

Contribution of Non-Water Ices to Salinity and Electrical Conductivity in Ocean Worlds

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Key Points:

- Accreted CO₂ and NH₃ can significantly increase the salinity and electrical conductivity of deep oceans
- Water to rock ratio and ammonia abundance drive the concentrations of carbonate and bicarbonate ions in solution
- Predicted electrical conductivity estimates can be used to plan future ocean search missions at icy moons and dwarf planets

Abstract

Modeling of the electrical conductivity (EC) of icy moon oceans has previously assumed that chloride, sulfate, and other ions released from rock leaching are the main solutes and carriers of electrical conductivity. Here, we show that accreted volatiles, such as carbon dioxide and ammonia, can add a significant fraction of solutes in bodies whose volatile content was in part supplied from cometary materials. These volatiles can increase the EC of aqueous solutions above 1 S/m. Our salinity and EC estimates can serve as a basis for planning future magnetometer investigations at icy moons and dwarf planets. In particular, oceans expected in some of the Uranian satellites and Neptune's satellite Triton could have EC above 3 S/m as a result of accretion of large abundances of carbon dioxide and ammonia, even if rock leaching during water-rock separation was limited, and chlorine and sulfur abundances may be at CI carbonaceous chondritic levels.

Plain Language Summary

Searching for deep oceans in icy bodies is a major driver of planetary exploration. Magnetometry is used to detect electric current in deep oceans generated by a varying magnetic field, from a giant planet or solar wind, as Galileo did at Jupiter's moon Europa. Previous studies have assumed that the salinity of deep oceans is determined by the leaching of major elements from accreted rock, which generally yields brackish and low electrical conductivity solutions. We show that carbon dioxide, an abundant ice in the outer solar system, could contribute a significant fraction of solutes (carbonate and bicarbonate ions) in ocean worlds, regulated in particular by the presence of ammonia. The latest solar system dynamical models predict that dwarf planets and most icy moons accreted ices rich in carbon dioxide and ammonia. Hence, carbonate-rich oceans in these bodies may display a magnetic signature detectable by future spacecraft missions.

1 Study Motivation

The detection of induced magnetic fields has proven to be the most definitive approach to detecting water oceans in icy bodies (e.g., Khurana et al. 1998; Zimmer et al. 2000). In general, the magnetic field characteristics depend on the combination of the ocean thickness and electrical conductivity (EC). The electrical conductivity is an important parameter because it is related to the ocean's salinity (Vance et al. 2021). Salinity is defined as the mass of dissolved solids per kilogram of water. Note that only dissolved ions contribute to the solutions' conductivity. Knowledge of salinity can help to constrain both the habitability and geochemical evolution of ocean worlds.

The classical approach is to assume that ocean salinity is dominated by constituents that were leached from rock. This leads to endmember compositions of NaCl or MgSO₄ (e.g., Hand et al., 2007; Vance et al. 2020). However, it is increasingly evident that volatiles can play a larger role in the ionic chemistry of ocean worlds than previously considered. CO₂ and (bi)carbonate ions are major species in a plume sourced from the subsurface ocean of Enceladus (Postberg et al., 2009;

Waite et al., 2017). Glein and Waite (2020) emphasized the important role played by carbonate in that moon's chemistry. Carbonates have also been suggested as contributors to the salinity of Europa's ocean (e.g., Zolotov and Shock 2001). The most abundant primordial (e.g., cometary) species that can directly produce carbonates in liquid water environments is CO₂. While organic carbon oxidation can also generate CO₂ for carbonate formation, high ¹³C/¹²C ratios of carbonates in carbonaceous chondrites implicate CO₂ ice as a significant source of carbonate carbon (Fujiya et al., 2019). In this respect, it is relevant that CO₂ has been observed on the surface of Triton (Cruikshank et al., 1993).

Ammonia is another cometary volatile that has affected the chemistry of ocean worlds. Enceladus' plume gas contains NH₃ (Waite et al. 2017). There is spectroscopic evidence for the presence of some form of ammonia on Pluto's surface (Dalle Ore et al. 2019). The low ¹⁴N/¹⁵N ratio of Titan's atmospheric N₂ indicates that ammonia was accreted and participated in early chemical processes (Mandt et al. 2014). Some of this ammonia could still exist in Titan's subsurface ocean, but in the form of ammonium salts. A source of dissolved species beyond those that would be released from rock is apparently needed. Salinity estimates for Titan's ocean may be derived from the inversion of the tidal Love number *k*₂ (e.g., Durante et al. 2019). However, estimates so far suggest high ocean densities, up to 1350 kg/m³, at the base of the ocean (accounting for pressure). On the other hand, modeling of the ocean salinity as a result of leaching of major elements from rock yields a salinity of ~1 wt.% (Leitner and Lunine 2019), or a fluid density of ~1200 kg/m³ at the base of the ocean. Brasse et al. (2017) emphasized that Titan's ocean could be an ammonium-carbonate-bearing system, which is also the case for Ceres (Castillo-Rogez et al. 2018; Raponi et al. 2019). Carbon dioxide and NH₃ have been found on several of the Uranian moons in association with geological features (e.g., Cartwright et al. 2020 and references therein), which supports an endogenic origin.

