Salinity bias with negative pressure dependency caused by anisotropic deformation of CTD measuring cell under pressure examined with a dual-cylinder cell model

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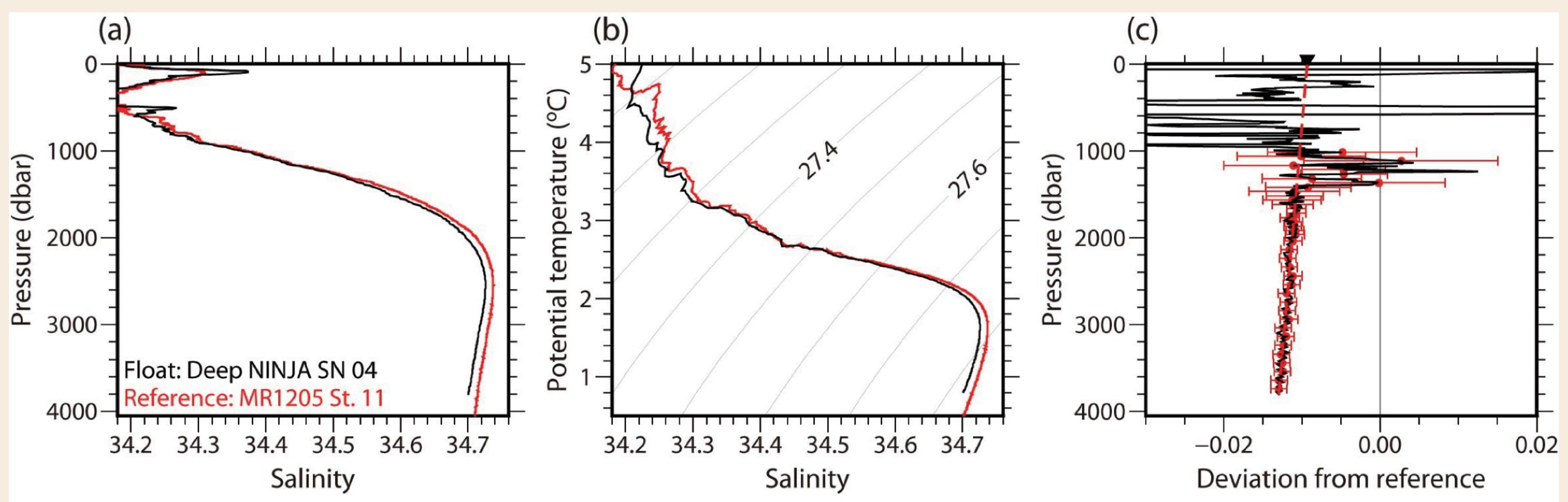
Salnity measured by deep floats

Salnity measurements by deep floats are compared with the shipboard CTD data obtained at float deployment.
=> Fresh salinity bias with negative pressure dependency was identidied.

