Fall-Rate Biases of XBT Devices and New Estimates of Ocean Heat Content

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Aims

- To test if XBT fall rate is affected by water temperature
- Use two methods:
  - The numerical/fluid dynamics model of Abraham et al, 2012
  - Thermal gradient method of Cowley et al, 2013

Use an XBT/CTD pairs database:

- Apply the fluid dynamics model to the XBTs
- Compare the corrected XBTs to their CTD partner
- Assess the impact of the model and compare with tyheCowley et al correction.

J.P. Abraham, R. Cowley, L. Cheng, Quantification of the Effect of Water Temperature on the Fall Rate of eXpendable BathyThermographs, *Journal of Atmospheric and Oceanic Technology*, Vol. 6, pp. 1271-1284, 2016.

Fluid dynamics model outline

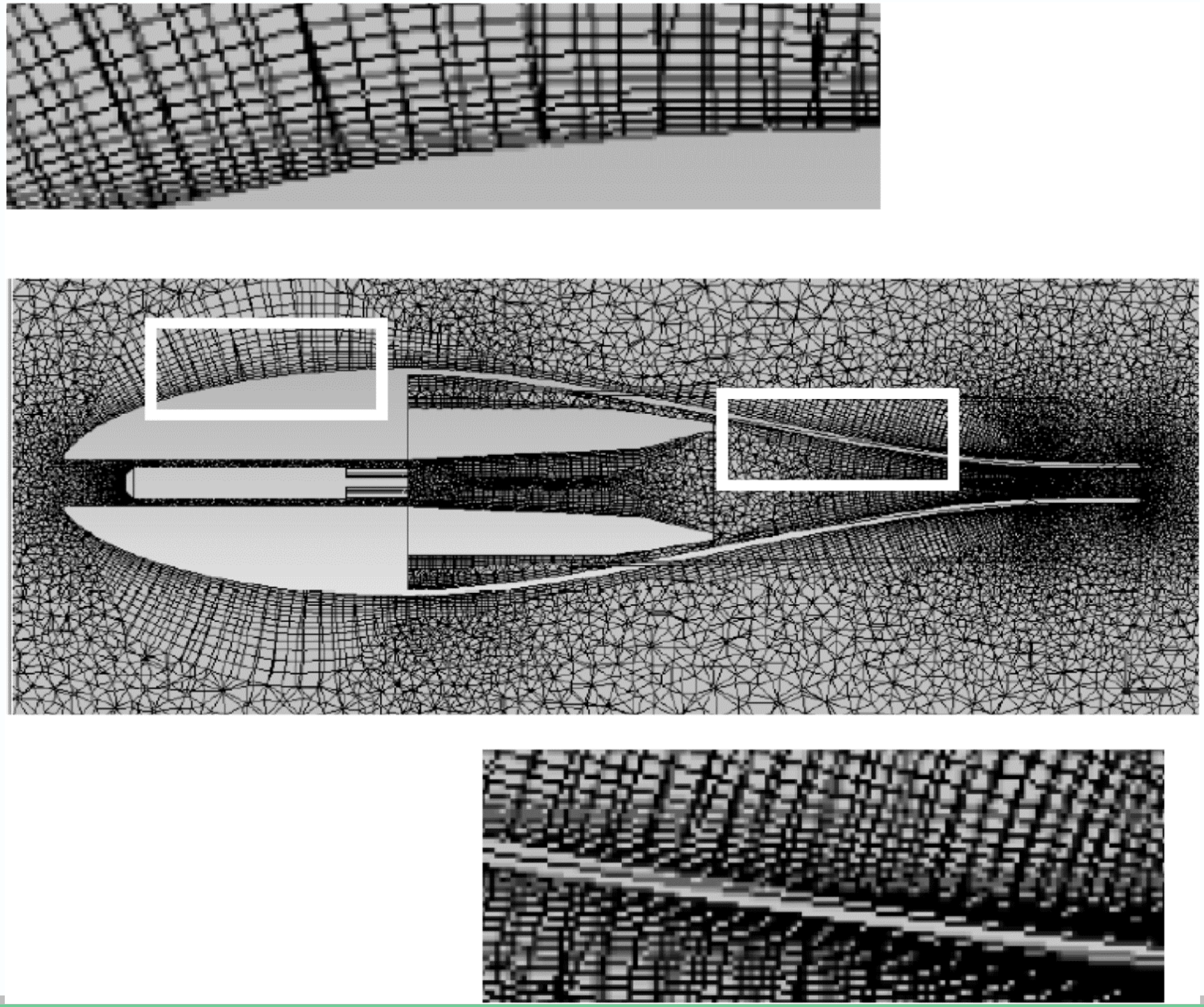
- Fluid dynamics calculation is dependent on:
  - Water (density, temperature, viscosity)
  - Velocity of the probe
  - Area of the front of the probe
  - Probe mass
  - Change in temperature with fall through the water

- Use a 'forward-stepping' algorithm to calculate velocity at each time step of the probe's fall

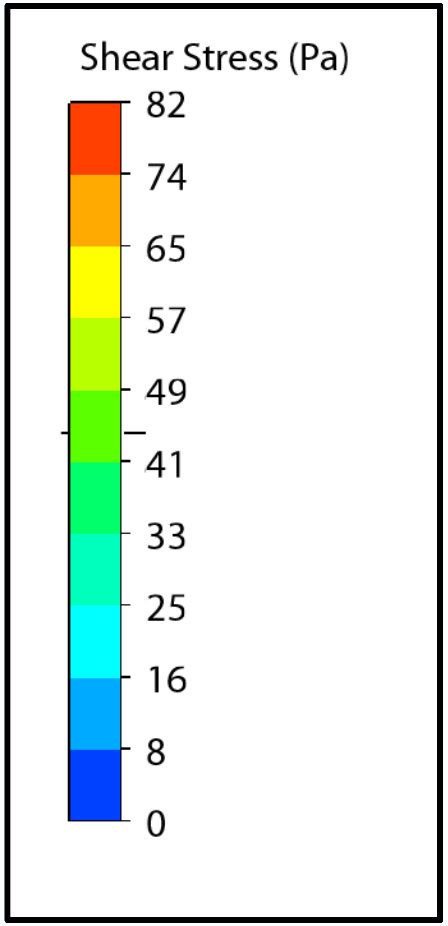
- Fit a quadratic to the relationship to determine A, B, C for each probe

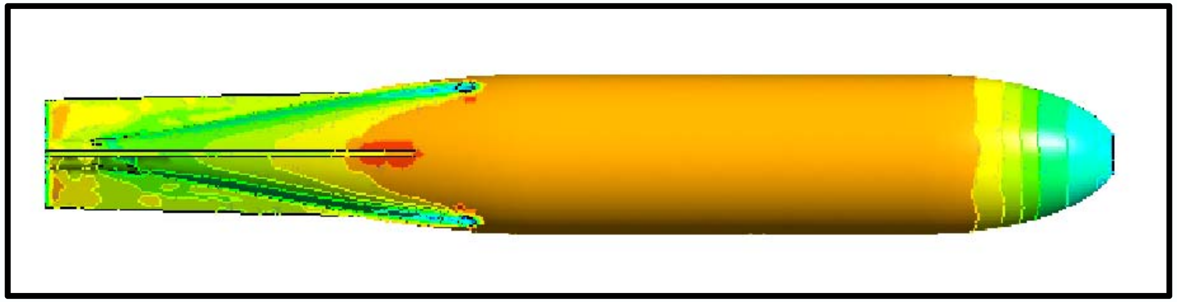
$$Depth = A \cdot t^2 + B \cdot t + C$$

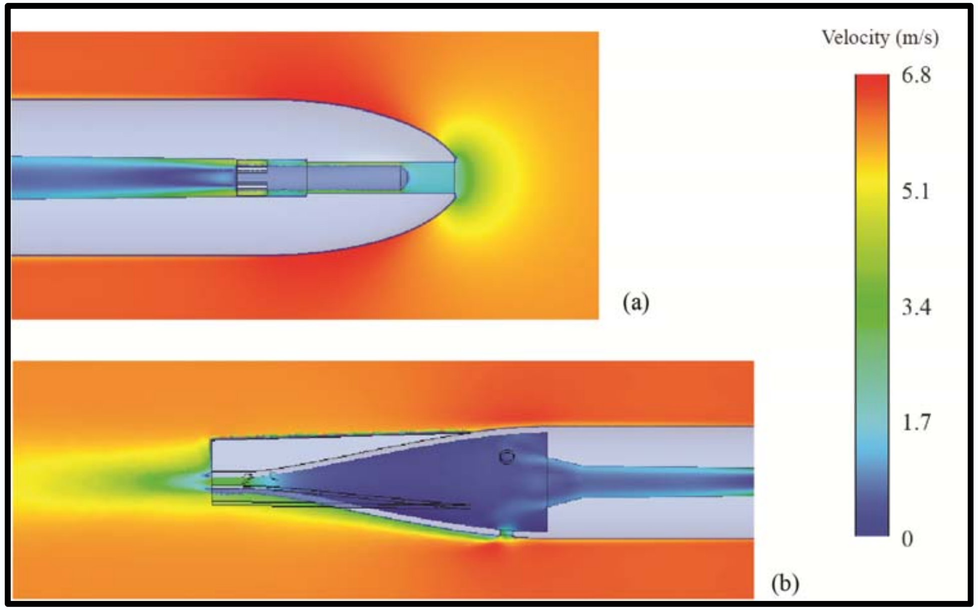
Fluid dynamics model



Fluid dynamics model results







J.R. Stark, J.M. Gorman, M.P. Hennessey, F. Reseghetti, J. Willis, J. Lyman, J.P. Abraham, and M. Borghini, A Computational Method for Determining XBT Depths, *Ocean Sciences*, Vol. 7, pp. 733-743, 2011.

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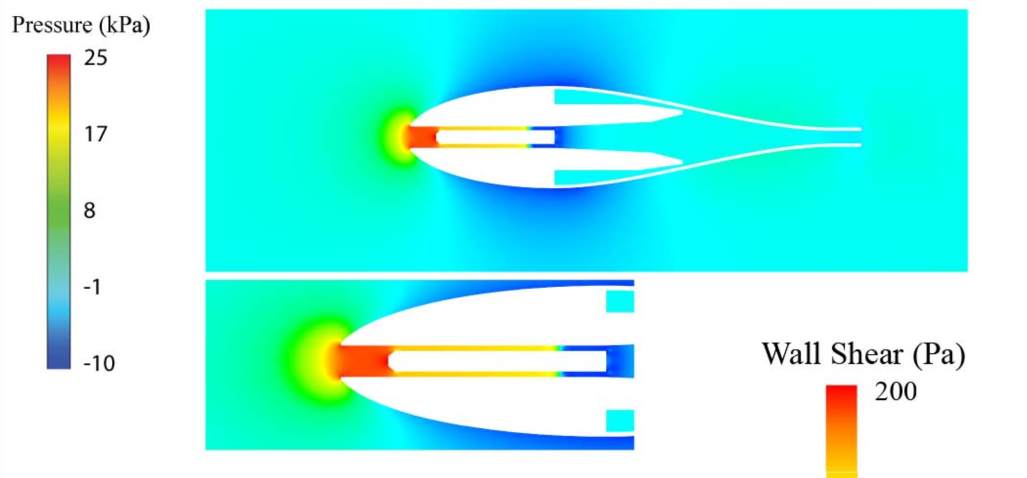

