapidly in the last few decades to include imaging spectrometers spanning ultraviolet to infrared wavelengths. Since water surfaces absorb more than land and sea ice, the light emerging from the water is dwarfed by Earth's atmosphere. Dedicated sensors with large dynamic ranges and longer integration times are often required to achieve the sensitivity needed for aquatic applications (Mouroulis et al. 2008; Muller-Karger et al. 2018). However, such considerations and corrections for atmospheric distortion of the remotely sensed signal may be different on other worlds depending on the media and distance through which the sensing occurs. Recently, NASA developed the FluidCam instrument and fluid lensing technology for robust imaging of underwater objects through refractive distortions from surface waves by exploiting surface waves as magnifying optical lensing elements, or fluid lensing lenslets, to enhance the effective spatial resolution and signal-to-noise properties of remotely sensed images (Chirayath & Li 2019; Chirayath & Instrella 2019; Chirayath 2018; Chirayath & Earle 2016). Fluid lensing has applications to remote sensing of Ocean Worlds with varying fluid interfaces. Miniaturized hyperspectral imaging spectrometers have been successfully developed to assess the broad range of spectral requirements for remote sensing of both snow/ice and water (Bender et al. 2018).

Hyperspectral imagery contains a "spectral fingerprint" that can assess the composition of inorganic and organic matter in the water or within snow and ice. Extensive hyperspectral algorithms have been developed to characterize properties of snow including grain size and radiative forcing by impurities (Bender et al. 2018). Hyperspectral data can also be used to detect different types of light-absorbing compounds like ancillary pigments in microalgae and different types of colored dissolved organic matter (e.g., humic materials) that are associated with algal life on snow or ice and in the ocean (Bracher et al. 2017). For example, major groups of phytoplankton can be differentiated in the global ocean (cyanobacteria, diatoms/dinoflagellates, haptophytes, and green algae) by diagnostic biomarker pigments that absorb different parts of the visible spectrum (Oranelli et al. 2017; Kramer & Siegel 2019). Methods have also been developed to quantify red and green snow algae using subtle shifts in spectral properties (Khan et al. 2020). In addition, hyperspectral reflectance contains information about the amount of scattering related to particle concentration and fluorescence of different types of pigments, such as chlorophyll *a* (Behrenfeld et al. 2009), among others (Dierssen et al. 2015). Underwater hyperspectral imaging has also been used to assess benthic flora and fauna on the seafloor from an autonomous vehicles with artificial lights (Johnsen et al. 2013; Dumke et al. 2018). Classification techniques from hyperspectral imagery are diverse and range from neural networks (Chirayath & Li 2019) to semi-analytical inversion models.

Active Optical Remote Sensing

In passive optical remote sensing, atmospheric conditions and the Sun's radiation distribution drive limitations on multispectral imaging on Earth. In aquatic systems, further bounds are introduced as only UV and visible bands of light penetrate the photic zone, or the first 100m of the clearest waters, the photic zone. As such, current passive multispectral/hyperspectral imagers are limited by ambient conditions along the optical path, ambient illumination spectrum, optical aperture, photodetector SNR and, consequently, relatively long integration times.

Active sensors produce and sense their own stream of light (e.g. Radio and Light Detection and Ranging (RADAR/LiDAR) and are generally flown on aircraft, although several space-based lidars have been launched. Lidar uses the round-trip travel time of a pulse of light to estimate distance to the seafloor (Dierssen & Theberge 2012) or to particle fields in the ocean (Hostetler & Skakuna et al. 2017). Aircraft-mounted lasers pulse a narrow, high frequency laser beam toward the earth and are capable of recording elevation measurements at rates of hundreds to thousands of pulses per second. Since they do not rely upon sunlight, Lidar systems can be operated at night. Lidars have long been successfully used to assess the vertical structure of aerosols and thin clouds (Winker et al. 2003). Space-based green lidars are commonly used to assess the temporal and spatial characteristics of ice sheet elevation changes. The most advanced active sensor in space presently is the Advanced Topographic Laser Altimeter System (ATLAS) on ICESat-2, a six-beam, photon-counting lidar operating at 10kHz providing high spatial resolution measurements of altimetry with applications spanning sea ice thickness, vegetation canopy changes and shallow water bathymetry (Markus et al., 2017).