$$\Delta S = \Delta S_{offset} + a_p \times p \text{ and } a_p < 0$$

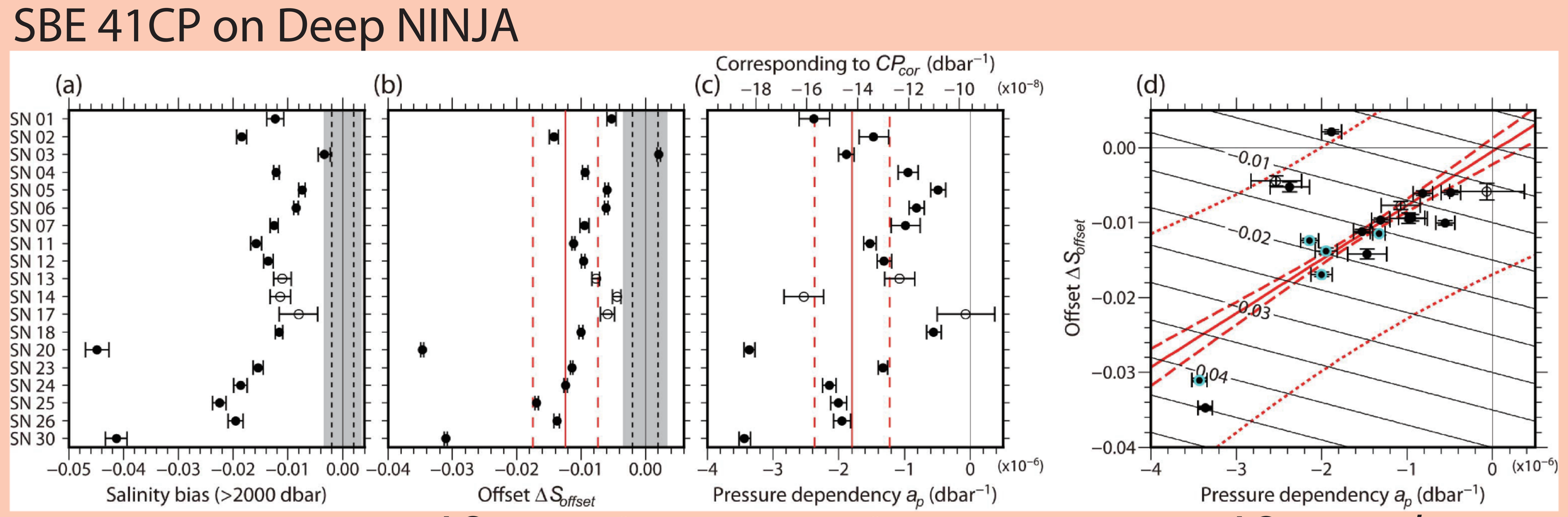


(a) P–S and (b) θ–S for the first profile obtained by SBE 41CP on Deep NINJA SN 4 (black) and the shipboard reference (red). (c) Deviation of salinity from the corresponding reference (on isotherms).