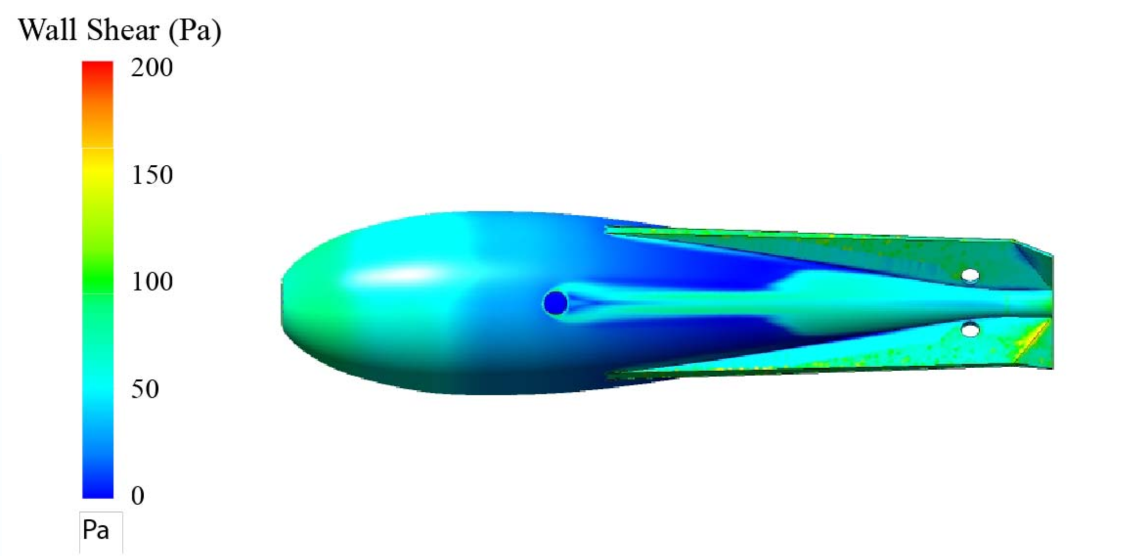

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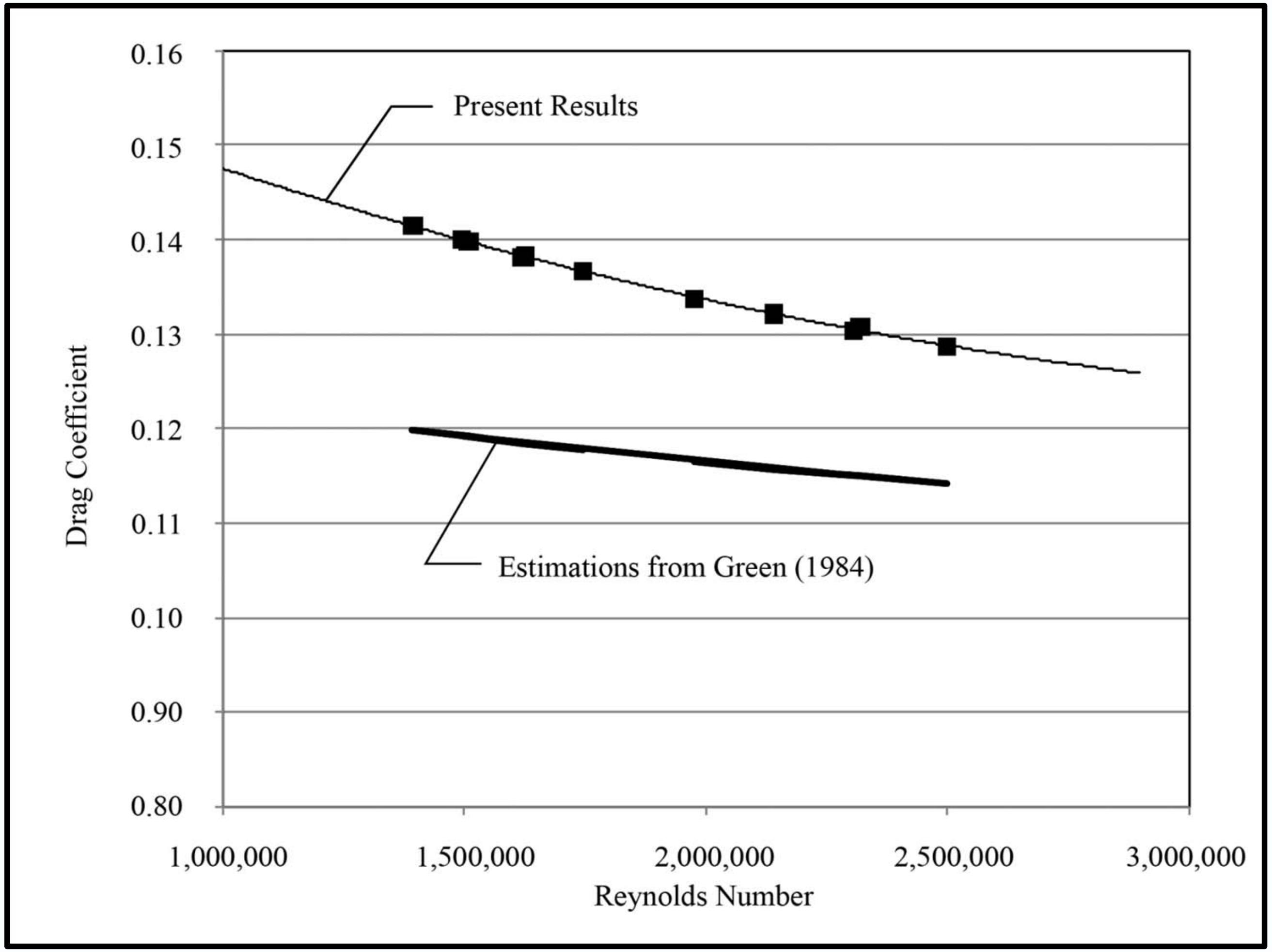

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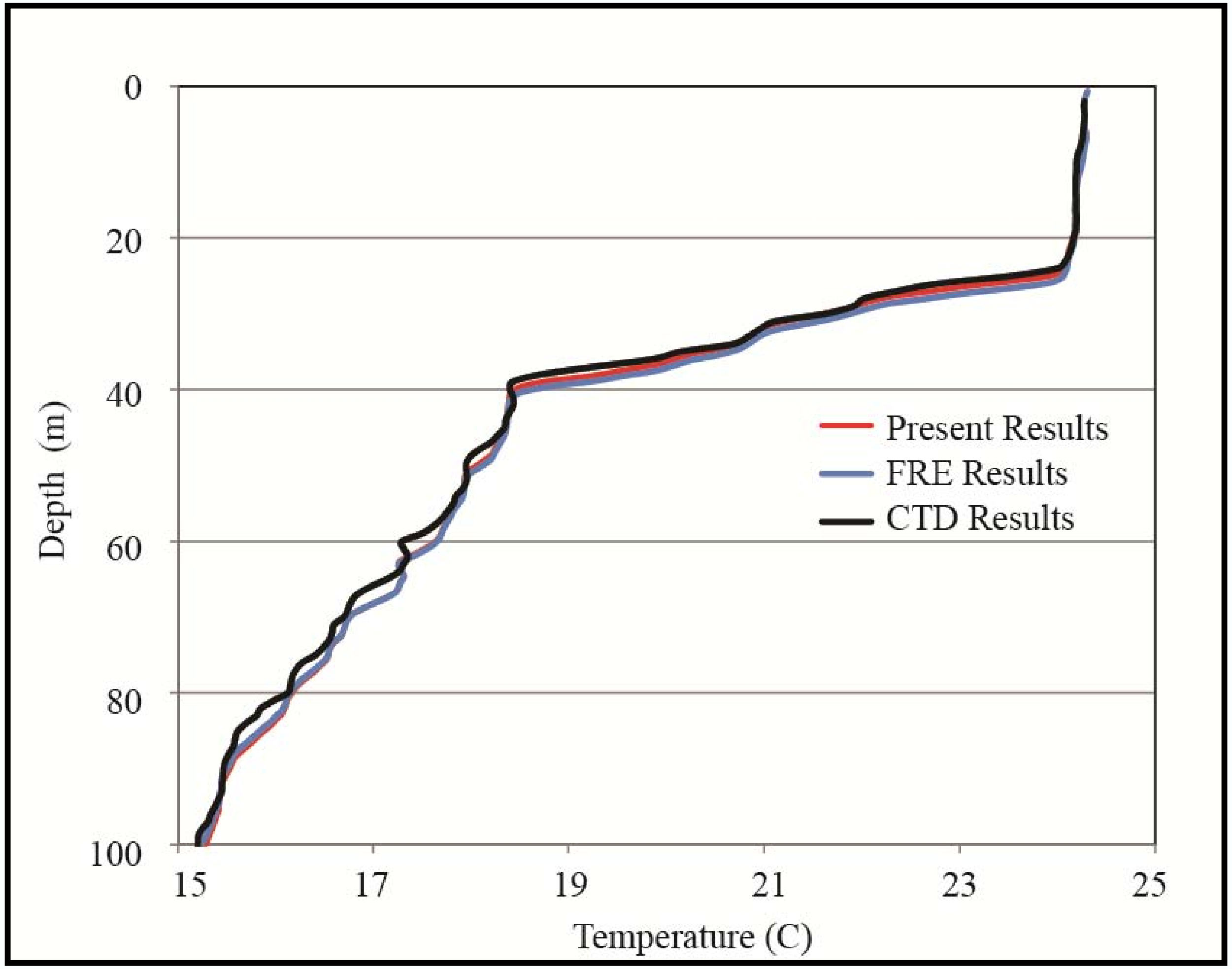

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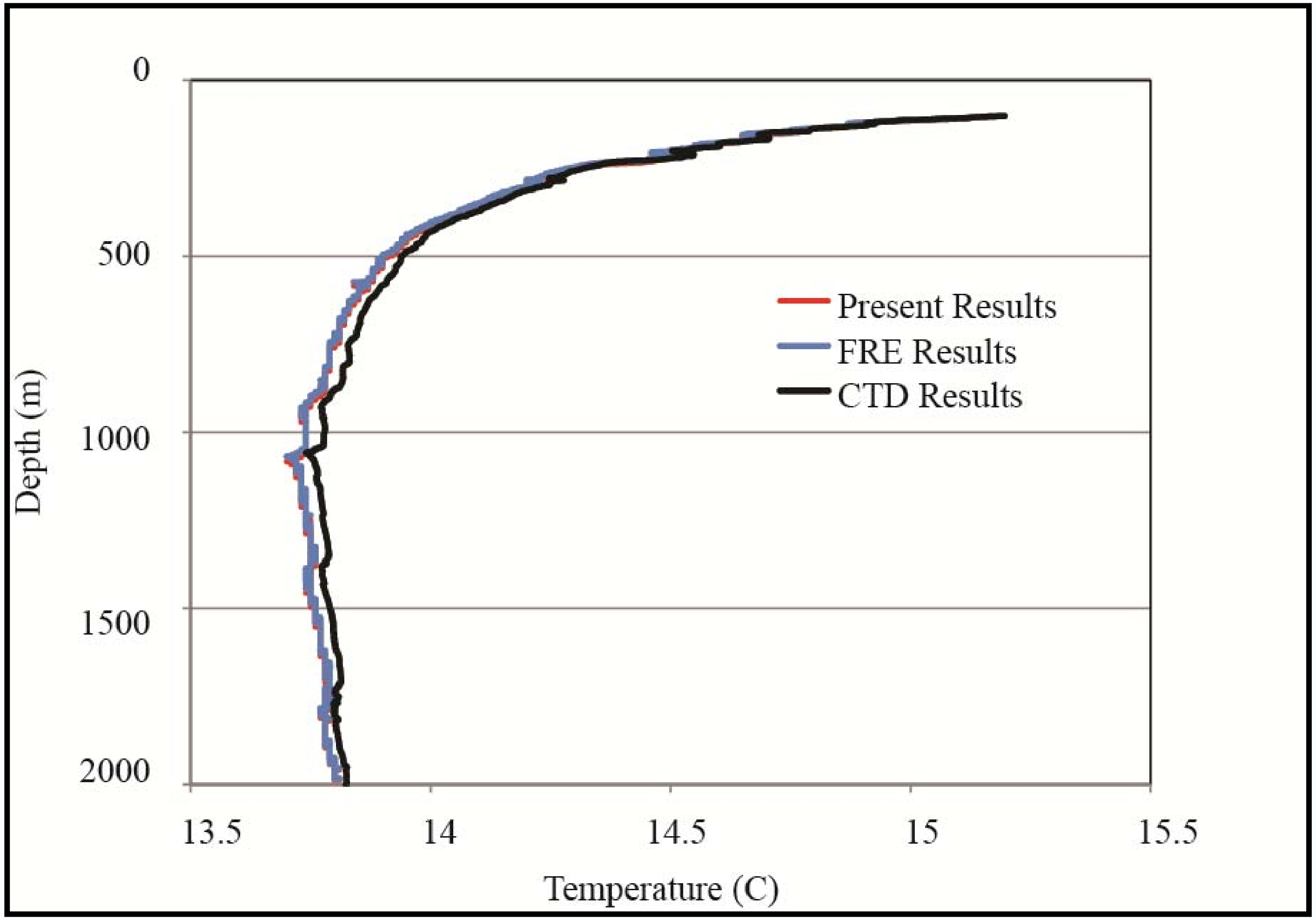