The combination of CO₂ and NH₃ in water is of special relevance, as these species react with each other and water to produce predominantly dissolved ammonium bicarbonate in moderately alkaline environments hosted by ocean worlds (Kargel 1992; Zolotov 2007; Castillo-Rogez et al. 2018) (see Figure S1) via



The potential to produce ions from non-water ices is not a new topic of research; however, little systematic work has been done on the contribution of solutes derived from accreted ices to EC values. Thus, our current understanding of the links between ocean composition, salinity, and EC is incomplete.

Here, we quantify the impact of major volatiles on the salinity and EC of ocean worlds in support of future electromagnetic field investigations at these bodies, as currently planned for, e.g., JUpiter

ICy moons Explorer and Europa Clipper, and under consideration for missions to the icy giant systems and Ceres. The whole geochemical system is considered, not just rock leaching or the CO₂-NH₃-H₂O ternary. Water-rock interactions and the fate of accreted volatiles are all tracked together. We perform geochemical modeling (Section 2) to derive salinity for a range of plausible compositions and environmental conditions prior to concentration as a consequence of ice shell freezing (Section 3). Implications for future observations are addressed in Section 4.

2 Materials and Methods

We assess the fate of primordial volatiles in oceans using the *Geochemist's Workbench* (GWB) (Bethke 2007) and especially the React application, building on previous work (Castillo-Rogez et al. 2018; Glein and Waite, 2020). GWB is a commercial suite of geochemical modeling tools. It uses databases of thermodynamic equilibrium constants to determine chemical equilibrium of solutions that may involve a variety of volatiles. GWB can describe a wide range of conditions relevant to ocean worlds. However, the default pressure of 1 atm. Pressure effects on aqueous equilibria from 1 to 5000 bar were found to be insignificant compared with variation caused by other parameters (see Figure S2 for an example). We use a temperature of 0°C, which corresponds to the melting temperature of pure water ice. To first order, this is appropriate because oceans in the outer solar system are covered by ice. Generalized conductivity models (see below) do not exist at sub-zero temperatures. We use the thermo.com.V8.R6+ thermodynamic database that is largely based on the database used by SUPCRT92 (Johnson et al., 1992). It contains the volatile compounds of interest as well as broad ranges of minerals, aqueous inorganic species, and organic compounds.

GWB computes electrical conductivity using the approach by McCleskey et al. (2012), which is suitable for ionic strengths up to 0.7 mol/kg over relevant ranges of temperature (0–95 °C), pH (1–10), and conductivity (0.03–7 S m⁻¹). The empirical relationships (EC as a function of temperature and ionic strength) at the basis of this method were derived from conductivity measurements obtained for ~30 electrolytes over a wide range of conditions. The equations were then coupled to a geochemical speciation model. McCleskey et al. (2012) found that the predicted conductivity is accurate to within ±5% of measurements.

Key parameters driving the evolution of the system are (1) volatile concentrations; (2) the bulk chemistry of rock; and (3) the extent of aqueous alteration of rock.

The initial volatile composition of ocean worlds depends on an object's accretional environment. Assuming that comets are relatively pristine remnants of outer solar system building blocks, the process of accretion implies that the initial volatile composition of larger solid bodies is likely to be of cometary nature (e.g., Triton, Shock and McKinnon 1993). In the case of the Jovian satellites, the origin of their volatiles is not well constrained, but could have been sourced from a reservoir of planetesimals between Jupiter and Saturn (Batygin and Morbidelli 2020). We consider cometary volatile abundances from the review by Mumma and Charnley (2011) as a standard reference.