Sammary: salinity biases observed for deep floats

Salinity bias: $\Delta S = \Delta S_{offset} + a_p \times p$ and $a_p < 0$

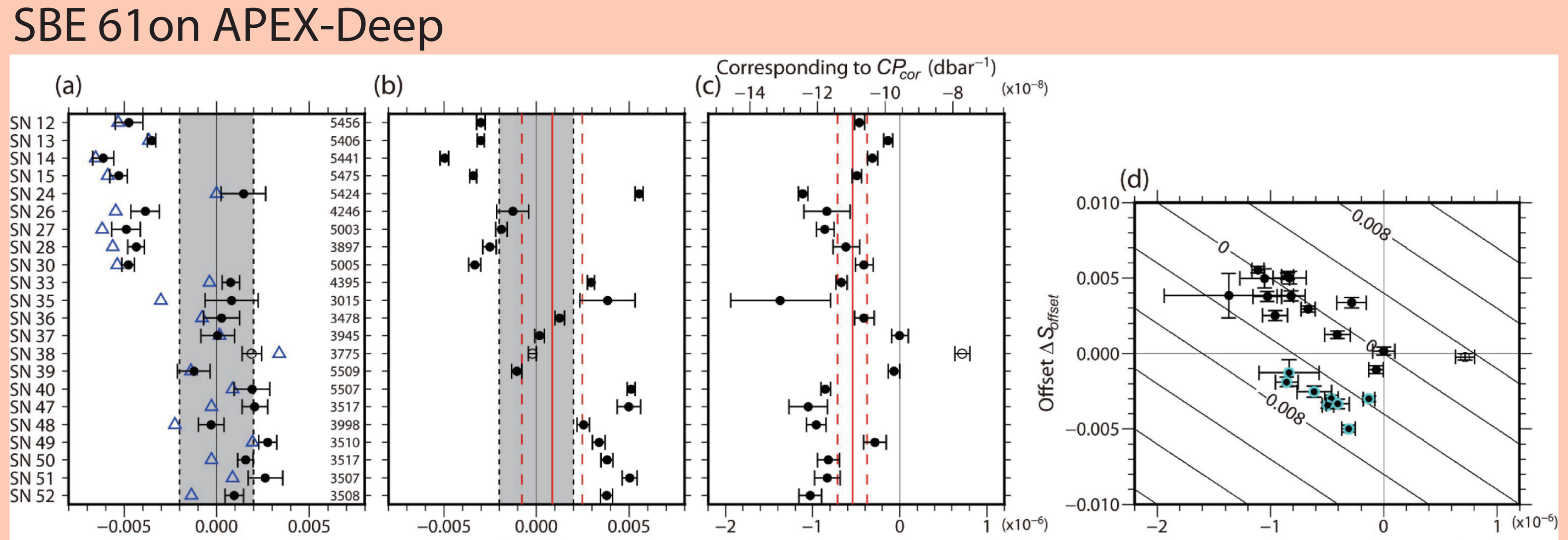
SBE 41CP on Deep NINJA



ΔS <~ -0.01 $\Delta S_{offset} < 0$ $a_p < 0$ $\Delta S_{offset} \sim k\, a_p$

Average: $\Delta S_{offset} = -12.5 \pm 5.1 \times 10^{-3}$ $a_p = -1.80 \pm 0.58 \times 10^{-6}$ (N = 16) (corr. $CP_{cor} = -14.2 \times 10^{-8}$)

SBE 61on APEX-Deep



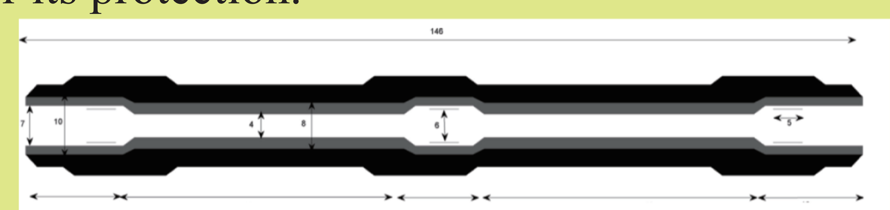
$\Delta S_{offset} \approx 0$ $a_p < 0$

Average: $\Delta S_{offset} = 0.8 \pm 1.7 \times 10^{-3}$ $a_p = -0.54 \pm 0.18 \times 10^{-6}$ (N = 21) (corr. $CP_{cor} = -11.0 \times 10^{-8}$)

Salinity bias for the first profile measured by (upper) SBE 41CP on Deep NINJA and (lowr) SBE 61 on APEX-Deep. (a) Average of salinity bias for layers deeper than 2,000 dbar, (b) offset component ΔS_{offset} (with bar for SE), (c) coefficient a_p for the pressure dependency component (with bar for SE), and (d) relationship between a_p and ΔS_{offset}. a_p and ΔS_{offset} are obtained for layers deeper than 1,000 dbar. Open circles represent the results for less-consistent float–reference pairs. In (b) and (c), the red solid and dashed lines represent the average and the upper/lower limits of the 95% CI, respectively. At the top of (c), the canceling factor for pressure CP_{cor} corresponding to a_p is shown. In (d), the solid, dashed, and dotted red curves represent the linear regression, the upper/lower limits of the 95% CI, and the 95% prediction interval, respectively.

Measuirng cell of SBE 41CP and SBE 61

The measuring cell for SBE 41CP and SBE 61 CTD sensors is composed of a Pyrex (i.e., borosilicate glass) cell and a polyurethane (PU) jacket which overs the glass cell for its protection.