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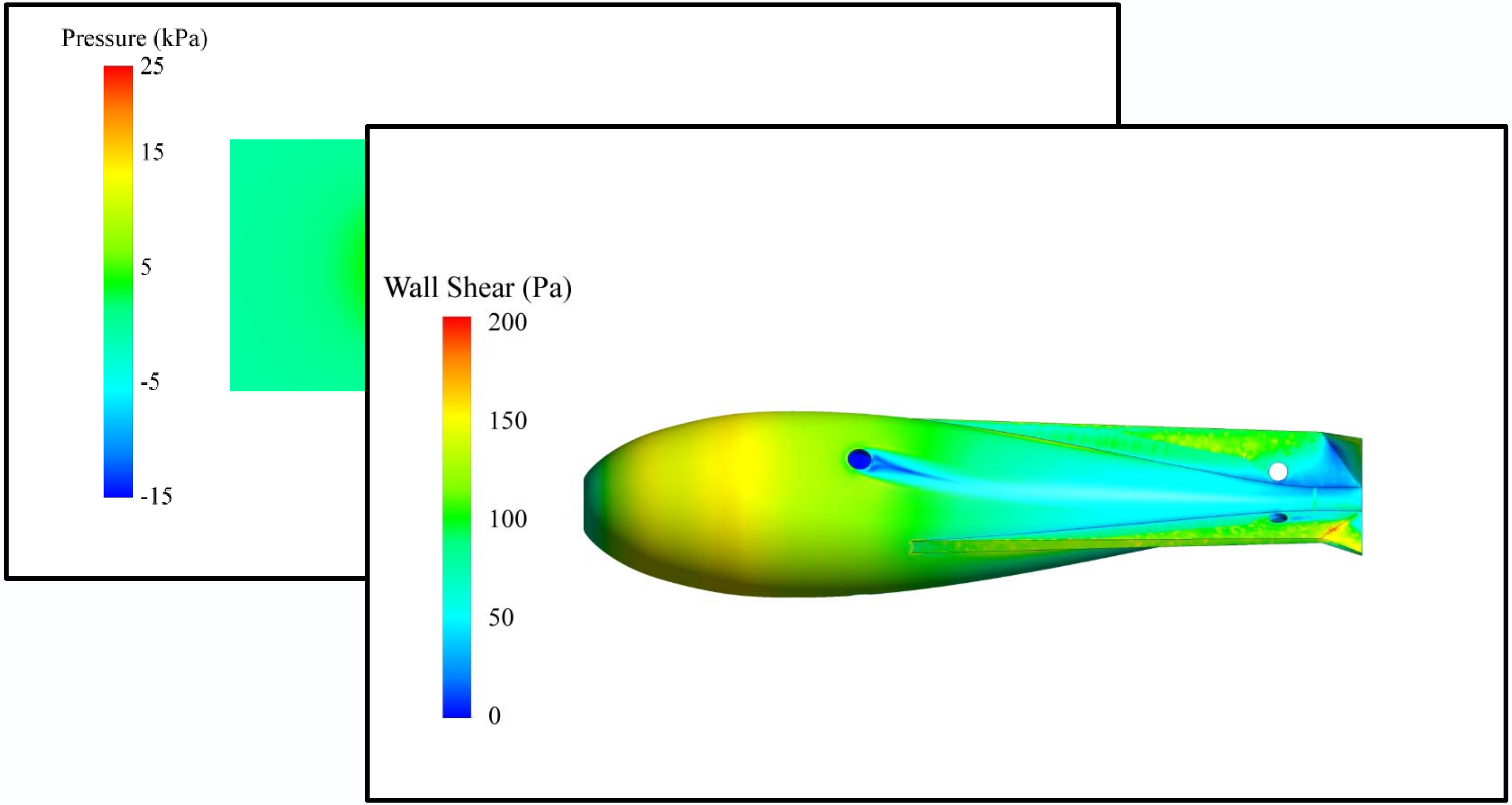

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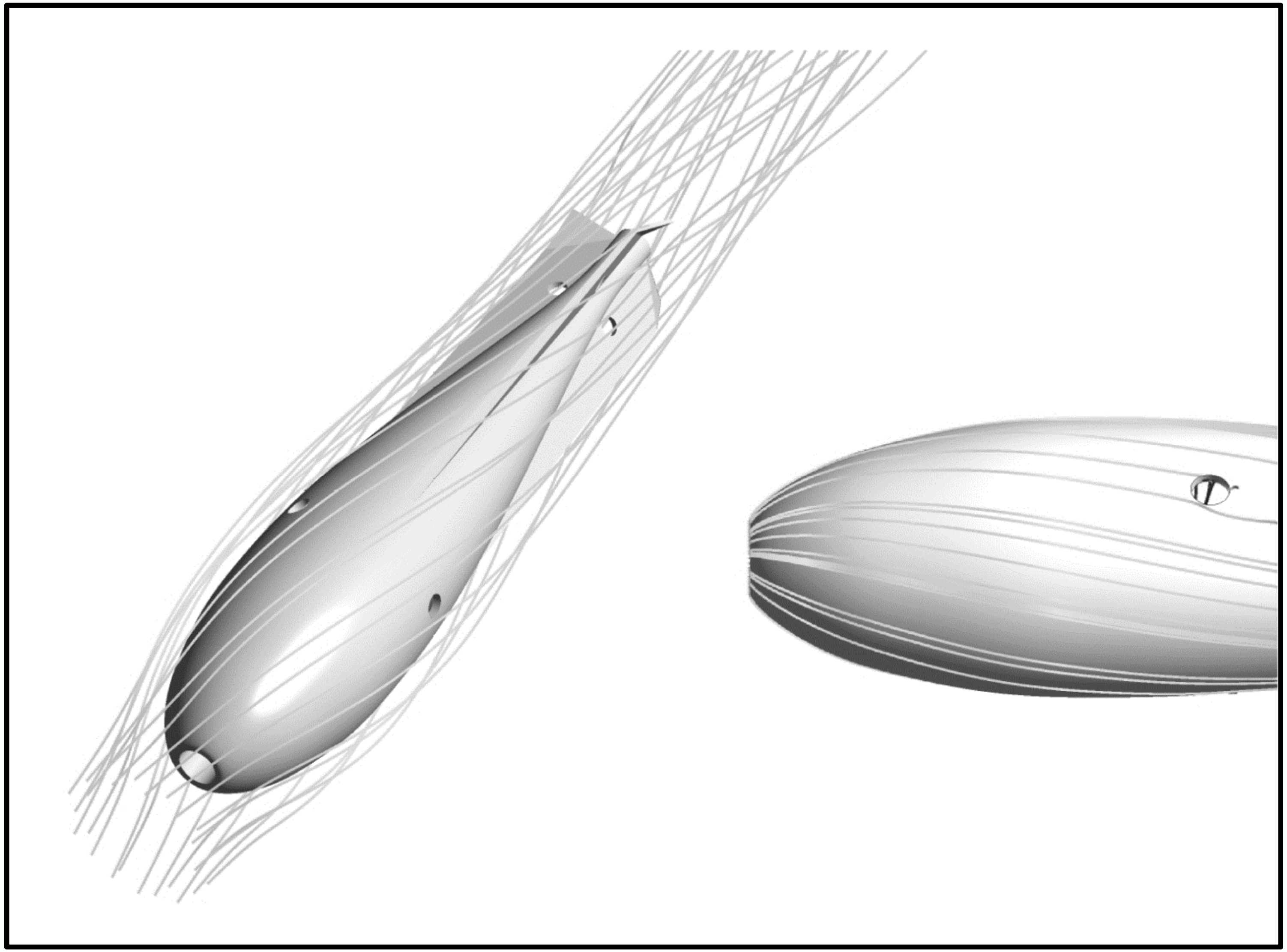

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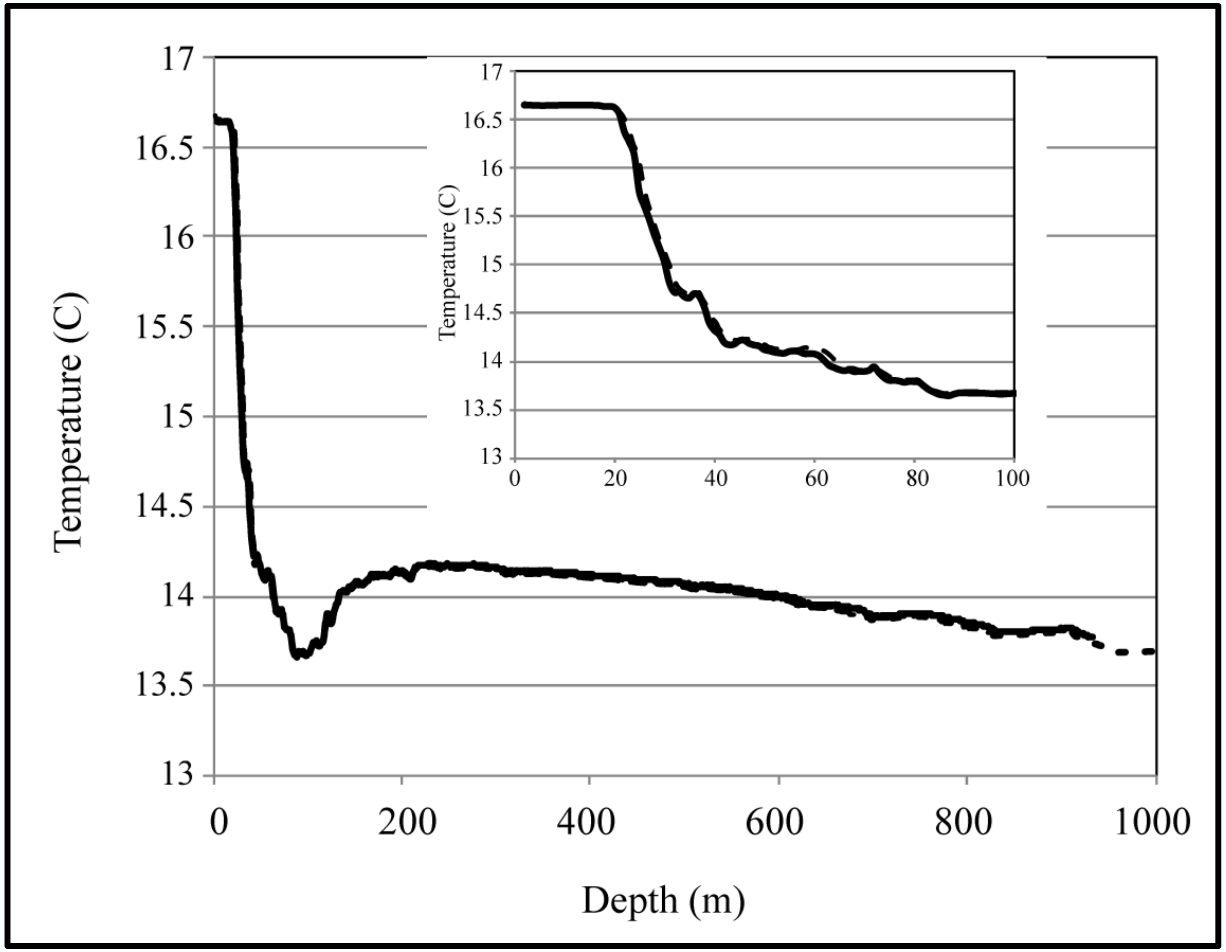


J.P. Abraham, J.M. Gorman, F. Reseghetti, E.M. Sparrow, and W.J. Minkowycz, Drag Coefficients for Rotating Expendable Bathythermographs and the Impact of Launch Parameters on Depth Predictions, *Numerical Heat Transfer A*, Vol. 62, pp. 25-43, 2012.