Lidars can be used to measure backscattered light off of ocean particles (Behrenfeld et al. 2013), as well as fluorescence from chlorophyll and colored dissolved organic matter (CDOM) (Hoge et al. 2005). Although elastic backscatter lidar is effective at retrieving vertical profiles of particle concentration, it does not provide information about the particle composition (mineral or organic) (Hostetler & Skakuna et al. 2017). Applications of airborne lidar that also involve the use of fluorescence techniques with chlorophyll and CDOM provide more diagnostic information about particle content (Hoge et al. 2005). A significant leap in retrieval accuracy and particle information is also achieved with a high-spectral-resolution lidar (HSRL) which can provide an estimate of spectral light attenuation in the water column Hostetler & Skakuna et al. 2017). Spectral light attenuation has long been used in oceanographic studies to estimate absorption properties of pigments and other organic matter in ocean waters (Smith & Baker 1978). New research in subsea lidar systems from ships that couple backscattering measurements with linear depolarization also has relevance to detecting the vertical distribution and optical properties of suspended ocean particles, including optical measurements related to absorption and the index of refraction of particles (Zimmerman, Sukenik & Hill 2013; Collister et al. 2018).

Active remote sensing technologies such as radar and lidar are largely independent of ambient illumination conditions, provided sufficient transmitter irradiance over background, and advantageously contend with attenuation along the optical path by exploiting phase information using heterodyne receivers. Thus, hardware requirements for receiver sensitivity, aperture and SNR can effectively be relaxed given increased transmitter power (up to MW of power in the case of radar). Recent advances in lidar have also enabled multiple wavelengths of laser diodes to be used simultaneously in green and two infrared bands to achieve a 'color' lidar point cloud (Briese et al. 2013; Briese et al. 2012). MiDAR, a recently-patented NASA active multispectral remote sensing and optical communications instrument technology, is also helping to create a new generation of multi/hyperspectral active remote sensing systems (Chirayath & Li 2019; Chirayath 2018; McGillivary, Chirayath & Baghdady 2018; Chirayath 2018). MiDAR is also designed with fluid lensing compatibility, helping to extend the depth range of the passive NASA FluidCam instrument to be used in underwater applications for entirely light-limited environments (Chirayath & Li 2019).

Synthetic Aperture Radar (SAR) is an active radar instrument application where a series of radar signals are sent from an observing platform (spacecraft, airplane), they bounce off the surface, and then are received by an antenna to build up an image that is viewed at radar wavelengths (Henderson & Lewis 1998). The returned signal is referred to as backscatter, and an SAR image shows the various amounts of backscatter. The amount of radar backscatter is sensitive to the grain-size roughness of materials at the scale of the radar wavelength, angular faces that reflect radar energy back (or away) from the receiver, volume scattering, dielectric constant of the material, and the presence of dielectric constant changes (layering). Due to its dependence on roughness and physical parameters, radar backscatter provides complementary information than regular visible or infrared spectroscopy. Radar wavelengths are also longer than visible and infrared wavelengths (usually radar is on the order of cm to 10s of cm), and thus interrogate deeper into the surface than visible spectroscopy, on the order of 10s of cm, with the exception of liquid water.

Planetary SAR has been useful on worlds that have thick or obscuring atmospheres that make shorter-wavelength imaging not practical, such as Venus and Titan (Ford, J.P. L. & States 1993; Elachi et al. 2005; Elachi et al. 2006; Elachi et al. 2004). At Titan, SAR by the Cassini spacecraft was used extensively to examine the surface of Saturn's haze shrouded moon Titan (Lopes et al. 2019). SAR was able to interrogate surface morphologies and determine structures such as dunes, dissected plateaus, craters, lakes, and channels at high resolution. The SAR data was used to define Titan's terrain unit classification system and enabled a global geological map to be constructed (Malaska et al. 2016; Lopes et al. 2020).