However, no single composition can be adopted because comets are compositionally diverse. We focus on CO_2 and NH_3 in this work because they are the most abundant cometary volatiles that can easily participate in acid-base reactions that affect electrical conductivity (see Section 3 for other volatiles). The concentration of CO_2 in comets can be > 20 wt.% relative to H_2O (e.g., Ootsubo et al. 2012). Ammonia abundances measured at comets are < 1.5 wt.%. However, the recent discovery of ammonium salts in comet 67P/Churyomov-Gerasimenko (Altwegg et al. 2020; Poch et al. 2020) and comets in general (Mumma et al. 2019) indicate that potentially a greater amount of NH_3 condensed in planetesimals. The exact abundance of ammonium salts in comets is not well constrained but estimated to be a few percent (Poch et al. 2020) to 5–10 wt.% of the rocky material (Mumma et al. 2019). We capture much of the reported variability and current uncertainty by varying the amount of CO_2 input to the system from 0 to 10 wt.% and that of NH_3 from 0 to 5 wt.%.

The adopted rock composition is based on the elemental composition of CI carbonaceous chondrites (without organic matter) (see Castillo-Rogez et al. 2018 for more detail on input to *GWB*). These objects are thought to be relevant to bodies formed beyond Saturn's orbit (Desch et al. 2018). A canonical abundance (680 ppm) of chlorine is included in the model rock (after Wasson and Kalleyman 1988 and consistent with Lodders 2021).

We use water/rock ratio (W/R) to represent reaction progress. It is defined as the initial fluid over reacted rock mass ratio (e.g., Seyfried and Bischoff 1981). One can think of the ocean system as initially being all fluid. As more of the rock inventory equilibrates with the fluid, W/R decreases. In the limit of total equilibrium, the model's W/R converges to the bulk W/R. This path toward chemical equilibrium is presumed to begin during ice melting that enables differentiation, and may continue at later times via circulation of ocean water below the seafloor. The W/R for ocean worlds is not well constrained because the internal evolutionary processes that control it are inadequately understood. As an example, the relevant W/R for differentiation depends on the timescale for rock particles to separate from volatile materials and settle into a rocky core. If this timescale is short relative to the kinetics of mineral dissolution reactions, then only a small fraction of the soluble components may end up in solution. Large particles (millimeters to centimeters) such as chondrules may gravitationally settle from the water column faster and be only partially altered, whereas fines (10s of μm) may remain in suspension for longer and be pervasively altered (Bland and Travis 2017). The depth of circulation of ocean water into the rocky core depends on the lifetime of the ocean, the permeability of underlying rocks, and the thermal evolution of the core. In large icy moons (Triton, Europa, etc.), the faster sinking of rock particles due to higher gravity and the decreased permeability of the seafloor due to higher pressure could limit the extent of interaction between water and rock. It is difficult to determine how all of these processes come together to yield a globally representative W/R, although past studies can provide some guidance. Castillo-Rogez et al. (2018) derived a $\text{W/R} \geq 3$ to explain Ceres' surface mineralogy. Sekine et al. (2015) assumed $\text{W/R} = 4$ for Enceladus, per analogy with terrestrial submarine environments. Glein

and Waite (2020) estimated a somewhat lower W/R (~ 0.85 – 2.8) for Enceladus from Cassini data. Zolotov's (2012) study of aqueous alteration in CI chondrite parent bodies (with pressures up to 200 MPa) focused on $W/R \leq 2$. Similarly, we expect low W/R overall but compute results for W/R between 1–500.

A few simplifications are made based on our current knowledge of higher order issues and other modeling limitations. First, a potential caveat of our approach is that magnesite (MgCO_3) and dolomite ($\text{CaMg}(\text{CO}_3)_2$) are allowed to form in these chemical equilibrium models. The formation of these carbonates is kinetically controlled at temperatures lower than 60°C (e.g., Zhang et al. 2000; Power et al. 2019). Temperatures in the early oceans of large water-rich bodies were likely lower, at least during the differentiation phase, due to cooling via active hydrothermal convection (e.g., Bland and Travis 2017). Metastable hydrated carbonates likely initially formed instead, such as hydromagnesite and lansfordite. On the other hand, magnesite can precipitate over timescales of a few hundred thousand years, much shorter than the ocean lifetimes (>100 m.y.) of large water-rich bodies (Power et al. 2019). Many parameters come under consideration, such as $p\text{CO}_2$, nucleation and degree of saturation (e.g., in pores). Here, we consider that magnesite and dolomite could form and also consider the consequences of inhibiting their formation in Figure S6. Both minerals have been found in abundance on Ceres (Palomba et al. 2019). Magnesium-rich carbonates have also been found in a variety of carbonaceous chondrites (e.g., Tagish Lake, Nakamura et al. 2003) that experienced shorter phases of aqueous alteration.