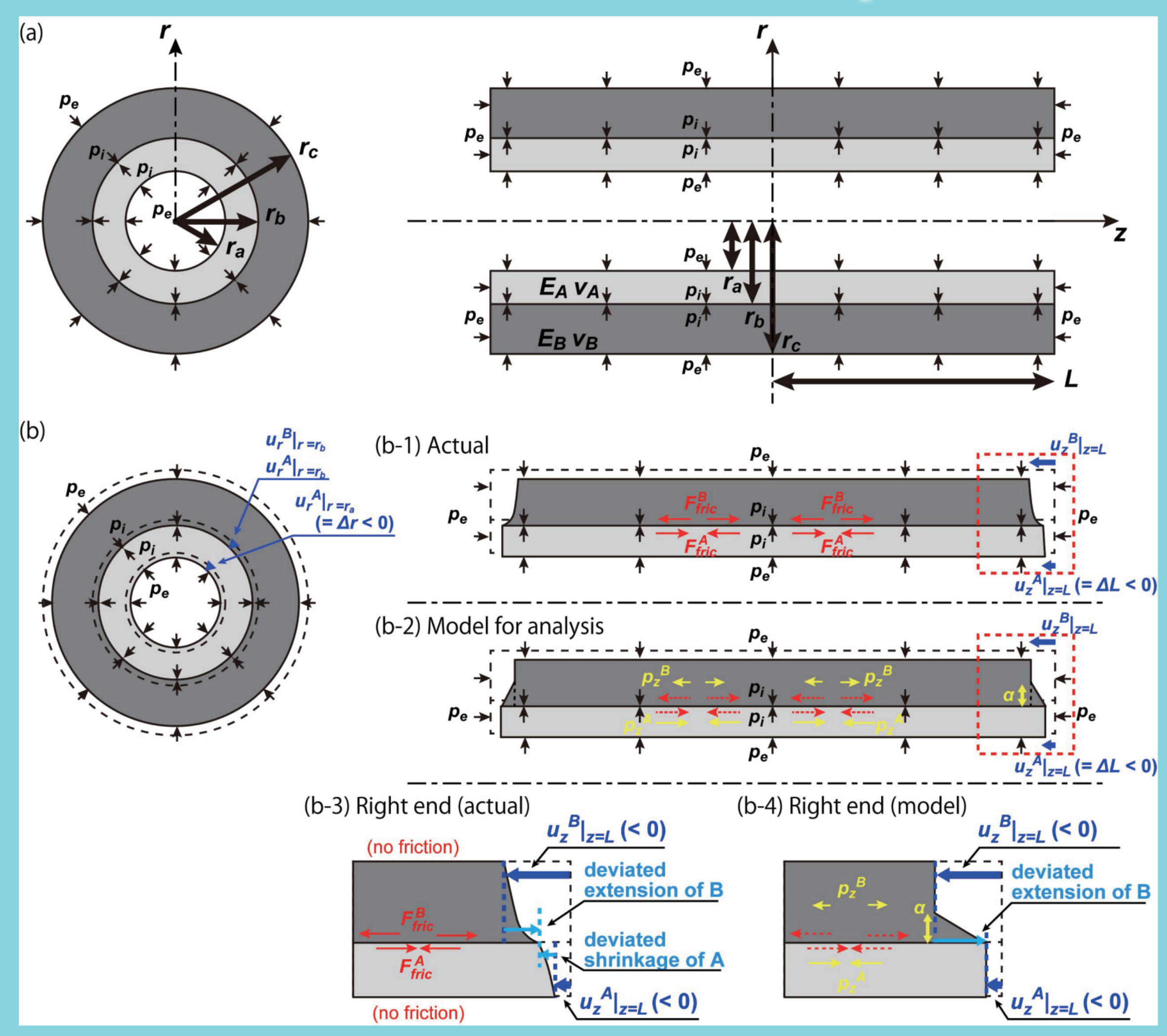
From Fig. 1 of Alvarez (2018; DSR1)

Raw measurements of conductivity are influenced by P and T at the measurement depth because the measuring cell is deformed by changes in P and T. Thus, SBE CTD sensors has a cancelling factor of CP_{cor} and CT_{cor} for the cell deformations caused by P and T.

$$C_0 = \frac{C_p}{1 + CT_{cor} \times T + CP_{cor} \times P}$$

Present CP_{cor} is -9.57×10^{-8} dbar^{-1} based on a theoretical model with a single-cylinder cell made of Pyrex.

Model: Deformation of dual-cylinder cell under pressure



Equations

$$u_r^A = \left\{\frac{v_A}{E_A}(p_e + p_z^A) - \frac{1-v_A}{E_A}\frac{p_e r_a^2 - p_i r_b^2}{r_a^2 - r_b^2}\right\} r - \frac{1+v_A}{E_A}\frac{r_a^2 r_b^2}{r_a^2 - r_b^2}(p_e - p_i)\frac{1}{r}, \quad (r_a \le r \le r_b)$$

$$u_z^A = -\frac{1}{E_A}\left\{(p_e + p_z^A) - 2v_A \frac{p_e r_a^2 - p_i r_b^2}{r_a^2 - r_b^2}\right\} z. \quad (0 \le z \le L)$$

$$u_r^B = \left\{\frac{v_B}{E_B}(p_e + p_z^B) - \frac{1-v_B}{E_B}\frac{p_i r_b^2 - p_e r_c^2}{r_b^2 - r_c^2}\right\} r - \frac{1+v_B}{E_B}\frac{r_b^2 r_c^2}{r_b^2 - r_c^2}(p_i - p_e)\frac{1}{r}, \quad (r_b \le r \le r_c)$$

$$u_z^B = -\frac{1}{E_B}\left\{(p_e + p_z^B) - 2v_B \frac{p_i r_b^2 - p_e r_c^2}{r_b^2 - r_c^2}\right\} z, \quad (0 \le z \le L)$$