Other instrument techniques include microwave emissivity, which is a passive technique where microwave (radar) energy is detected by an antenna. This technique can also be performed during SAR acquisition, when signals are not being actively received, or at larger distances where SAR is not practical. Microwave emissivity uses natural radio emission to determine brightness of a terrain. When coupled with an understanding of the physical temperatures, it can provide information on grain size, volume scattering, and material properties (Janssen et al. 2009; Janssen et al. 2016; Le Gall et al. 2016). For Titan, many of the terrains had a characteristic microwave emissivity that allowed differentiation between terrain units and classification between organic terrains and icy terrains (Malaska et al. 2016; Malaska et al. 2020).

Ice & Ground Penetrating Radars

Ice penetrating radar sounding is a primary geophysical method for the subsurface observation of terrestrial ice sheets and ice shelves (Schroeder et al. 2020). It has also played a leading role in the subsurface exploration of Martian (Seu et al. 2007; Jordan et al. 2009) and Cometary (Kofman et al. 2015) cryospheres and is included in the payloads of planned missions to the Ocean Worlds of Ganymede (Bruzzone et al. 2011) and Europa (Blankenship & Young 2018). Recent advances in radar sounder data analysis have enabled improved characterization of subglacial (Carter et al. 2007; Jordan et al. 2018) and englacial (Chu, Schroeder & Siegfried 2018) water systems as well as ice shelves (Peters et al. 2007; Grima et al. 2019) and grounding zones (Christianson et al. 2016) which can be adapted to the exploration of Ocean Worlds ice shells for detection and characterization of extant liquid subsurface water (Culha et al. 2020; Michaelides & Schroeder 2019). Similarly new approaches to constrain the attenuation (Hills et al. 2020), temperature structure (Macgregor et al. 2015), and advection/melt-rates of (Winebrenner, Kintner & MacGregor 2019) of terrestrial ice sheets stand to constrain the thermophysical structure of ocean-world ice shells (Kalousová, Schroeder & Soderlund 2017). Finally, stationary active (Nicholls et al 2015; Kendrick et al. 2018) and/or passive (Peters et al. 2018) radar sounders offer the ability to create time-series observations of subsurface conditions (Romero-Wolf et al. 2016) from an ocean-world lander. Adapting and expanding this rich array of terrestrial radio glaciological techniques to the exploration of Ocean Worlds stand to dramatically increase the subsurface geophysical capabilities of both scientific communities.

Plume sampling

For sampling plumes at actively venting worlds, such as Enceladus or possibly Europa, a plume fly-through mission while at orbital speeds is a potential option. Mass spectrometry (MS) using impact-induced ionization is an effective means of detecting inorganic and organic molecules entrained within ice grains, though care must be taken when selecting sampling speeds. Cassini spacecraft instruments sampled the Enceladus plume gases and grains at hypervelocity (7-17km/s) during multiple flyby encounters, and detected H_2, NH_3, CH_4, Ar, silica nanograins, salts, and simple and complex organic molecules (Waite et al. 2006; Waite et al. 2009; Postberg et al. 2008; Postberg et al. 2009; Postberg et al. 2011; Hsu et al. 2015; Sekine et al. 2015; Postberg et al. 2018). Recent developments have focused on developing advanced instrumentation to determine biotic and abiotic distributions (Klenner et al. 2020) and predicting optimal encounter velocities, which are thought to be 3-6km/s for amino and fatty acids (Klenner et al. 2020). The SUrface Dust Analyzer (SUDA) and the MAss Spectrometer for Planetary Exploration /Europa (MASPEX) aboard the Europa Clipper will analyze dust sputtered from the moon’s surface (Srama et al. 2004; Waite et al. 2019). A return mission to Enceladus to analyze the plume with particular focus on biosignature detection and quantification (Reh et al. 2016) and a mission to Triton (Frazier et al. 2020) to determine if it hosts a subsurface ocean and to characterize its plumes are in the concept stages.