Another simplifying assumption is that the low temperature reaction kinetics are too slow for appreciable concentrations of hydrocarbons (e.g., CH_4) to form from CO_2 (or CO) equilibria with water and molecular hydrogen (Shock and McKinnon 1993). Similarly, we assume that the ocean temperature is too low for molecular nitrogen to form from the decomposition of ammonia (Matson et al. 2007). Should any of these processes occur, then the consequence would be similar to assuming lower concentrations of CO_2 and NH_3 to start with. Ammonium may also be removed from the system via exchange with cations (especially K^+ and Na^+). The consequences of that exchange are addressed in Section 3.

Lastly, we restrict our quantitative analysis to 1 atm total pressure, as the effects of pressure on the electrical conductivity of aqueous solutions is presently insufficiently parameterized at higher pressures (see Supporting Information for other details).

3 Results

Results for five different volatile abundances are presented in Figures 1–2 and S3 for the salinity and EC as a function of accreted (i.e., initial) concentrations of CO_2 and NH_3 , as well as water to rock ratio. These compositions were chosen to illustrate the various effects acting on the system. A broader range of compositions is explored later on.

If ocean salinity is a sole function of fluid-rock reaction under equilibrium conditions, then the salinity should be on the order of 0.1–0.2 wt. %, consistent with previous modeling (e.g., Leitner and Lunine, 2019), yielding an EC \sim 0.2 S/m (black diamonds in Figure 1).

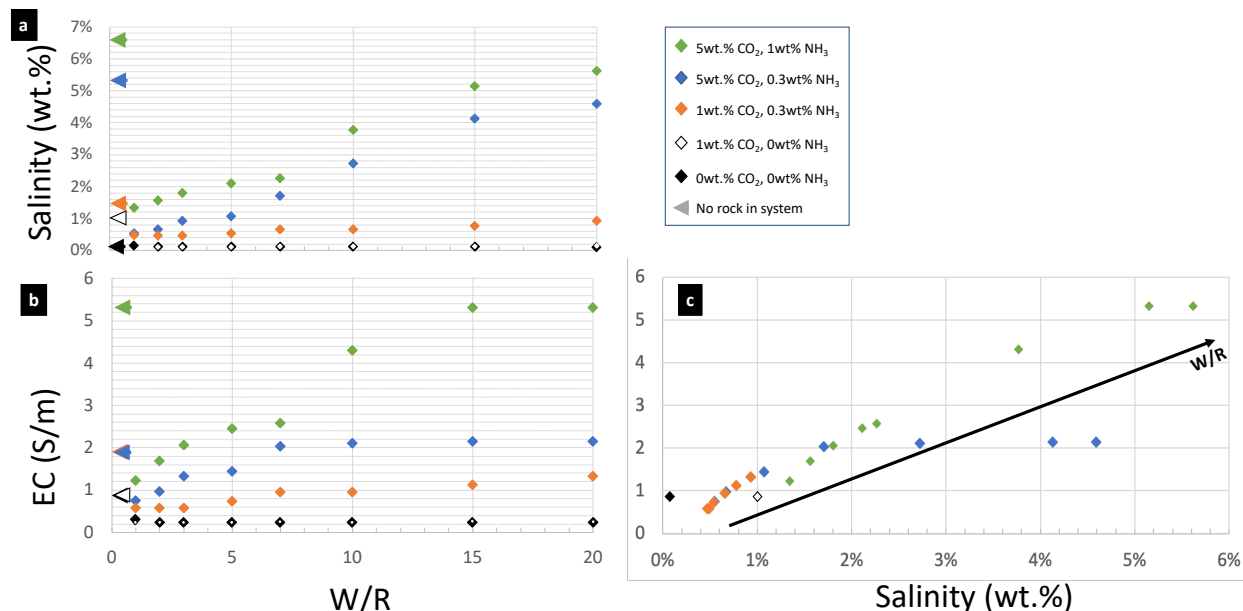


Figure 1. Effect of the water to rock ratio (W/R) on (a) salinity and (b) electrical conductivity (EC) for several accreted volatile compositions and $\log_{10} \text{pH}_2$ (bar) = 2. Salinity is defined as the mass of dissolved salts per kilogram of solution. Dashed lines show the salinities and ECs obtained for solution based on accreted volatiles only, i.e., with no rock present. The latter results do not depend on W/R. (c) represents EC as a function of salinity of the covered space of parameters.