Boundary condition: case 1

Both cylinders adhere to each other at interface.

$$u_r^A|_{r=r_b} = u_r^B|_{r=r_b}.$$

$$p_z^B = \frac{1}{2}\alpha E_B\left(\frac{u_z^A|_{z=L}}{L} - \frac{u_z^B|_{z=L}}{L}\right), \qquad p_z^A = -\frac{S_B}{S_A}p_z^B = -\frac{r_c^2 - r_b^2}{r_b^2 - r_a^2}p_z^B.$$

Boundary condition: case 2

The inner radius of the outer jacket decreased by $-\Delta R$ due to uniform shrinkage of PU under high pressure (i.e., compression set).

$$u_r^A|_{r=r_b} = u_r^B|_{r=r_b} - \Delta R,$$

$$p_z^B = \frac{1}{2}\alpha E_B\left(\frac{u_z^A|_{z=L}}{L} - \frac{u_z^B|_{z=L}}{L} + \frac{\Delta R}{r_b}\right), \quad p_z^A = -\frac{S_B}{S_A}p_z^B = -\frac{r_c^2 - r_b^2}{r_b^2 - r_a^2}p_z^B.$$

$$C_0 = C_p\frac{1 + \Delta L/L}{(1 + \Delta r/r)^2} = \frac{C_p}{(1 + 2\Delta r/r - \Delta L/L)}$$