Plume fly-through sampling and analysis tools are under development and testing in terrestrial settings. For example, LACROSS (Life Analysis, Capture, and Retention on an Orbiting Saturn Spacecraft) is a Raman instrument concept designed to minimize sample alteration and maximize signal-to-noise for analysis of plume ices in Ocean Worlds (Sobron et al. 2018). Plates have been designed to capture plume material (New et al. 2020; Mathies et al. 2017) and are shown to be capable of collecting particles containing organics at velocities of up to 1-2km/s. Organic molecule capture efficiencies at these velocities range from 10-50% for more than a quarter of the particle impacts on the plate. A funnel collector could be positioned on an external surface of the spacecraft to collect plume material at Enceladus or other planetary body exuding icy material (Eigenbrode et al. 2018; MacKenzie et al. 2020). The material would flow to a collection system at the base of the funnel where it would be captured and transferred to an internal sample handling system for delivery to internal instrumentation for sample preparation and analyses. One such funnel, the EFun collector (Adams et al. 2018), is in development to capture ice particles.

In Situ Technologies

In situ technologies for Ocean Worlds spans systems and instruments that operate above, on, under, or within ice, slush, and fluids. Terrestrial oceanographic measurements and sensing technologies focus on determining biological, chemical, and physical properties from a variety of sensing techniques. Measurements and sensing technologies relevant to Ocean Worlds are summarized here.

Robotic Platforms, Access & Sampling Technologies

Significant progress has been made in the past decade with underwater remotely operated or autonomous underwater vehicles (ROVs and AUVs) (Roberts, Shedd & Hunt Jr. 2006), unmanned surface vehicles (USVs) (Mordy et al. 2017), profiling floats (Roemmich & Gilson 2009), and unmanned aerial vehicles (UAVs) to characterize the seafloor, ocean surface, and ocean column over large geographic areas. Three-dimensional photogrammetry, active acoustical methods, and *in situ* water column measurements have been used with remarkable effectiveness on such platforms to narrow the gap in observational capacity between terrestrial and aquatic systems, revealing mesophotic and deep sea habitats with unexpected biodiversity and ecological complexity (Pizarro, Eustice & Singh 2004; Bodenmann, Thornton & Ura 2013).

Sub-ice-shelf instrumentation and ROVs have been deployed through hundreds of meters of ice using hot-water and electro-mechanical drilling methods. For example, the IceFin vehicle was deployed, most recently in 2019-2020 beneath approximately 600m of ice using hot-water drilling technology similar to that described by Makinson and Anker (Makinson & Anker 2014). Fiber-optic instrumentation for ice and ocean temperature measurement was deployed through 193m of ice using an electro-mechanical drilling method (Tyler et al. 2013). However, logistical costs for these methods increase rapidly with increasing ice thickness and decreasing ice temperature. This has spurred development of ice melt probe technology, in which modern materials and methods are used to make melt probes far more reliable than the first such probes (which were developed in the 1960s and 70s) (Cwik et al. 2019; Winebrenner et al. 2016; Oleson et al. 2019). Melt probe technology is thus now among the candidates for outer solar system flight hardware (Howell et al 2020).

A number of subsurface access technologies have flown on previous missions and are in development in terrestrial settings. Underwater sampling tools include flow-through systems developed for terrestrial oceans including McLane Remote Access Sampler (RAS), AquaLAB (Dodd et al. 2006), and MBARI 3G-ESPG. Drills used to explore shallow subsurface environments have been flown to Mars, e.g. Phoenix & InSight, and the TRIDENT drill is a 1m class shallow drill in development for lunar access. For deeper access, drills currently in development for Moon and Mars missions in the 2020's aim to access 10m and deeper and can inform OW technology developments (Dachwald et al. 2020). Other technologies currently being developed for Ocean World access feature NASA's Scientific Exploration Subsurface Access Mechanism for Europa (SESAME) program include hot water jet drilling (e.g. VALKYRIE (Stone et al. 2018)), mechanical and hybrid thermo-mechanical drills (e.g. SLUSH (Zacny et al. 2018), an ice melt probe (Cwik et al. 2019; Winebrenner et al. 2016), and a cryobot combining these methods (Cwik, Zimmerman & Smith 2019) and through-the-ice communication (e.g. Europa STI (McCarthy et al. 2019)). Significant work has been done to understand realistic concepts for operation of a planetary cryobot and the corresponding system requirements, including the NASA Compass study into a Europa Tunnelbot (Oleson et al. 2019), the Jet Propulsion Laboratory's Probe Using Radioisotopes for Icy Moons Exploration (PRIME) architecture study (Fleurial et al. 2019).