The presence of CO₂ affects solute speciation in the NH₃ system, and vice versa. For example, dissolved CO₂ increases the acidity of the solution, which in turn determines whether accreted NH₃ remains predominantly in this form, or NH₄⁺ becomes another important source of ions to the ocean (see Figure S1). If a small amount (\lesssim 2 wt.%) of CO₂ (and no NH₃) is added to the solution, it would be sequestered to form dolomite and magnesite with little contribution to salinity (less than [Na⁺] and [Cl⁻], see Figures S4, S5) unless these minerals cannot form over the lifetime of the ocean. Figure S6 shows the difference in salinity and EC obtained when magnesite and dolomite are suppressed from the system to reflect kinetic limitations (calcite and hydromagnesite form instead) and when these minerals are allowed to form. The difference is particularly significant for [CO₂] < 3 wt.% and [NH₃] < 1 wt.%. Then, the salinity and EC remain \ll 1 wt.% when no carbonate is suppressed while these parameters can reach 2 % and $>$ 1 S/m, respectively, when magnesite and dolomite are suppressed. A factor two difference between the results is found for [CO₂] between 3–7 wt.% and low [NH₃]. For higher [NH₃], the salinity and EC are generally similar for the two

types of models. For the rest of this paper, we assume equilibrium is reached for the reasons noted in Section 2.

The fraction of bi/carbonate ions in solution increases with increasing $[\text{NH}_3]$ (Figures 1–2, S3), as ammonia provides a charge-balancing cation (NH_4^+). To further illustrate the contributions of CO_2 and NH_3 to the system, we compute the salinity and EC of endmember mixtures without rock (Figure 1). These simulations almost systematically lead to salinities and EC that are higher than their counterpart with rock. This is because carbonate ions are removed to form carbonate minerals if reactant rock is added.