Thermal gradients correction outline

- A yearly linear depth correction is applied to the H95 depths (Cowley et al, 2013)
- Time and probe-type dependent
- Temperature independent

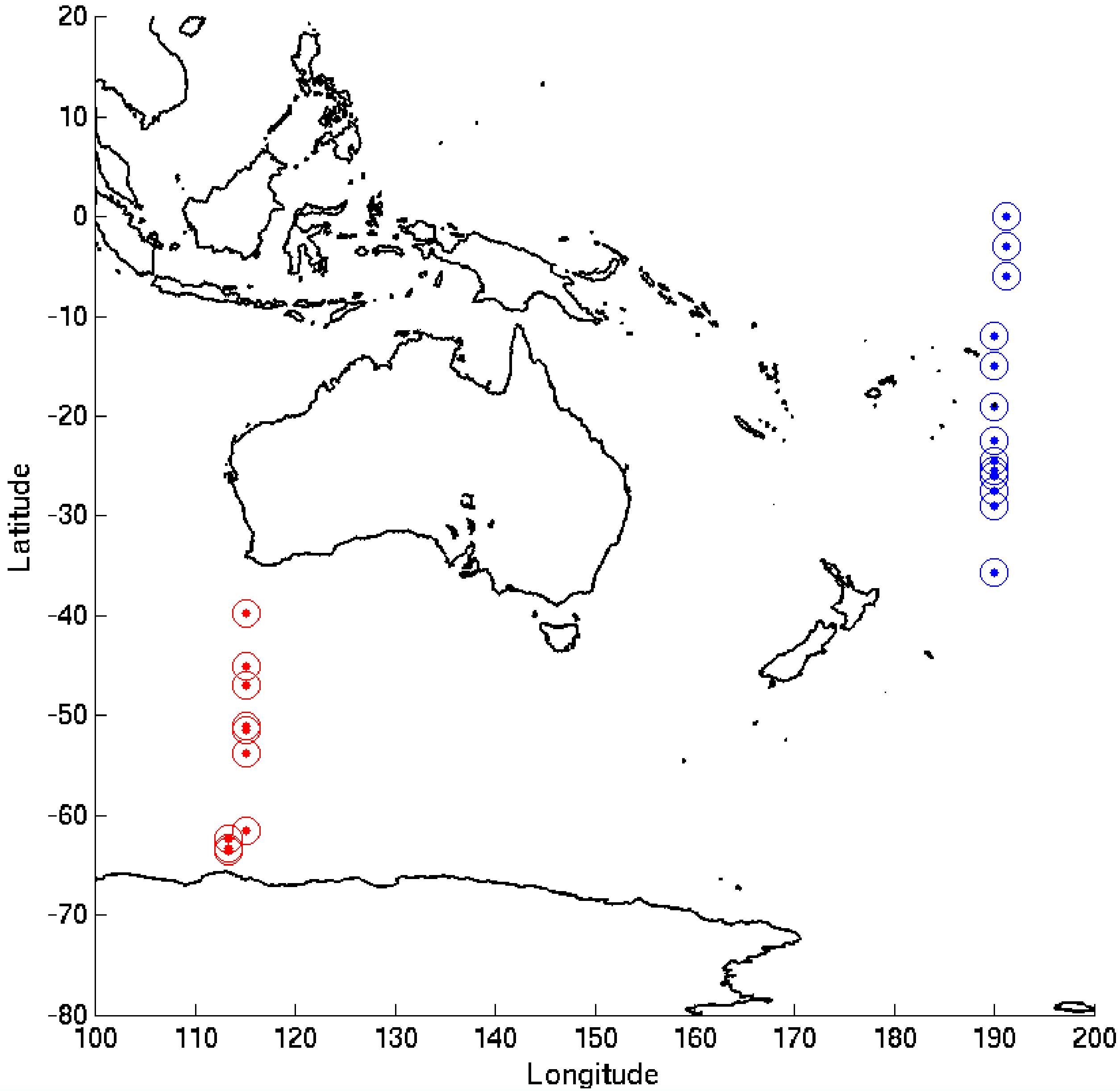
- Temperature bias correction not applied in this work.

Test of method

From the XBT/CTD pairs database:

190 Sippican Deep Blue casts from *Aurora Australis* (2012)

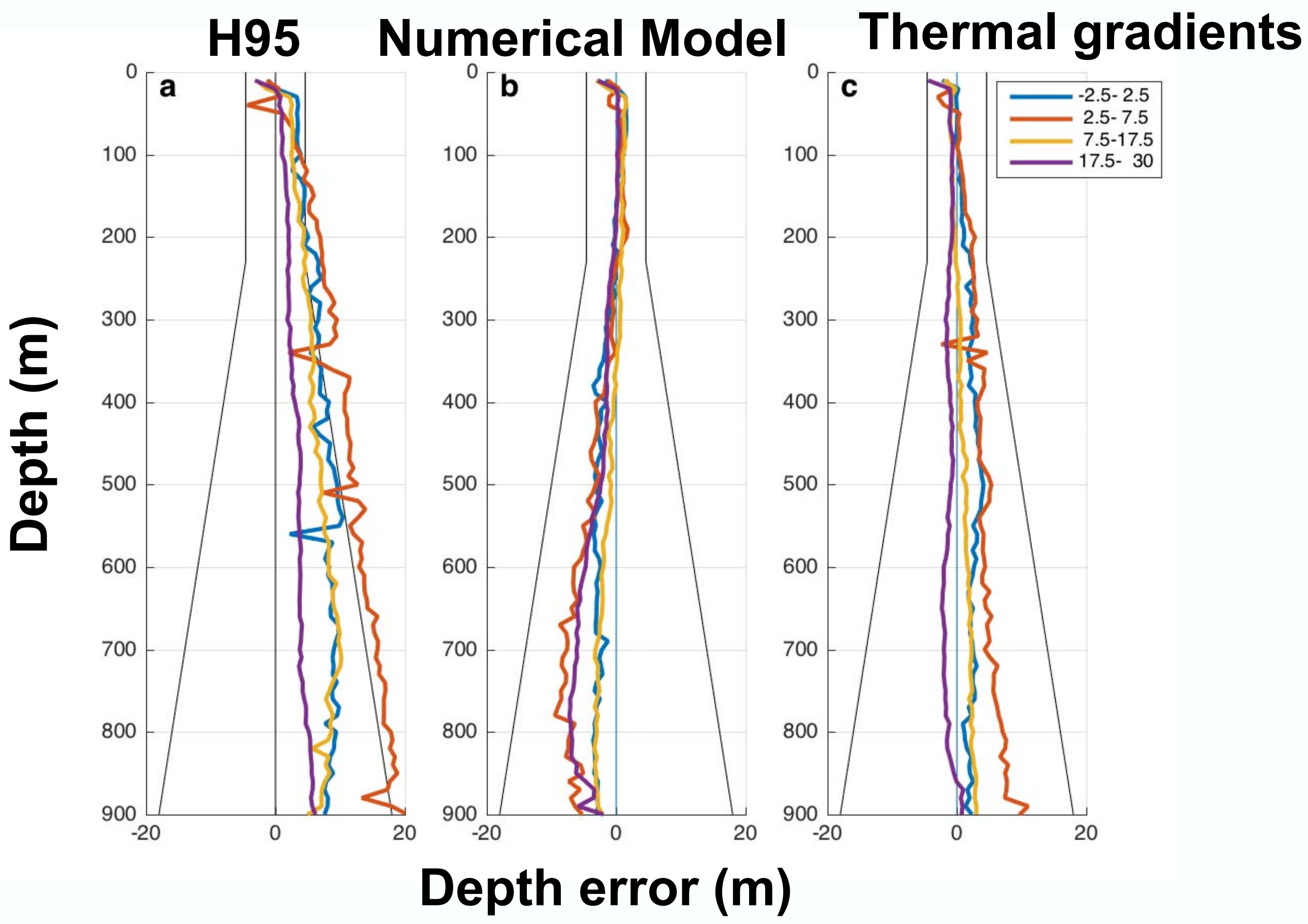
79 Sippican Deep Blue casts from *Southern Surveyor* (2009)



Test of method

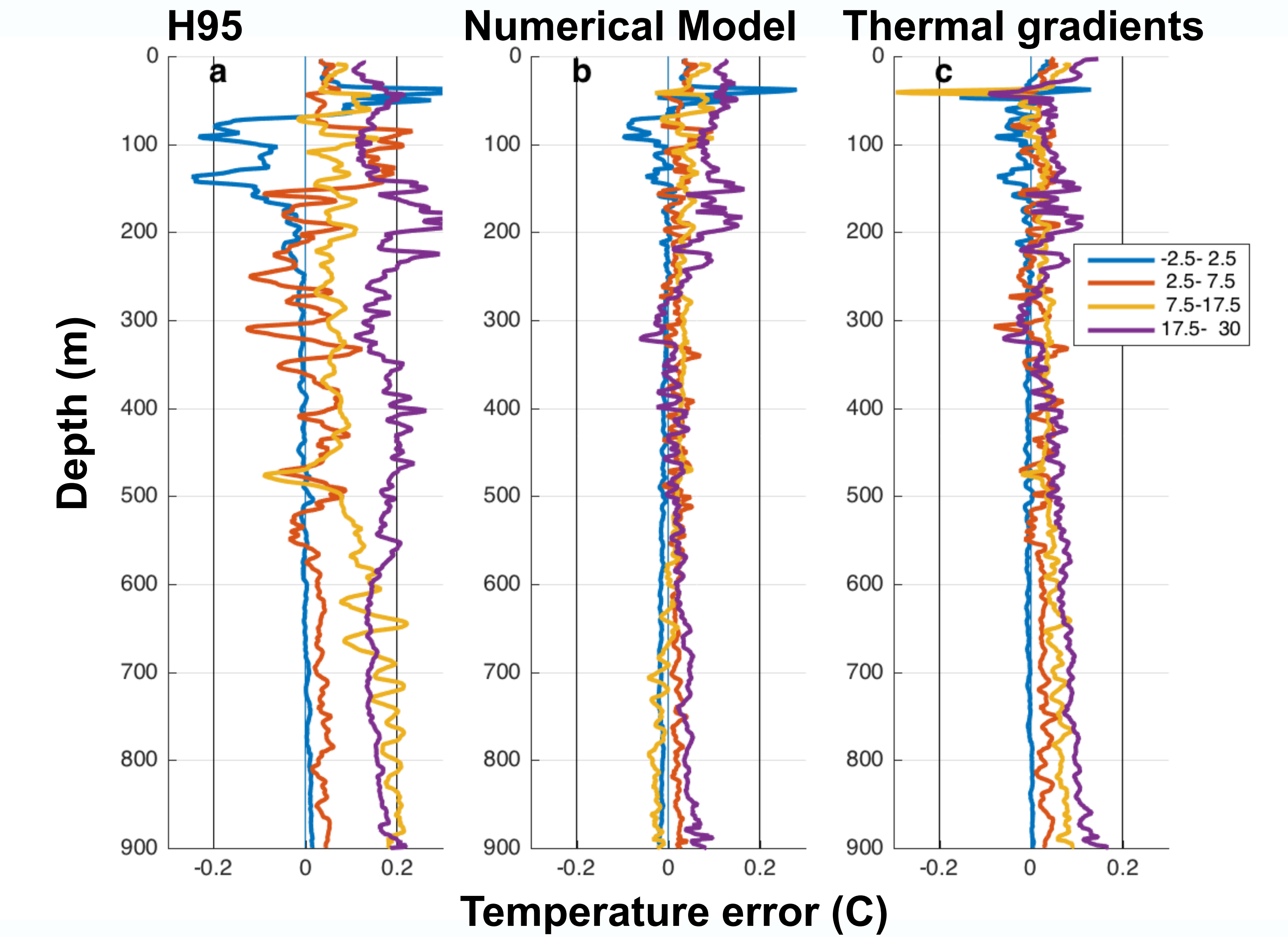
- A correlation of drag coefficient was attained using 269 co-located XBT/CTD drops. Results were then applied to a larger body of 2937 XBT/CTD pairs.