Ice and soil sample collection technologies have been developed for landed technologies for Mars missions and for Europa, mostly consisting of surface disruption or cutting tools and scoops (Scoops: Phoenix mission, Honeybee; Europa Lander scoop, JPL; Rasps (Badescu et al. 2019), JPL; Pneumatic transfer: Zachny, Honeybee), and also plume flythrough collection devices including funnels and impact plates (e.g. Adams, JHU APL). Milli- and micro-fluidic systems are in development to bring in and process ice to liquid samples. NASA ICEE2 grants are particularly focused on sample processing and analyses for a Europa Lander type *in situ* mission to search for biosignatures. Other instrument development grants (PICASSO, MatISSE, COLDTech) also focus on Ocean World *in situ* technologies.

Planetary seismology provides a direct probe of interiors. Europa is thought to have a global subsurface ocean in contact with a mineral-rich silicate interior—one of the Ocean Worlds in the outer solar system with the greatest potential for hosting life. Investigations of Europa's liquid water have focused on determining the thickness of the ice crust and corresponding depth of the subsurface ocean—with estimates ranging from 5 to 50 km (Pappalardo et al. 1998, Greenberg et al. 1999; Nimmo, Giese & Pappalardo 2003; Tobie, Choblet & Sotin 2003; Showman & Han 2004; Bray et al. 2014). Additional habitable environments may be smaller, transient subsurface lakes within Europa's ice shell (Schmidt et al. 2011) that would be a very different niche for life. Understanding the size and location of such perched environments would inform their habitability and accessibility. Knowledge of ice/water layer interfaces is also important as undulations in the basal ice or 'slush' layer could suggest diapirs (O'Brien, Geissler & Greenberg 2002; Goodman et al.

2004) that indicate the location of hydrothermal vents on the ocean floor (Collins et al. 2000; Thomson & Delaney 2001). Determining the ice depth to a subsurface ocean and any intermediate water deposits is a priority for NASA's Europa Lander concept—to assess habitability and help prioritize areas of future exploration (Hand et al. 2017).

In the terrestrial cryosphere, seismic methods are an established way to determine ice thickness and discriminate between sub-ice materials (Clarke & Echelmeyer 1996; Blankenship et al. 1987). On Europa, long period (<1 Hz) seismic data can help constrain the depth of the ice crust, ocean, and global structure (Kovach & Chyba 2001; Panning et al. 2006; Stähler et al. 2018), while high-frequency events (>1 Hz) will aid investigations of local structure and identify nearby deposits of liquid water (Lee et al. 2003). Seismic measurements may also provide constraints on the salinity of the ocean (Vance et al. 2018).

Similar science investigations might be usefully deployed on Saturn's moon Enceladus, which also has a global ocean and signs of hydrothermal activity (Choblet et al. 2017). In addition, a seismic experiment could help in determining the plumbing the eruptive jets around the south-polar Tiger Stripe features (Vance et al. 2018). On Saturn's moon Titan, the seismic experiment on NASA's planned DragonFly mission can help to determine the structure and composition of near-surface organics and underlying ice and may be able to determine the thickness of the underlying liquid water ocean (Lorenz et al. 2019). It may also be capable of detecting wind-driven waves on Titan's northern seas (Stähler et al. 2018).