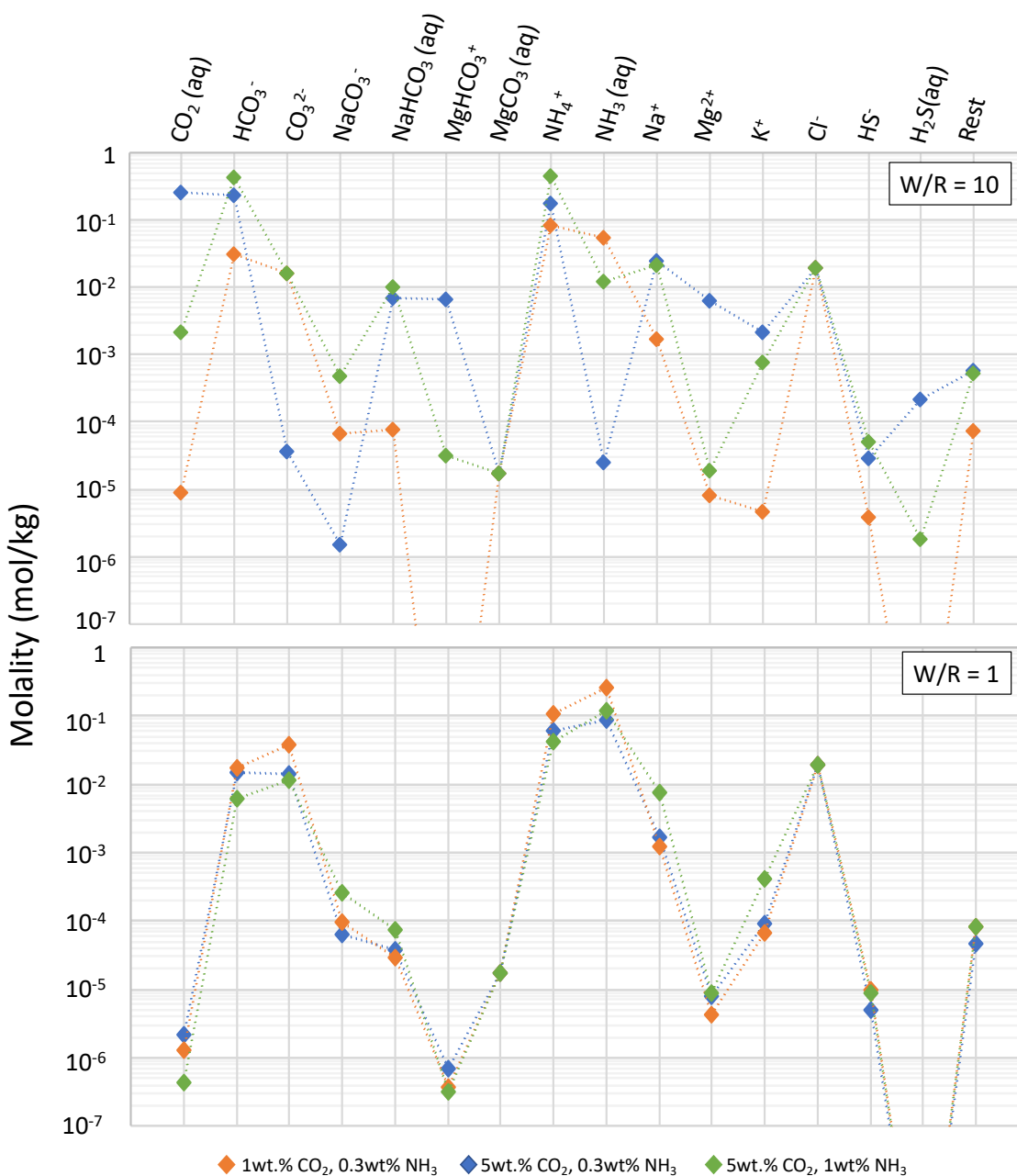


Figure 2. Concentrations of the main solutes obtained for three different solutions introduced in Figure 1 for (Top) $W/R = 10$ and (Bottom) $W/R = 1$. This figure shows HCO_3^- , CO_3^{2-} , and NH_4^+ are the main contributors to salinity by up to one order of magnitude more than Cl^- , alkali, and alkaline earth metals. See also Figure S4 for a summary of mol fraction for each class of solutes and Figure S7 for concentrations obtained for $W/R = 100$. Off-scale data points correspond to a molality very low or even equal to zero.

The W/R ratio increases salinity significantly when high abundances of CO_2 and NH_3 are accreted. The molality of HCO_3^- increases by one order of magnitude (15x) when W/R increases from 1 to 10, while the CO_3^{2-} molality decreases by two orders of magnitude (350x) over that range. For $W/R = 10$, inorganic carbon is sequestered by magnesite, dolomite, and siderite (FeCO_3) (Figure S5), yielding six times as much carbonate precipitates than in the lower W/R case. Overall, for low abundances of CO_2 and NH_3 (1 wt.%, 0.3 wt.%, respectively in Figure 1), the salinity is $\lesssim 1$ wt.% and $\text{EC} \lesssim 1$ S/m for $W/R < 20$. For higher abundances of accreted CO_2 (5 wt.% cases in Figure 1), the salinity increases sharply for $W/R > 5$ and yields an $\text{EC} > 5$ S/m.

Another finding, presented in Figure 2, is that at low W/R ($= 1$), the relative abundance of each solute remains about the same for the three compositions. On the other hand, for the high W/R example ($W/R = 10$), the solution speciation varies significantly. Figure S7 shows that the speciations obtained at W/R of 10 and W/R of 100 are similar. A high initial $[\text{CO}_2]$ increases the dissolved concentrations of Na^+ , K^+ and Mg^{2+} as a consequence of increased acidity (Figure 1a) destabilizing the mineral sinks of these cations. For example, the concentration of K^+ decreases by three orders of magnitude if $[\text{CO}_2]^1$ decreases from 5 to 1 wt.%.

We also test the effect of the partial pressure of H_2 (redox conditions) on the results. We find that results remain almost constant over a range of partial pressures of H_2 relevant to ocean worlds, between -3 and +2 on a \log_{10} scale (e.g., McKinnon and Zolensky 2003). Observations at Enceladus support reducing ocean conditions based on the presence of H_2 , CH_4 , organic compounds, and the lack of detection of sulfate salts in the plume (Ray et al. 2021).

The difference in salinity and EC between the two for the range of conditions covered in Figure 1 is $< 10\%$ and $< 2\%$, respectively, in the majority of cases (Figure S8).

The solutions modeled in this study did not produce any sulfate in solution (Figures 2, S4, and S7), which is expected in deep oceans with high partial pressures of hydrogen (McKinnon and Zolensky 2003) and consistent with observations at Enceladus (Ray et al. 2021). Instead, sulfur is in the form of sulfide minerals (especially pyrrhotite), consistent with observations of carbonaceous chondrites (Bland et al. 2004). Sulfates start becoming a significant form of sulfur for $\log_{10} \text{pH}_2 < -6$. This is roughly consistent with the results from Zolotov and Kargel (2009) who found sulfate could become a significant species for $\log_{10} \text{pH}_2 < -7$. Furthermore, while the pH in the modeled

¹ Potential exchange with NH_4^+ can also increase the amount of K^+ in solution (see section 3.2).

compositions is consistently > 6 , Tan et al. (2021) find that sulfate reduction to sulfide is favored at $\text{pH} < 6$.

