Ice-Covered Oceans in Our Solar System

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Outline

1) Introduction to the solar system’s ice-covered oceans
2) Earth
3) Europa
4) An introduction to Europa’s geysers using ocean dynamics
5) Summary
1. Ice-Covered Oceans in the Solar System
2. Earth
Arctic Ocean
Arctic Ocean Stratification and Circulation

Cold Arctic air freezes seawater

Newly formed ice

Multiyear pack ice

Salt is released

Cold, fresh water

Denser, salty water sinks

ARCTIC HALOCLINE

50 meters

Cold, saltier water

200 meters

Warm, salty Atlantic water

(Jayne Doucette, WHOI)

(Polyakov et al., 2012; Carmack, et al. 2015)
3. What about Europa?
Missions to Europa

Voyager II, 1979  
Galileo, 1996, 1997  
Clipper, ~2023

(NASA)  
(NASA/JPL/Uni. Arizona)
cycloidal features

cracks and ridges

Fig. 3. Cycloidal double ridges [class 1 in Greenberg et al.'s taxonomy (6)] viewed in the northern hemisphere of Europa (60°N, 80°W).

(Hoppa, et al. 1999)
Figure 8. Regime diagram showing the values of $\sigma_m/E$ and $H$ for which we expect to observe each of the deformation types observed. Photographs courtesy of Weeks (submitted manuscript, 2008).
A (salty) ocean?
Inferences of Water Vapor

(Molecules From Ocean)  (Charged Particle Radiation)  (Molecules Breaking Down)

EUROPA SURFACE  EUROPAN SURFACE  OCEAN

(NASA/JPL-Caltech)
4. A hypothesis that convection controls Europa’s geyser activity

(Shibley & Laughlin, in prep.)
Four Components

• Clathrate buoyancy
• Two-layer Ocean and Convection
• Ice Fissure
• Vulcanian eruption
Clathrate Hydrates

• water ice + carbon dioxide (or methane etc.)

Fig. 1. Giant craters and mounds are located in the northern Barents Sea. (A) The Barents Sea Ice Sheet reached the continental shelf break during the LGM (15). Methane hydrate is currently stable in the deepest part of Bjørnøyrenna and other troughs of the Barents Sea (red polygons). (B) Giant craters and mounds within the local area of the study site. The black stippled polygon shows previous investigations of the area (II, I2). White circles indicate locations of gas samples shown in tables S2 and S3.

(Andreassen et al., 2017)
A two-layer Europan Ocean

Stability Condition

\[
\frac{\alpha \Delta T}{\beta \Delta S} < 1
\]

\[
\frac{\alpha F_b}{\beta C_p \rho_i F_h S_0} < 1
\]

**Figure 1.** Model schematic depicting a (left) low-latitude and (right) high-latitude column. The uppermost (gray) boxes represent the ice shell. Heat is exchanged from the ocean to the ice, \( F_{\text{ocn}} \) (W m\(^{-2}\)), and is transported away from the ocean-ice interface by diffusion. The freshwater layer is denoted in blue, with salinity \( S^e \), temperature \( T^e \), and depth \( d \). Red lines indicate heat transport, green lines indicate salt transport, and the purple lines indicate the transport of both temperature and salinity. \( F_b \) is the geothermal heat flux from the seafloor.

(Zhu et al., 2017)
Geyser Model

(Shibley & Laughlin, in prep.)
What if the column is statically unstable?

MgSO$_4$ or NaCl

$\rho_c \sim 1040 - 1100$ kg m$^{-3}$

$\rho_1, \rho_2 \sim 1039 - 1100$ kg m$^{-3}$

(Priesto-Ballesteros et al., 2005; Zhu et al., 2017)

(Shibley & Laughlin, in prep.)
Fissure in the Ice

- pressure $p$
- vertical velocity $w$
- density $\rho$
- height $z$
- time $t$
- gas density $\rho_g$
- liquid density $\rho_l$
- mass fraction of gas $\phi$
- volume fraction of water $f$

(Turcotte, et al. 1990; Shibley & Laughlin, in prep.)
Eruption
Assumptions

- The explosion can be modelled as a 1D process.
- The liquid water and the CO$_2$ gas (density $\rho_g$) move at the same speed.
- The ice conduit area does not change in space or time.
- Viscous stresses are small compared to the inertia of the fluid.