Biological and Physical Sensing Technologies

Oceanographic sampling technologies include automated water samplers for marine chemistry (Enochs et al. 2020), oceanographic time series (van der Merwe et al. 2019), deep sea microbial sampling (Peoples et al. 2019), and for automated eDNA sampling (Nguyen et al. 2019; Yamahara et al. 2019). Sampling technologies also include biodiversity sampling systems relying on settlement plates such as the autonomous reef monitoring structures (ARMS) that can reveal marine biodiversity, cryptic biodiversity, community structure, and microbial community diversity when using high-throughput DNA sequencing methods (Leray & Knowlton 2015; Pavloudi et al. 2019; Pearman et al. 2019).

Autonomous sensor technology is well established for assessing water quality across Earth's aquatic ecosystems (Greb, Dekker & Binding 2019). including measurements of the optical properties of different dissolved and particulate matter in the aquatic habitats (Werdell et al. 2018) and radiative transfer models to interpret the mixtures of these materials (Mobley 1995; Elsevier 2017; Twardowski & Tonizzo 2018). The color of light reflected from or within a water body is related to the absorption and scattering properties of different types of dissolved and particulate matter, as well as inelastic processes like Raman scattering and fluorescence. Absorption of light by dissolved humic substances and nonhumic substances such as pigment-like components, amino acid or protein-like components and small colloids, known as colored dissolved organic matter (CDOM) or gelbstoff, has a distinct spectral shape and can be measured optically both from space and in the field. Measurements of particulate absorption can be used to assess living phytoplankton of a wide range of sizes and shapes, as well as larger detritus from living cells, suspended minerals and sediment. In addition, *in situ* laser diffraction measurements that can be relevant to finding the size distribution related to resuspended plumes of sediment and algal blooms in water (Andrew, Nover & Schladow 2010; Buonassissi & Dierssen 2010), volume scattering measurements which can help deduce the index of refraction of particles (Sullivan et al. 2005; Zhang, Twardowski & Lewis 2011), and subsea lidar systems (Collister et al. 2018). When seeking life on other Ocean Worlds, such optical measurements can provide direct evidence of the types of organic and inorganic matter found within the ocean world.

To perform *in situ* detections of biosignatures at planetary environments, several instruments are in development including the Enceladus Organic Analyzer for detecting amino acids (Mathies et al. 2017), Search for Extra-Terrestrial Genomes (SETG) instrument for nucleic acid detections (Bhattaru et al. 2019), Europan Molecular Indicators of Life Investigation (EMILI) for detecting molecular biosignatures (Brickerhoff et al. 2018) and others. Novel, small, low-mass and low-power nanopore devices have been developed commercially that can detect, and in some cases, characterize Lipidic Cubic Phases (LCPs) including DNA, RNA and proteins as they pass through the pore (e.g. MinION (Jain et al. 2016). This technology has been demonstrated on the International Space Station (Castro-Wallace et al. 2017), but uses biologic protein pores which are susceptible to degradation over long space missions and in high radiation environments. Synthetic nanopore devices are in development (Xue et al. 2020) that would be more robust to these conditions and can form pores of various sizes to assist with detections, but have the challenge of increased flow-through speeds that reduces sensing resolution.

In situ instrumentation for remote locations has been developed that allows emplacement and monitoring while being embedded in ice. On Earth, these instruments can be used to measure the electrochemical parameters of meltwater and reveal the residence time and likely chemical weathering history of percolating meltwater, as well as determining links between sub-ice pressure and ice dynamics.

Raman Spectroscopy is an excellent tool to analyze biosignatures. Raman can be used to detect and (semi)quantitate minerals and organic compounds, and it is particularly sensitive to potential biominerals such as silica, carbonates, sulfates, magnetite, and metal oxides. Raman can also be used to detect salts (e.g. chlorides; sulfates), silicates, metals, metal (oxy)hydroxides, volatiles (e.g. CH_4; CO_x) and radiation products (e.g. H_2O_2 O_2) (Nakamoto 2008). This ability for broad chemical characterization greatly increases confidence in interpretation of the origin of minerals and organics. Many of these compounds also help constrain habitability parameters, such as the extent and style of water-rock interactions in the ocean; ocean pH, salinity, and redox state; the presence of bioessential elements (CHNOPS); and the availability of red-ox couples that life can use as an energy source. Raman instruments are flying in two upcoming missions to Mars (SHERLOC and SuperCam on NASA's Mars 2020 rover); and RLS on ESA's ExoMars rover; and are considered for flight in the Europa Lander Mission. Currently, instruments in development, such as the *in situ* Spectroscopic Europa Explorer (iSEE), will further increase Raman sensitivity for biosignature detection purposes (Sobron et al. 2018; Bar-Cohen & Zacny 2020).