A small fraction, $< 10^{-4}$ mol/kg of HS^- and H_2S are present in the three examples. As shown by Melwani Daswani et al. (2021), the potential breakdown of sulfides trapped in the rocky mantle as a consequence of thermal metamorphism may release sulfur to the ocean that may form sulfates if the conditions are sufficiently oxidizing. This potential additional contribution to salinity applies to highly evolved ocean worlds (e.g., Europa), and should be addressed in future studies.

GWB results also show that carbon dioxide reacts with ammonia to produce organic molecules and ionic species such as acids and carboxylates, urea, and acetamide at the (few) ppm level.

Lastly, we map in a more systematic manner the salinity and EC against the concentrations of CO_2 and NH_3 , for a reference $\log \text{pH}_2$ (bar) = 0, W/R = 10 in Figure 2. After a fraction of the CO_2 is taken up in the formation of low solubility carbonate minerals such as dolomite and magnesite, high concentrations of HCO_3^- and CO_3^{2-} still remain in solution. For 0 wt.% NH_3 , the salinity remains below 1 wt.% across the range of initial CO_2 concentration (Figure 1) and EC is < 1 S/m. Higher $[\text{NH}_3]$ in solution leads to increasing abundances of HCO_3^- and CO_3^{2-} , relative to CO_2 . Relative concentrations derived from observations at Enceladus are consistent with these results (Postberg et al. 2009; Glein et al. 2015). For $[\text{CO}_2]$ in excess of 10 wt.% and $[\text{NH}_3] = 3$ wt.%, the EC exceeds 5 S/m.

Other dependencies of salinity and electrical conductivity were explored in this paper and are reported in the Supporting Information. The dependence on hydrostatic pressure, other low-abundance cometary volatiles, and ammonium-cation exchange is minor