Depth error:



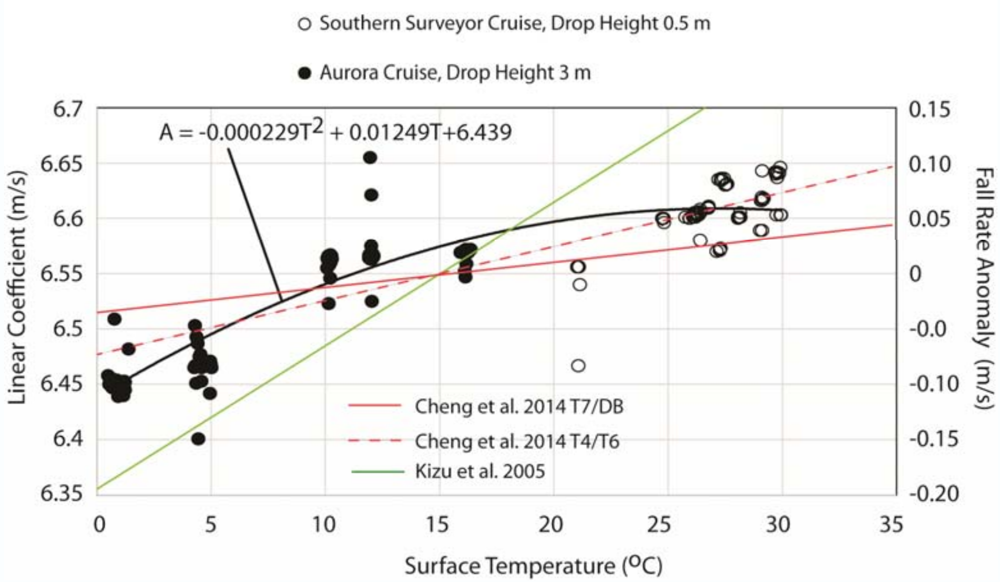
Mean depth errors in 269 XBT profiles (XBT-CTD). Color indicates temperature of upper 10 m. (a) using H95 FRE coefficients (b) after correction with temperature dependent coefficients; (c) after correction using linear depth correction values from Cowley et al, 2013.

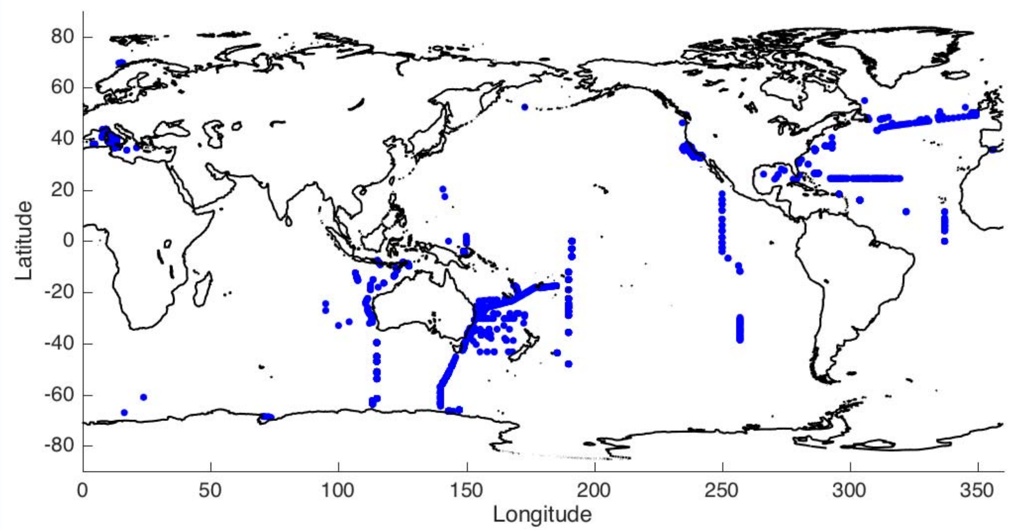
Temperature error



Simplified method

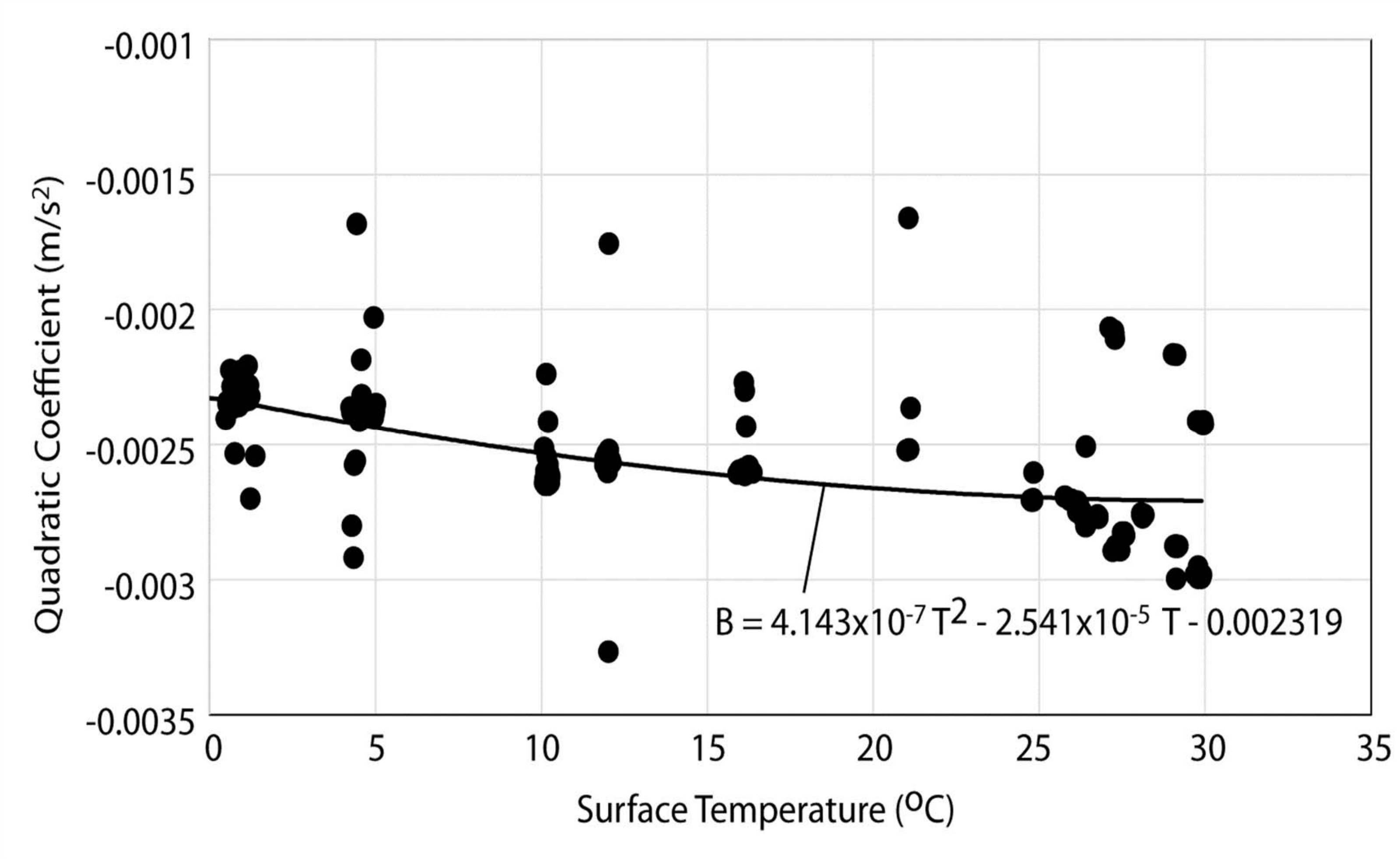
Calculate FRE coefficients based on the first temperature in the XBT profile.





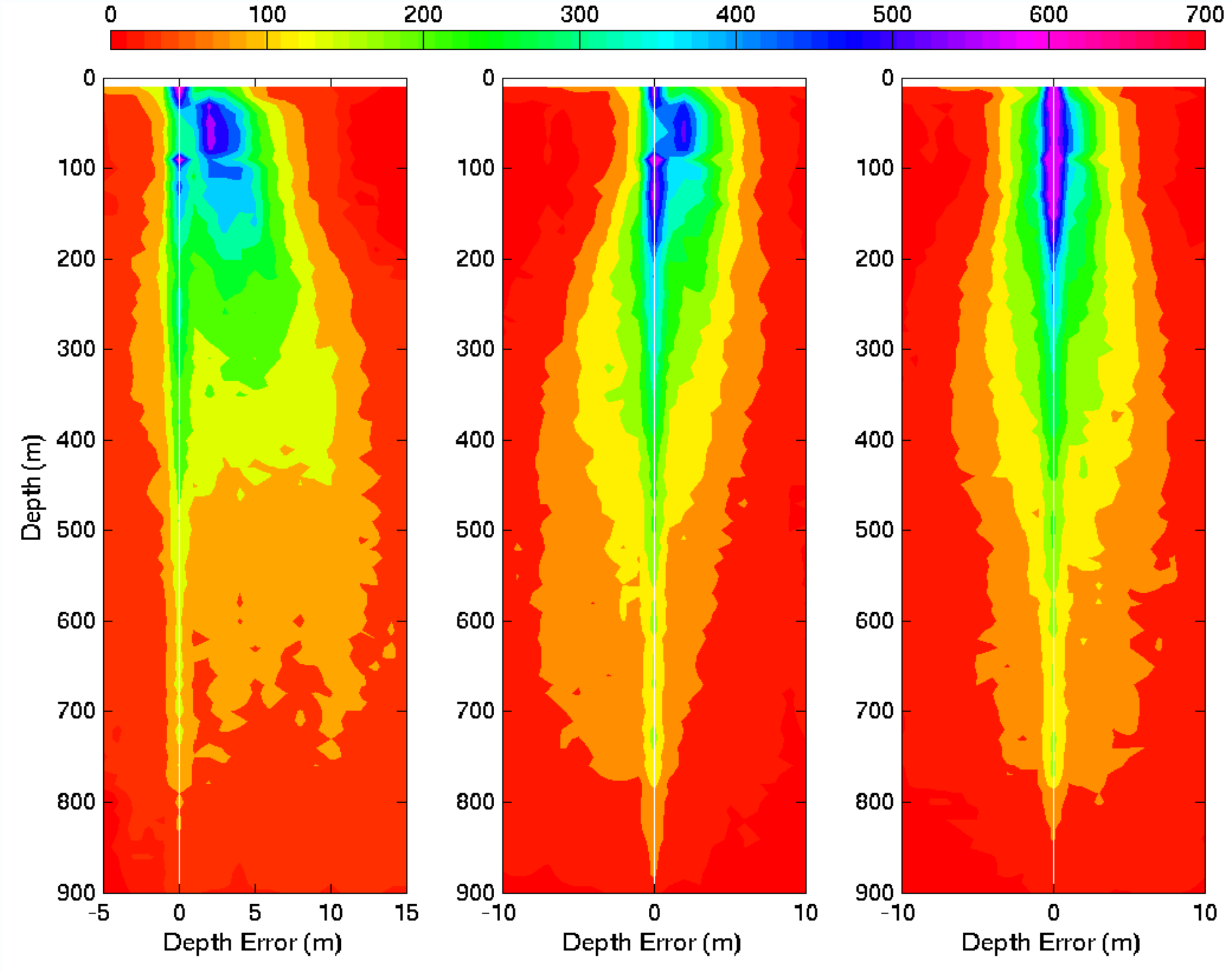
Apply these coefficients to 2,937 Sippican T4, T6, T7 and DB XBT/CTD pairs.