Fluorescence and Raman spectroscopy can reveal information about the electronic and rovibrational states of a molecule. Molecules that fluoresce include aromatic amino acids such as tryptophan, tyrosine, and phenylalanine as well as aromatic molecules such as benzene, naphthalene, and other polyaromatic hydrocarbon species (Bhartia et al. 2008). Fluorescence also has the advantage of being very sensitive with low limits of detection and quantitation. Raman spectroscopy determines rovibrational states based on functional group atom-atom vibrations, rotations, and stretching. In general, Raman is less sensitive when compared with fluorescence spectroscopy; this can be enhanced by using excitation wavelengths that are preferentially absorbed by the molecule, a technique is referred to as fluorescence-enhanced Raman (Sappers et al. 2019). The use of Deep UV excitation allows absorption of UV photons by aromatic molecules, which provides both fluorescence and fluorescence-enhanced Raman signals (Bhartia et al. 2008).

The current state-of-the-art instrument for planetary applications is the Mars Perseverance SHERLOC instrument, currently on its way to Mars (Beegle et al. 2015). The SHERLOC instrument is able to map a 7x7 cm surface with a 50 µm spot laser and acquire both fluorescence and Raman spectra. A companion instrument (WATSON) attached to the planetary deep drill has been demonstrated in the Greenland Ice sheet for down-borehole applications in ice and rock and uses a similar strategy, but the optical path and component have been reconfigured to fit into a tube (Eshelman et al. 2019; Malaska et al. 2020). While the SHERLOC instrument is designed for surface reflectance interrogation, the transparent nature of ice and evaporite deposits (gypsum, halite) allows the WATSON instrument to examine into the interior of the matrix (Eshelman et al. 2019; Carrier et al 2019).

Communications

Relaying data from underwater instruments to and through the surface at bandwidths common to airborne and spaceborne platforms has remained a significant obstacle to sustained deep sea mapping on Earth (McGillivary, Chirayath & Baghdady 2018). Robotic explorers on Ocean Worlds will need to communicate with one another and/or an orbital platform from challenging environments on a dynamic icy surface, under ice, and submerged in fluid or slush.

Recent developments have allowed wireless radio frequency sensor platforms to return data from the bed to the ice surface. 'Cryoegg' is a spherical, very high frequency subglacial probe that has been proven through 1.4km of Greenland ice (Prior-Jones et al. 2020). Its 15cm diameter allows deployment via standard ice core boreholes, followed by free-roaming in subglacial meltwater channels. It has been tested in moulins (Bagshaw et al. 2014) and deep boreholes (Prior-Jones et al. 2020) in Greenland, with data returned in real time from a depth of 1.4km. The current Cryoegg instrument measures simple electrochemical parameters (temperature, pressure, electrical conductivity), but the sensor suite is interchangeable and more complex biogeochemical sensors may be incorporated into the platform (for example, pH or dissolved oxygen).

Two other wireless systems have been tested in subglacial environments: The WiSe (Wireless Subglacial Sensing) system (Smeets et al. 2012) could return a signal through 2.5km of ice in Greenland. The Glacsweb system was also borehole-deployable, with a lozenge-shaped probe designed to lodge in subglacial till. Planetary applications of these systems would allow emplacement and sensing in the deep ice crusts of Ocean Worlds for long duration monitoring of changing chemical conditions, for example, during crustal flexure due to tidal cycle.