(Turcotte, et al. 1990; Shibley & Laughlin, in prep.)
Governing Equations

1. \( \frac{\partial \rho}{\partial t} + \frac{\partial (\rho w)}{\partial z} = 0 \), conservation of mass.

2. \( \rho \left( \frac{\partial w}{\partial t} + w \frac{\partial w}{\partial z} \right) = -\frac{\partial p}{\partial z} - \frac{\rho_{l0} g L}{p_0} \rho \), conservation of momentum.

3. \( \frac{\partial f}{\partial t} + \frac{\partial (f w)}{\partial z} = 0 \), conservation of volume.

4. \( p = \rho_g \), ideal gas law.

5. \( \rho = f [1 + \varphi_0 (1 - \varphi)] + \epsilon (1 - f) \rho_g \), equation of state.

6. \( \varphi + p = 1 \), Henry’s Law.

<table>
<thead>
<tr>
<th>variable</th>
<th>definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \hat{p} )</td>
<td>( p / p_0 )</td>
</tr>
<tr>
<td>( \hat{\rho} )</td>
<td>( \rho / \rho_{l0} )</td>
</tr>
<tr>
<td>( \hat{\rho}_g )</td>
<td>( \rho_g R T_0 / p_0 )</td>
</tr>
<tr>
<td>( \hat{\varphi} )</td>
<td>( \varphi / \varphi_0 )</td>
</tr>
<tr>
<td>( \hat{\epsilon} )</td>
<td>( p_0 / \rho_{l0} R T_0 )</td>
</tr>
<tr>
<td>( \hat{t} )</td>
<td>( t \left( \frac{p_0}{\rho_{l0} L^2} \right)^{0.5} )</td>
</tr>
<tr>
<td>( \hat{w} )</td>
<td>( w \left( \frac{\rho_{l0}}{p_0} \right)^{0.5} )</td>
</tr>
<tr>
<td>( \hat{z} )</td>
<td>( \frac{z}{L} )</td>
</tr>
<tr>
<td>( \hat{f} )</td>
<td>( f )</td>
</tr>
</tbody>
</table>

(Turcotte et al., 1990; Shibley & Laughlin, in prep.)
foam: liquid water \((\rho_p, f, 1-\varphi)\) + CO2 vapor \((\rho_g, 1-f, \varphi)\)

liquid water + CO2 clathrates

\[ \begin{align*}
f &= 0 \quad p \sim 0 \quad w = 0 \quad \rho = p\varepsilon \\
z &= L \\
\text{ice fissure blocked (\sim 1 MPa)}
\end{align*} \]

\[ \begin{align*}
f &= 1 \quad \rho = 1 \\
w &= 0 \quad \rho = 1 + \varphi_0 \\
z &= -L \\
\text{CO}_2 \text{ dissociates}
\end{align*} \]

(Shibley & Laughlin, in prep.)
Eruption velocities up to ~800 m/s.

$\phi$ – mass fraction of gas

(Shibley & Laughlin, in prep.)
Velocities depend on initial pressure.

\[ \phi_0 = 0.05 \]

\[ \phi \text{ – mass fraction of gas} \]

(Shibley & Laughlin, in prep.)
5. Summary
Summary

• Arctic Ocean properties are fairly well-constrained.
• This is not the case for Europa.
• We can use inferences from the Arctic to understand Europa’s ice-ocean dynamics.
• One inference may suggest that ocean convection generates Europa’s geysers.
• The NASA Clipper mission and subsequent landers may help solve these mysteries.