Simplified method



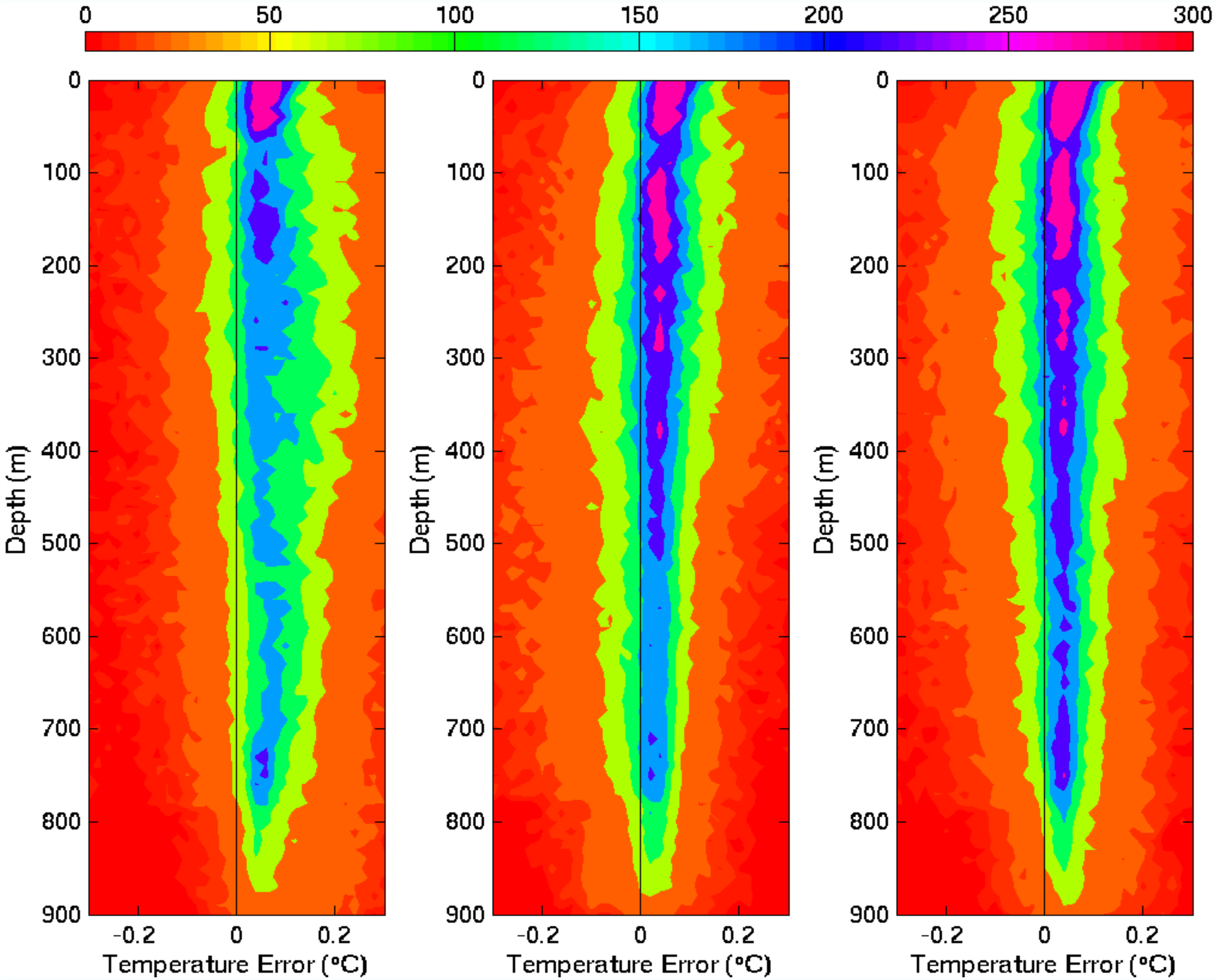
Correlation of the quadratic coefficient with surface temperature.

Depth errors



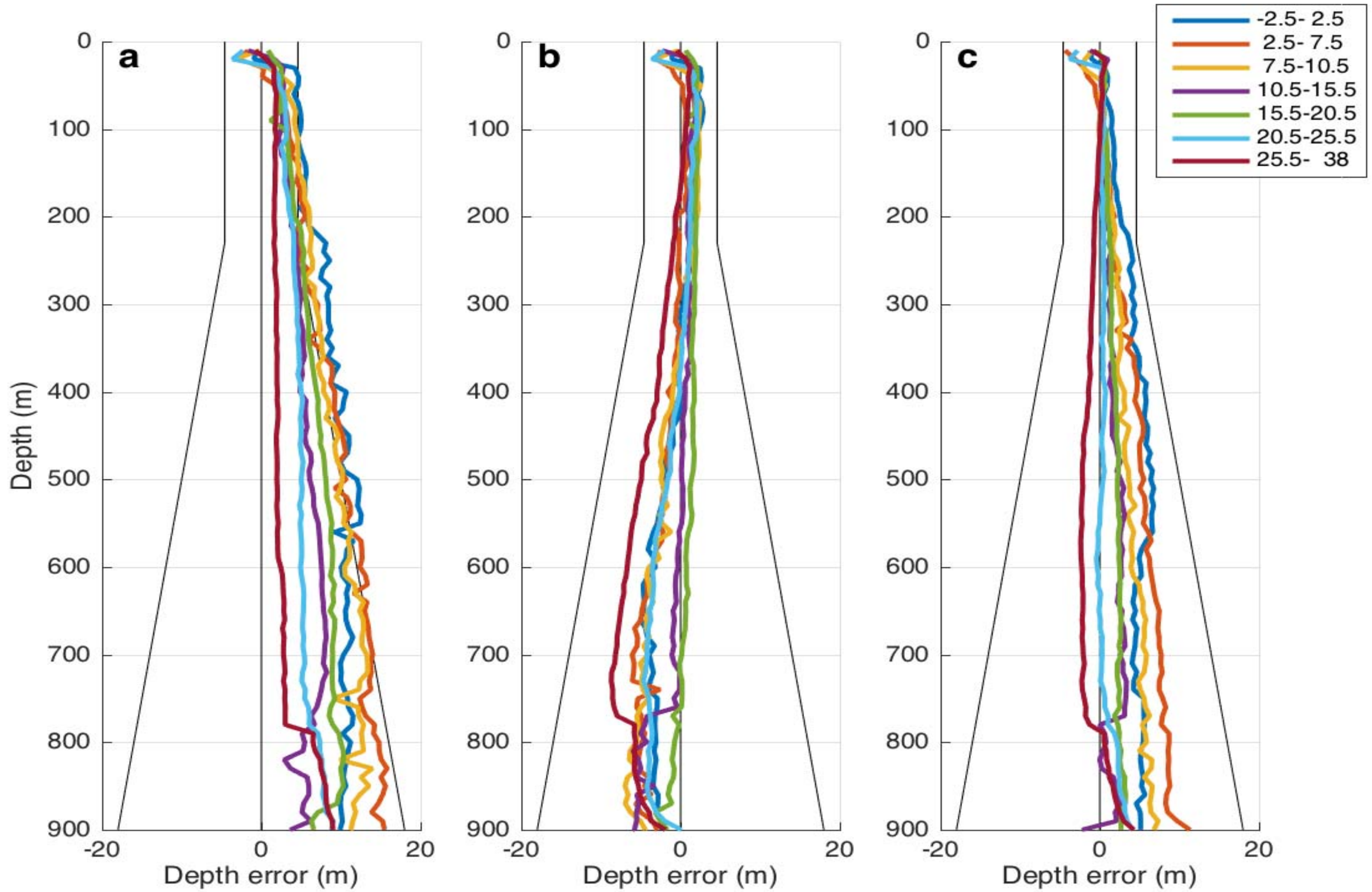
H95 **Numerical Model** **Thermal gradients**

Temperature Residuals



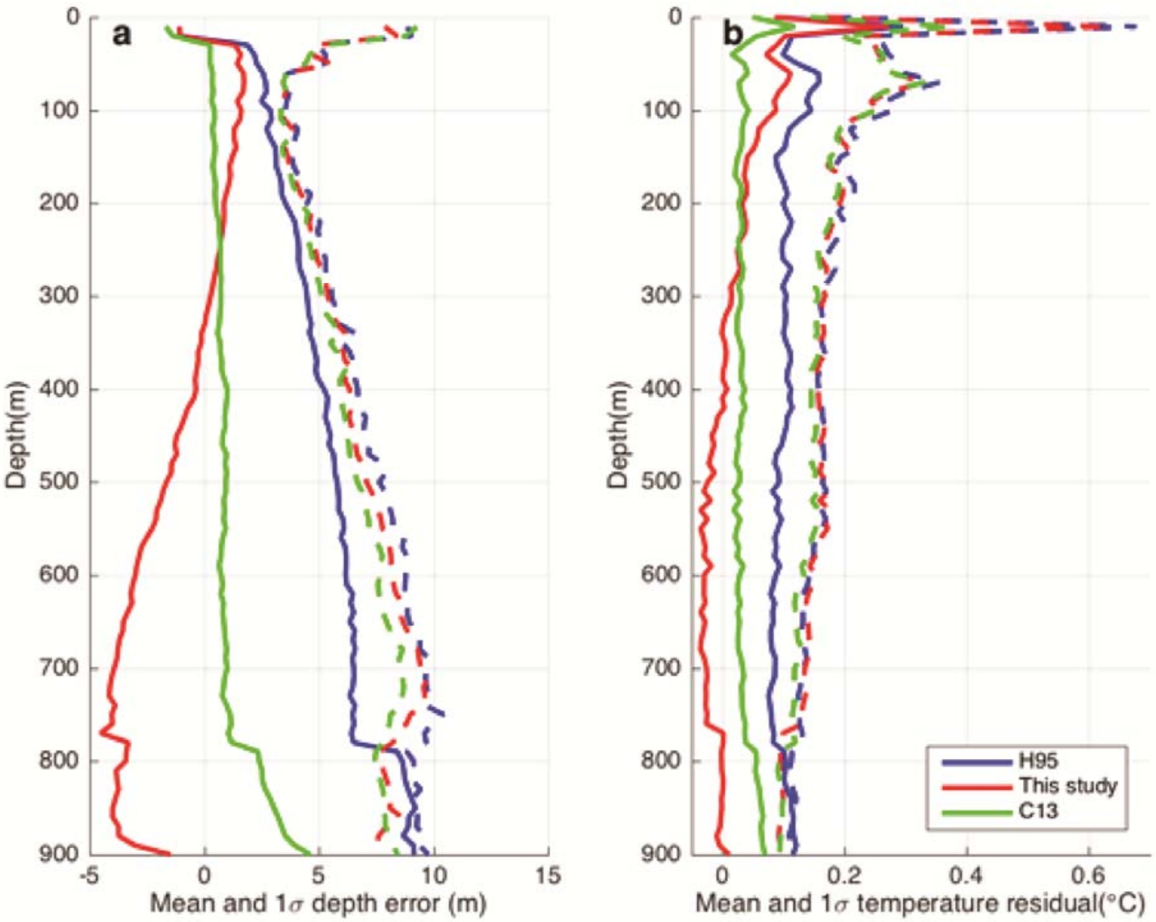
H95 **Numerical Model** **Thermal gradients**