Finally, NASA's recently developed MiDAR instrument (Chirayath & Li 2019; Chirayath 2018), an active multispectral/hyperspectral system, is capable of imaging targets with high-intensity narrowband structured optical radiation to measure an object's spectral reflectance, image through fluid interfaces, such as ocean waves, and demonstrated simultaneously transmission of high-bandwidth data optically through an air-ocean interface and underwater (McGillivary, Chirayath &Baghdady 2018).

Looking forward, NASA has recently selected five through-ice communications technology teams for planetary exploration for further funding within the 2020 Concepts for Ocean worlds Life Detection Technology (COLDTech) program. These include both standalone and hybrid devices that consider fiberoptic tethers and free space technologies. This comprises investments in radio-frequency, acoustic, and magneto-inductive transceivers.

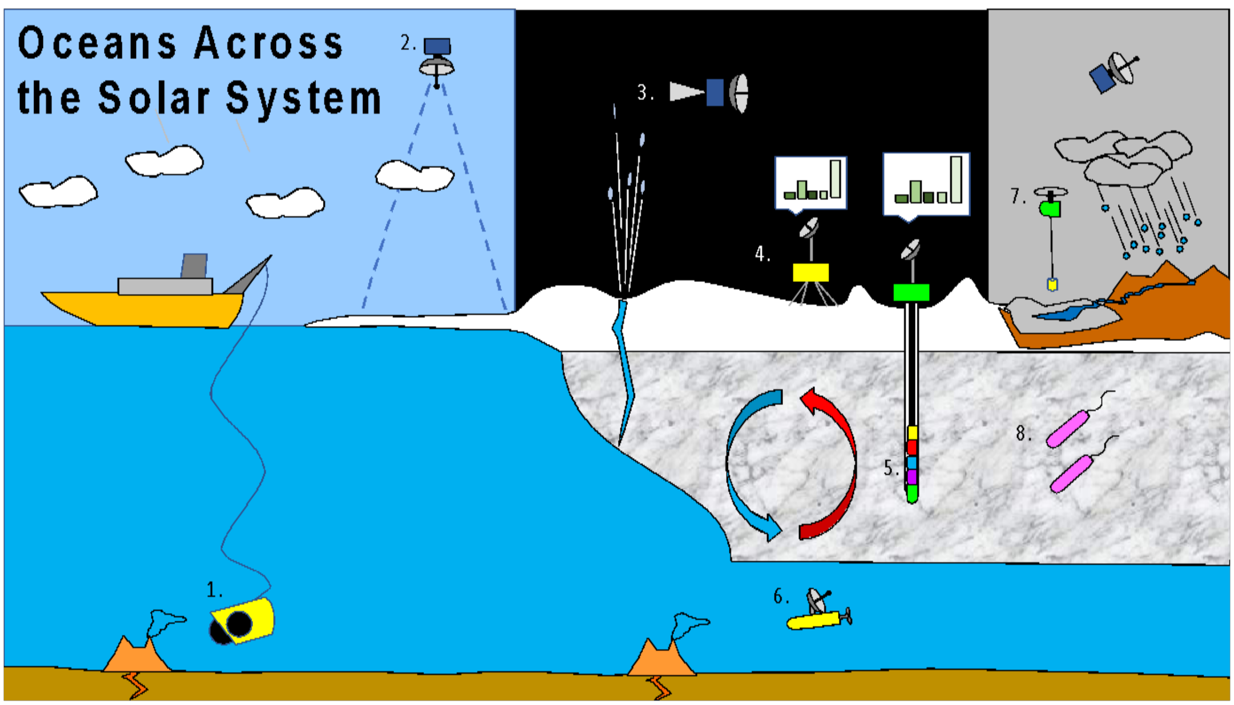

Fig. 4: Sample technologies for remote sensing and in situ exploration of Ocean Worlds. 1) Tethered robotic exploration; 2) Satellite based active and passive optical remote sensing; 3) Plume sampling; 4) Communications; 5) Planetary drilling; 6) ROVs and AUVs; 7) UAVs; 8) In situ ice emplacement and tunneling.

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