$$CP_{cor} = \left(\frac{2\Delta r}{r} - \frac{\Delta L}{L}\right)/p_e$$

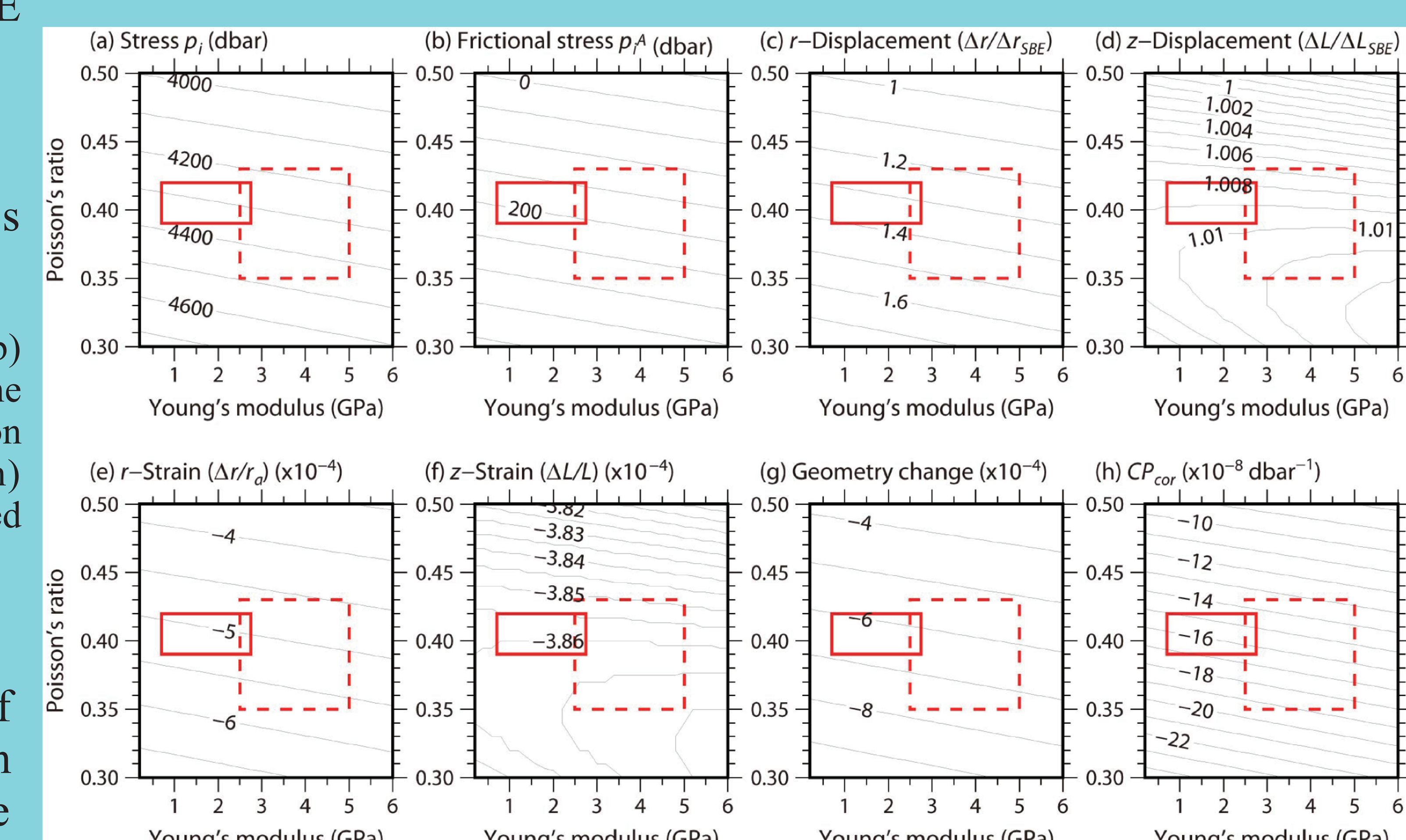
Negative pressure dependency: $a_p < 0$

Because of the interfacial stress stronger than the water pressure ($p_i > p_e$), the r-directioinal deformation of the internal cell (Δr) increases by 30% from the SBE consideration. The z-directional deformation is almost the same.

=> Measuring cell deforms anisotropically.

Evaluated CP_{cor} is -14.5 ~ -17×10^{-8}, which is smaller than the preset value.

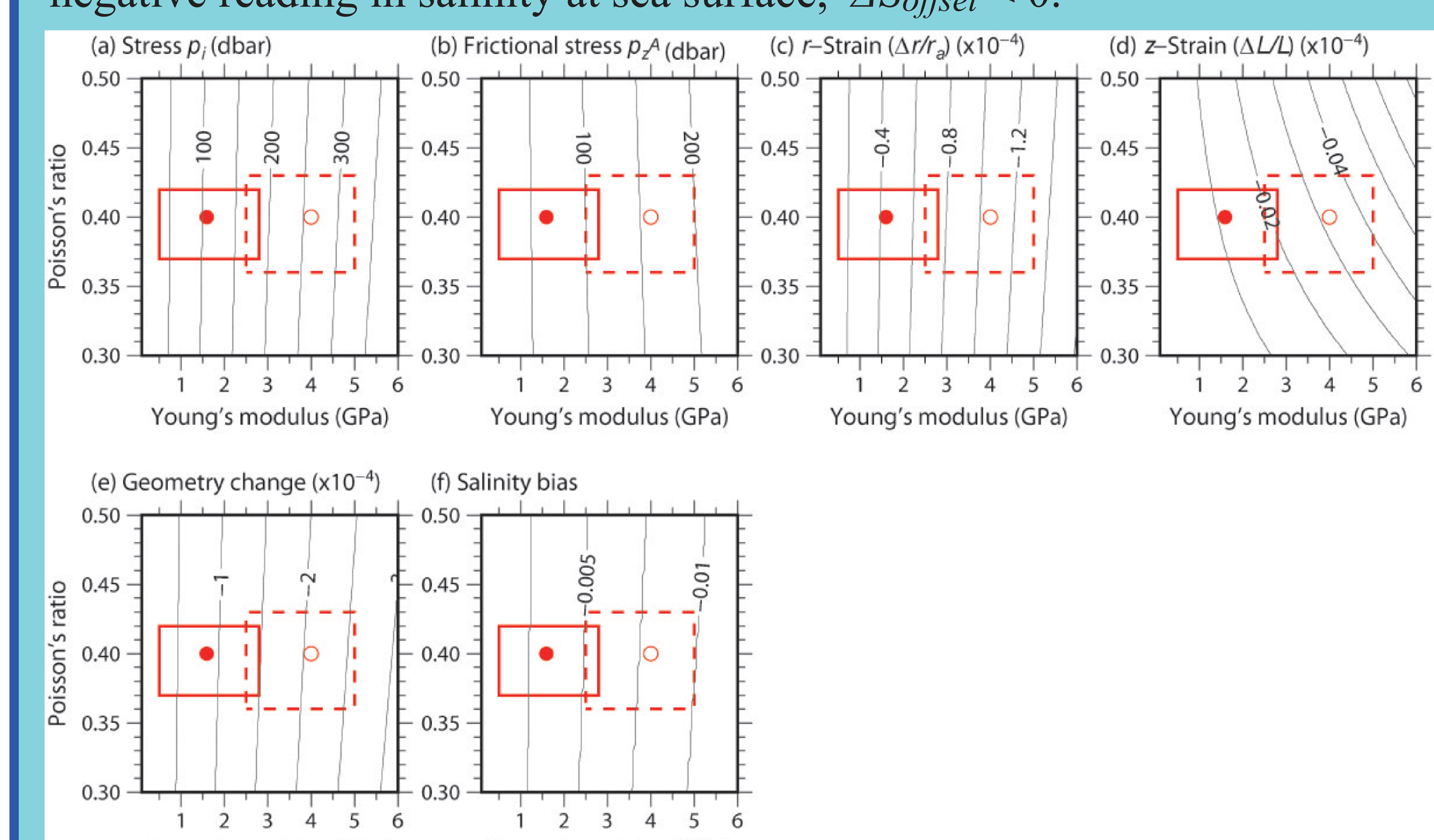
The model tells that the value of CP_{cor} increases as 1) the frictional force is stronger at the interface or 2) the outer-cylinder is thiner.