Depth errors for various temperatures

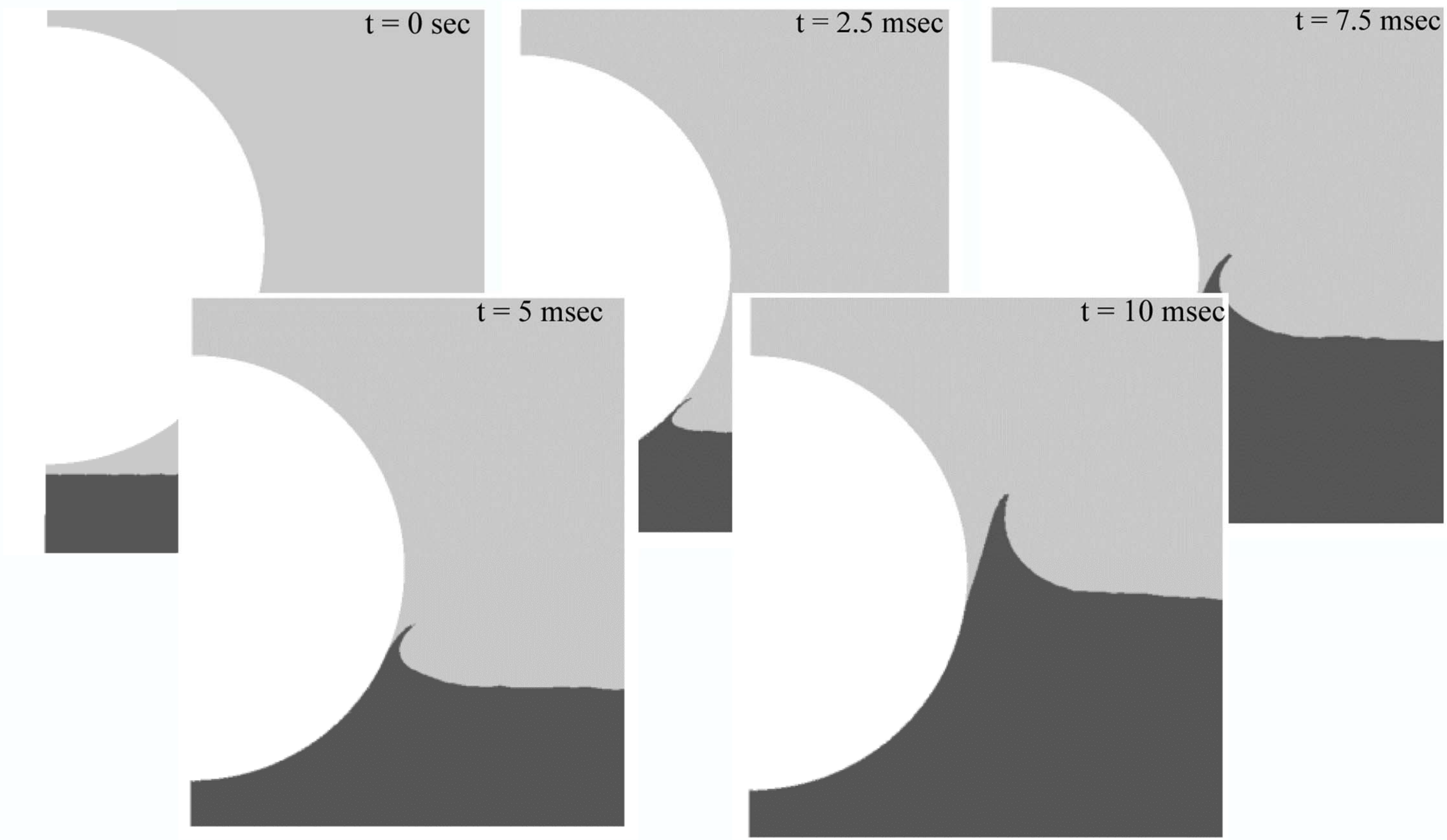


H95 **Numerical Model** **Thermal gradients**

Depth and Temperature Error Ranges



Work on Impact Forces



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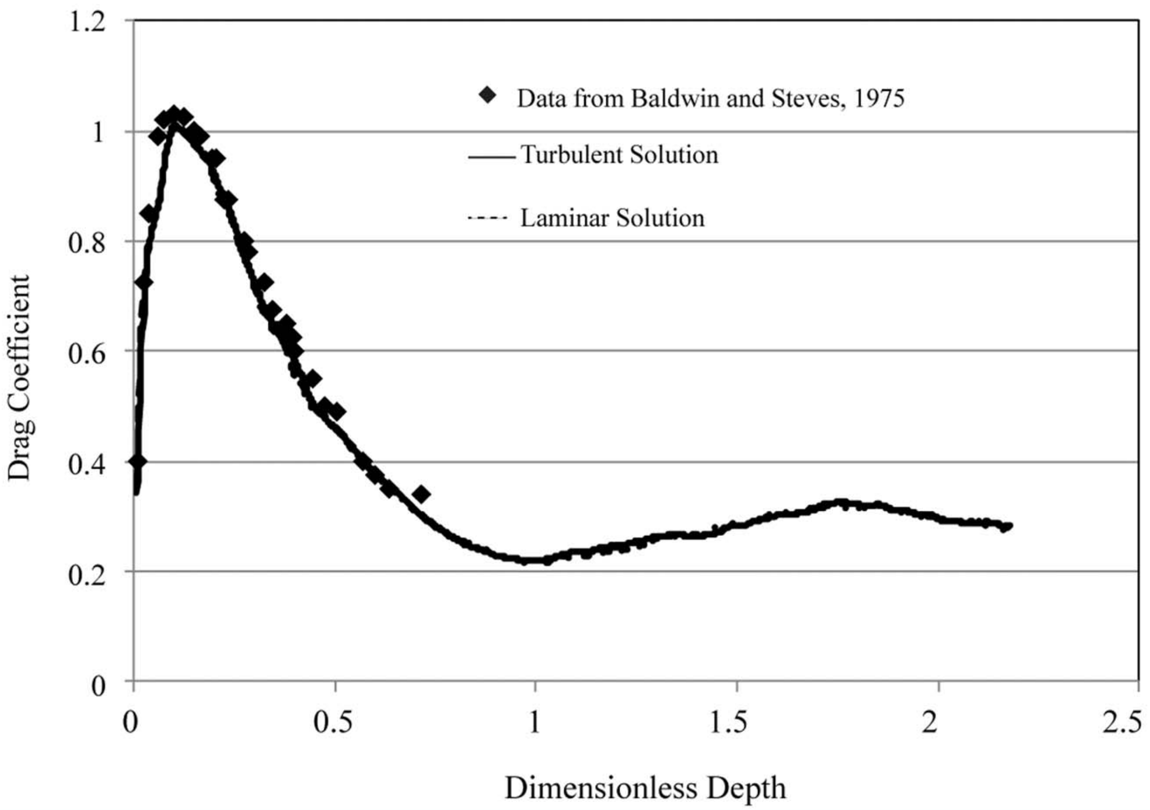

J.P. Abraham, J.M. Gorman, F. Reseghetti, E.M. Sparrow, J.R. Stark, and T.G. Shepard, Modeling and Numerical Simulation of the Forces Action on a Sphere During Early-Water Entry, *Ocean Engineering,* Vol. 76, 1-9, 2014.

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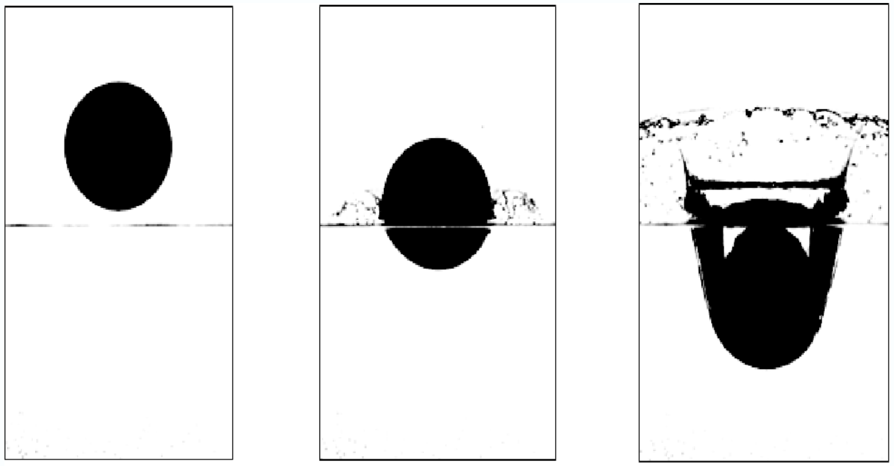

(a) (b) (c)

J.M. Gorman, J.P. Abraham, D. B. Schwalbach, T. S. Shepard, J.R. Stark, and F. Reseghetti, Experimental Verification of Drag Forces on Spherical Objects Entering Water, *Journal of Marine Biology and Oceanography*, Vol. 3, paper no. 1000126, 2014.

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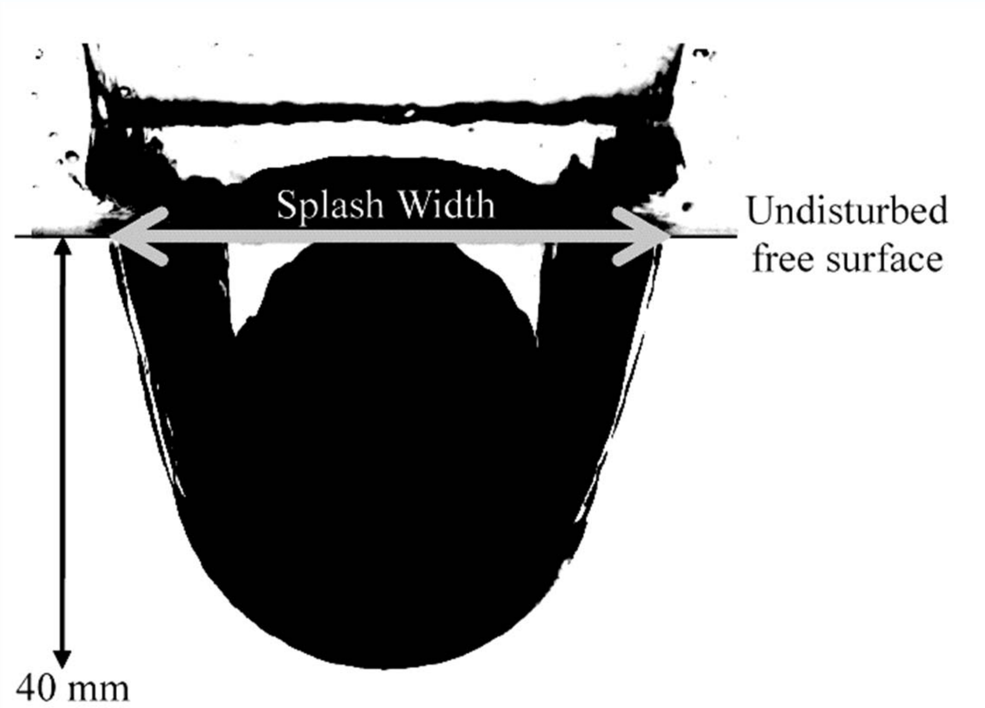