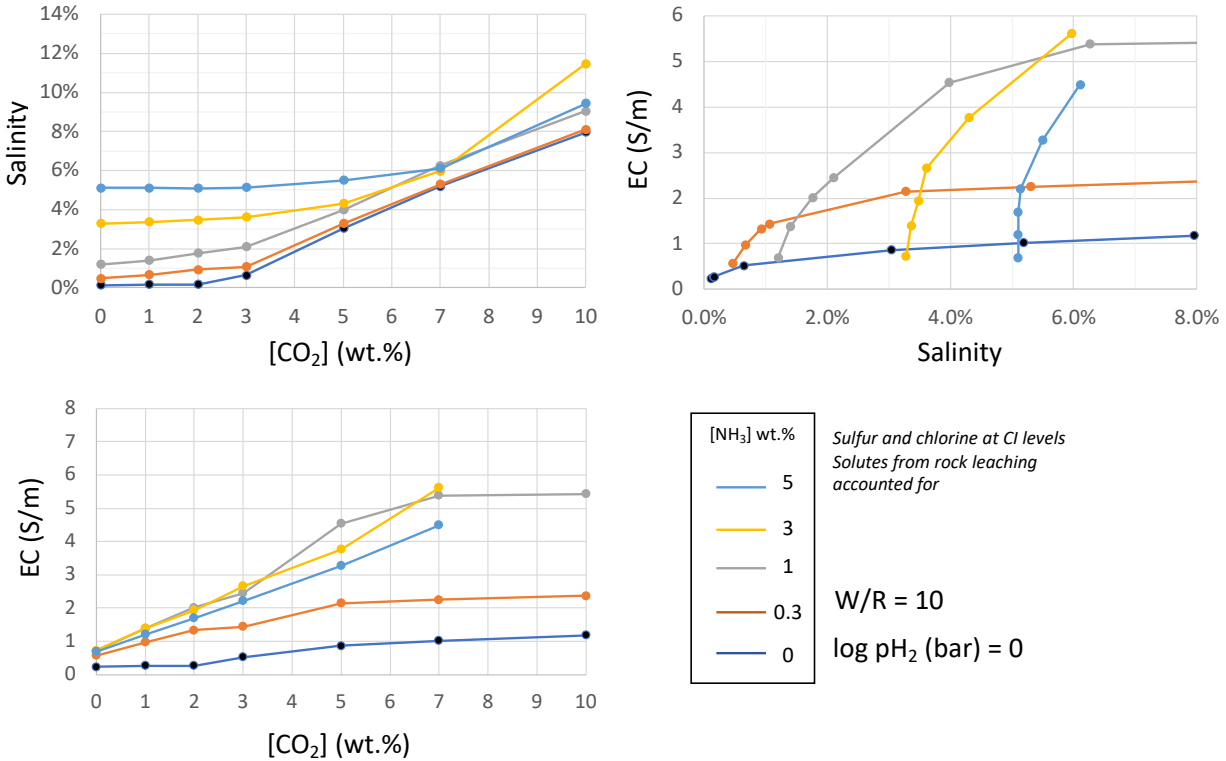


Figure 3. Salinity and EC as a function of accreted CO_2 and NH_3 abundances, calculated at 0 °C, 1 atm pressure, $W/R = 10$, and $\log_{10} pH_2 \text{ (bar)} = 0$, prior to concentration due to freezing of an ice shell. EC is estimated following McCleskey et al. (2012). For a few cases, when $[CO_2] > 7$ wt.%, the ionic strength of the solution falls above the range of applicability of this method.

5 Conclusions and Future Applications

We showed that volatiles expected in objects formed from cometary materials could be major contributors to the salinity and electrical conductivity of ocean worlds. The simulations reported in this study focus on the most abundant and reactive volatile compounds expected from cometary composition. This yields oceans enriched in CO_3^{2-} , HCO_3^- , and NH_4^+ , which could represent another endmember for the oceans of large icy moons and dwarf planets, besides chlorine- and sulfate-based oceans (e.g., Vance et al. 2020). The amount of accreted NH_3 and the water to rock ratio affect the solubility of carbonates. Reference abundances of $[CO_2] = 5$ wt.% and $[NH_3] = 0.3$ wt.% yield a salinity > 2 wt.% and conductivity > 2 S/m. Accounting for higher bounds on cometary volatile abundances could increase the EC above 5 S/m.

Higher conductivities resulting from salt concentration with corresponding ionic strengths > 1 molal fall outside the performance space of the McCleskey et al. (2012) method. This method does not account for ion-ion interactions. Pawlowicz (2010) highlights a discrepancy by up to a factor two between the predicted EC of highly concentrated solutions for a wide range of compositions based on theory developed for dilute solutions, and analytical measurements. Ionic interactions account for the bulk of that error, at least for ECs up to 10 S/m. However, EC estimates specific

to highly concentrated carbonate-rich solutions in conditions relevant to high $\text{NH}_4\text{-HCO}_3$ concentration oceans are lacking and should be the focus of future work.

Sulfates were not predicted to form in any of the solutions produced in this study as sulfur was taken up by sulfides, instead. Alternative scenarios for the case of Europa could lead to the presence of sulfates in solution, either delivered from Io-genic materials and transported to the ocean via crustal overturn or other geodynamical processes to be defined. Sulfate ions may also form from the oxidation of sulfides if the ocean becomes sufficiently oxidized (Zolotov and Kargel 2009) although low pH appears to favor sulfate reduction (Tan et al. 2021).

Bodies likely to have accreted a large fraction of cometary volatiles include Triton and Pluto. Triton could have lost a significant fraction of volatiles as a consequence of intensive heating upon capture (Barr and Schwamb 2016). It is possible, however, that it had at least partially melted and differentiated prior to capture. In this case, the loss of part of the hydrosphere would have resulted in salt concentration. Testing the presence of a deep ocean by searching for an induced magnetic field has been included in recently assessed mission concepts (e.g., at Triton, Prockter et al. 2021). In Ceres, the residual brine reservoir is expected to be highly concentrated in sodium, bicarbonate, ammonium, and chloride ions, in particular that make them amenable to an electromagnetic sounding investigation (Grimm et al. 2021). The Uranian moons are other candidate ocean worlds. These bodies are likely to be more closely related to their initial volatile compositions by being less thermally processed than larger bodies, such as Ceres and Triton. Lastly, a high concentration of carbonates in Titan (Brasse et al. 2017) could account for part of the high ocean density inferred from the Cassini mission gravity data (Durante et al. 2019) beyond salinities predicted from rock leaching only.

Estimates of salinity and EC for specific bodies need to account for evolutionary scenarios that determine the fate of volatile compounds. During differentiation of the rock from the volatile phase, some of the CO_2 inventory may be sequestered in carbonates. Later on in some bodies, the release of NH_3 and CO_2 from the breakdown of organics (e.g., amino acids, insoluble organic matter), ammoniated phyllosilicates, and carbonates as a consequence of thermal metamorphism in rocky mantles (Melwani Daswani et al. 2021; Nakano et al. 2020) could increase salinity.

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Open Research

This research uses the Geochemist's Workbench software, version 10 <https://www.gwb.com/> from Aqueous Solutions LLC (Bethke, 2007). An example of input to and output from the code is provided in the Supporting Information file.

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