Right: Results for the cell model at p_e = 4000 dbar and friction α = 0.5 (a) Stress p_i at interface, (b) stress p_z^A generated by friction at interface, ratio of the inner cylinder deformation compared with the SBE consideration for (c) r-direction and (d) z-direction, strain of the inner cylinder for (e) r-direction and (f) z-direction, (g) change of inner cylinder geometry that affects salinity reading, and (h) corresponding CP_{cor}. The typical value and its considered range for PU (epoxy) are shown by the red solid (open) circle and the region with the red solid (dashed) line, respectively.

Fresh salinitybiase at sea surface : $\Delta S_{offset} < 0$

The inner radius of the outer jacket decreased by $-\Delta R$ due to compression set of PU (i.e., Boundary condition case 2). The interfacial stress is generated, $p_i > 0$, even at $p_e = 0$, the internal cell deformes r-directionally ($\Delta r < 0$), which yields the negative reading in salinity at sea surface, $\Delta S_{offset} < 0$.



Left: Results for the cell model at p_e = 0 dbar and friction α = 0.5 when the outer cylinder shrinks isotropically by a ratio of −1.5 × 10^{-3} (corresponding to ΔR = 6 × 10^{-6} m). (a) Stress p_i at interface, (b) stress p_z^A generated by friction at interface, strain of the inner cylinder for (c) r-direction and (d) z-direction, (e) change of inner cylinder geometry that affects salinity reading, and (f) resultant salinity bias. The typical value and its considered range for PU (epoxy) is shown by the red solid (open) circle and the region with the red solid (dashed) line, respectively.

The suggested solution of the salinity bias

The model suggests changing the material for the outer jacket to an elastomer: a class of materials like rubber, which have E smaller than about 0.01 GPa and v of almost 0.5, in general. The elastmer jacket makes the current CP_{cor} (-9.57 ×10^{-8}) fairly appropriate and brings significant advantages at production.

Further information: see the following articles.

Kobayashi, T., 2021: *Deep-Sea Research Part-I*, 167, 103420, https://doi.org/10.1016/j.dsr.2020.103420.

Kobayashi, T., K. Sato, and B. A. King, 2021: *Progress in Oceanography*, 198, 102686, https://doi.org/10.1016/j.pocean.2021.102686.