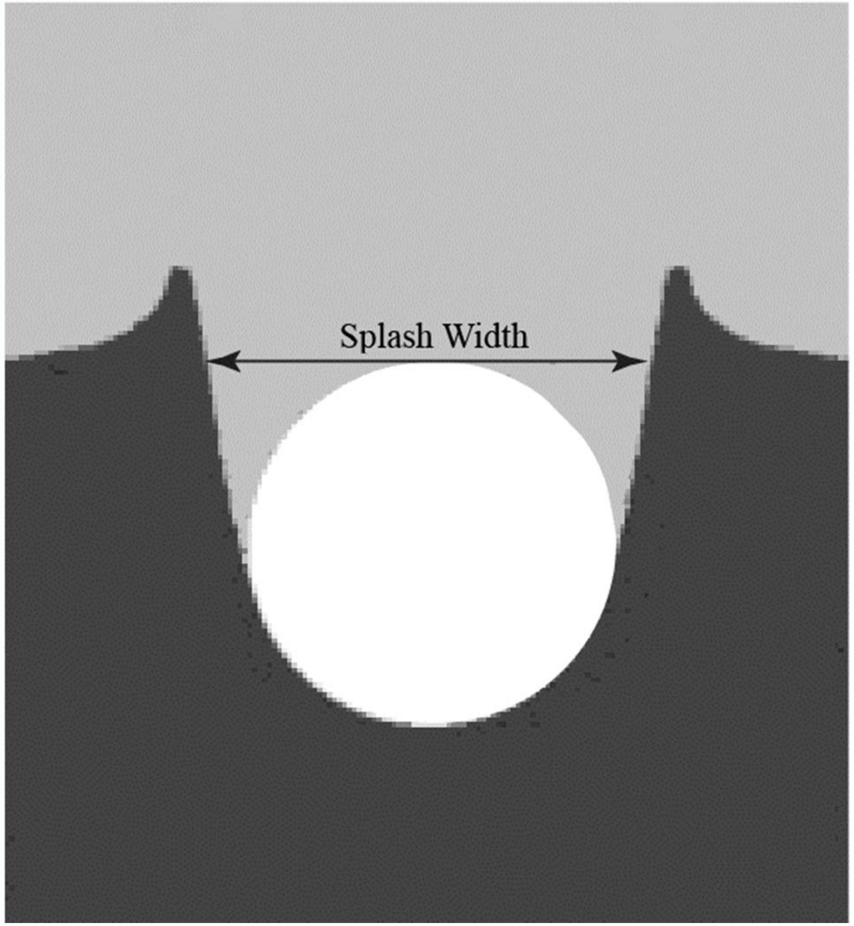

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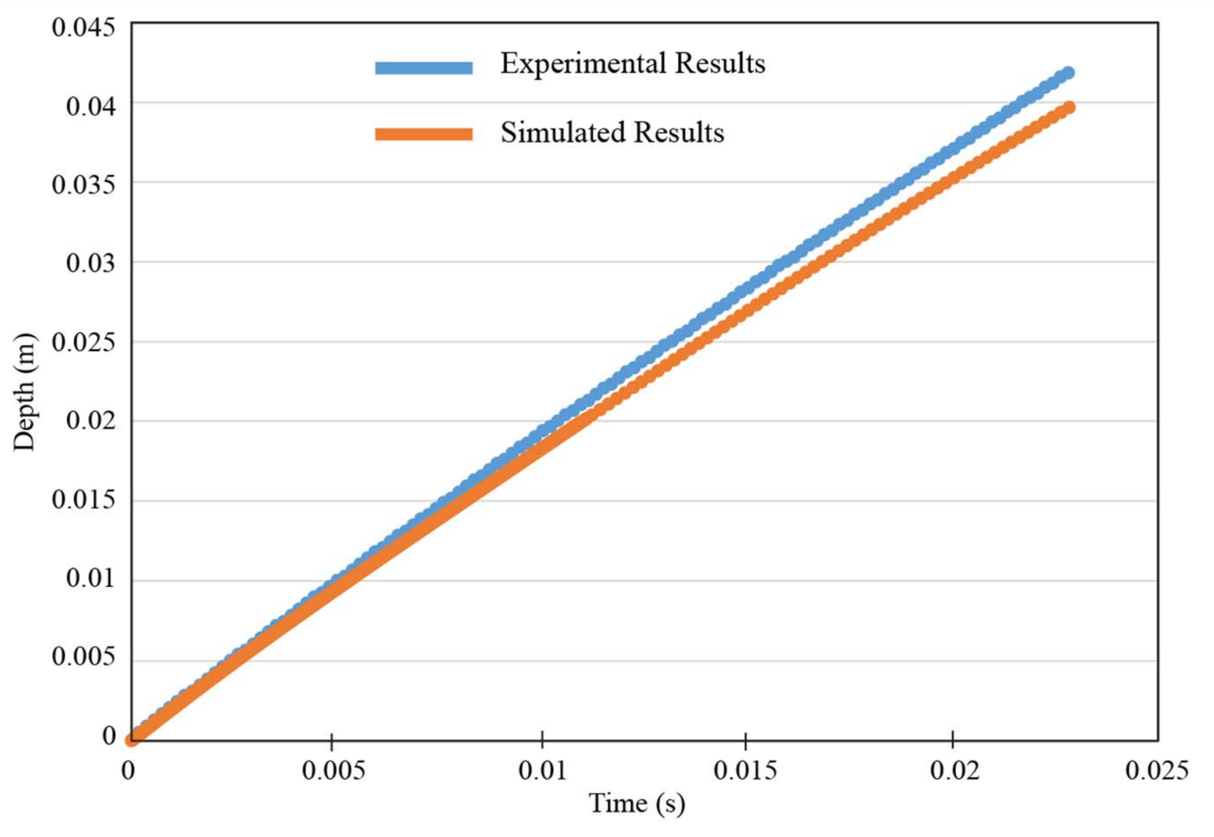

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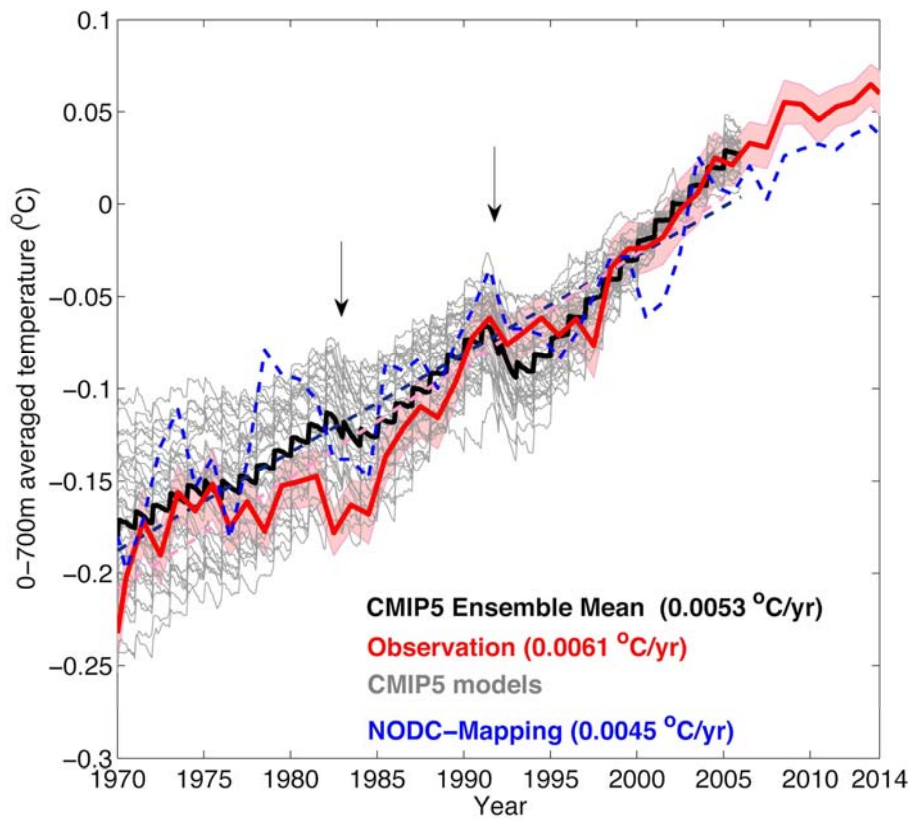
Updates to Upper OHC Rate Changes

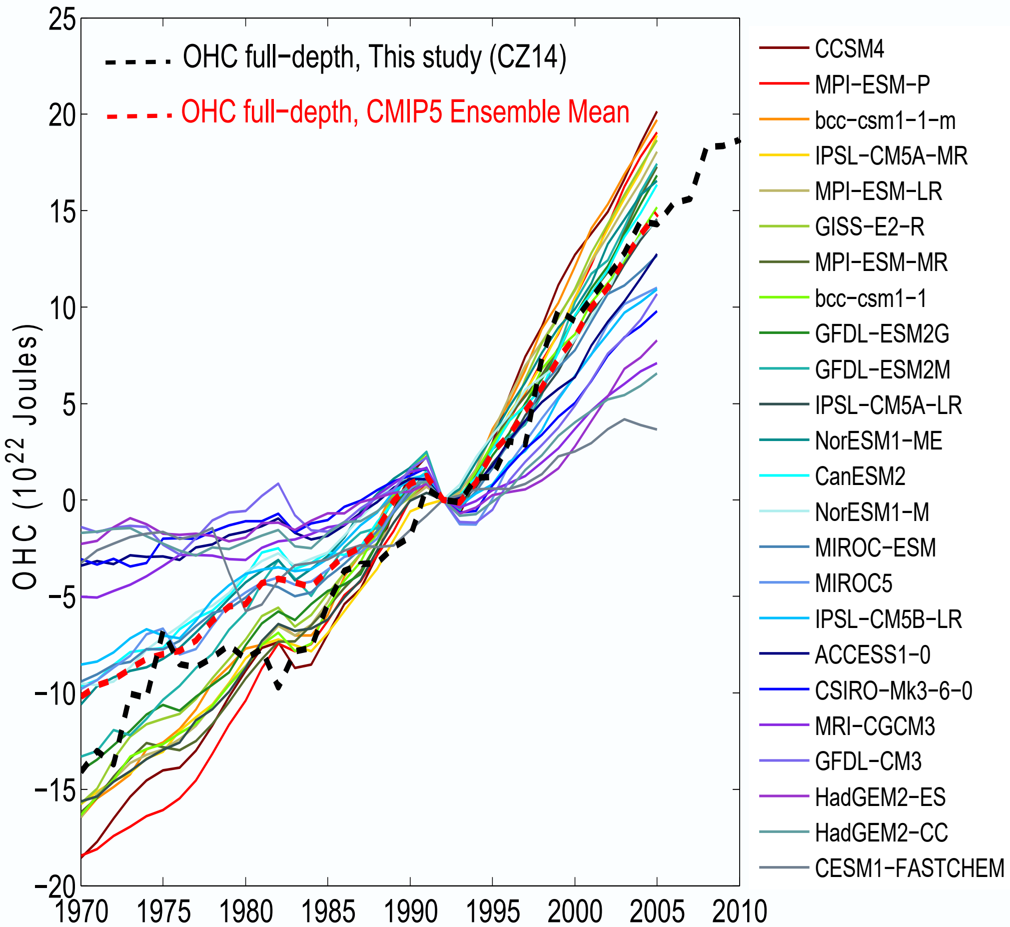


1. Corrections to XBT biases (CH14)
2. New mapping method（CZ14）
3. Climatology selection (2008-2012)
4. Data from WOD13 for 1970-2014
5. 0.56 x 10^{22} J/yr (0.78 mm/yr SLR)
6. CMIP5 models are 88% of upper OHC observations.

Upper ocean (700m) OHC changes calculated using 24 CMIP5 models (40 model runs). Black line is ensemble mean, grey lines are individual runs, red is from Cheng et al. 2015.

L. Cheng, J. Zhu, and J.P. Abraham, Global Upper Ocean Heat Content Estimation: Recent Progresses and the Remaining Challenges, *Atmospheric and Oceanic Science Letters*, Vol. 8, pp. 333-338, 2015.

Updates to Full-Depth OHC Rate Changes



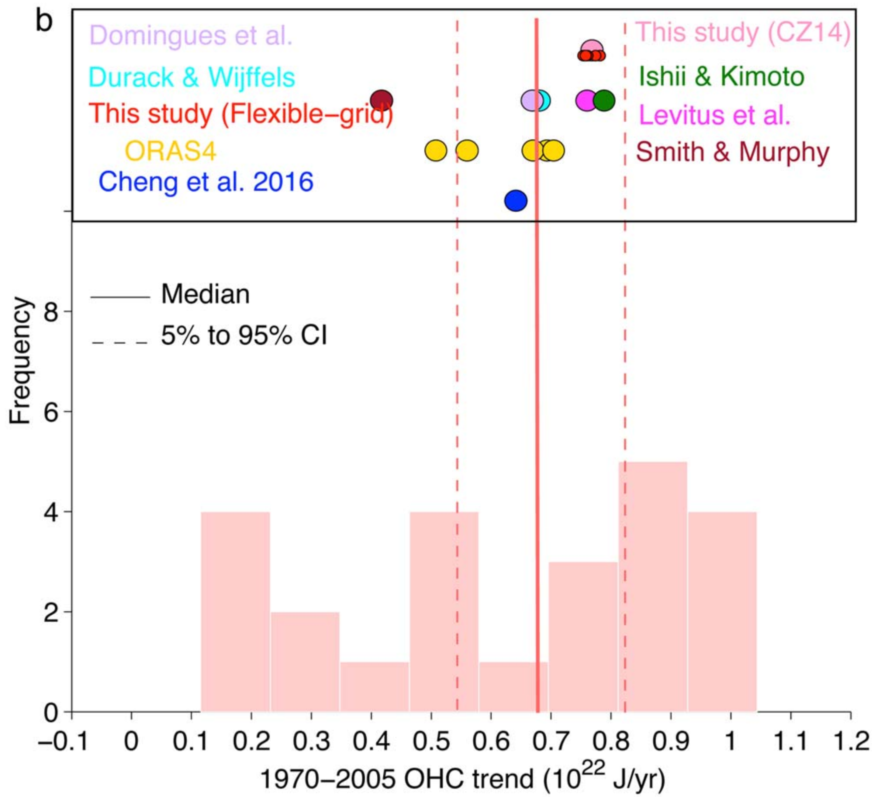
Full depth OHC by individual CMIP5 models and observations. The observational OHC time series (black dashed) is using CZ14 method (0-700m), *Levitus et al*., (2012), (700-2000m) and *Purkey and Johnson*, (2010) (2000m-bottom). The multimodel ensemble median is shown in dashed curve.

Measurements (ensemble median of 16 state-of-art OHC estimates):
1970-2005 = 0.46 W/m^2
1992-2005 = 0.75 W/m^2

CMIP5 mean:
1970-2005 = 0.41 W/m^2
1992-2005 = 0.77 W/m^2

L. Cheng, K.E. Trenberth, M.D. Palmer, J. Zhu, and J.P. Abraham, Observed and Simulated Full-Depth Ocean Heat Content Changes for 1970-2005, *Ocean Sciences*, (in press).

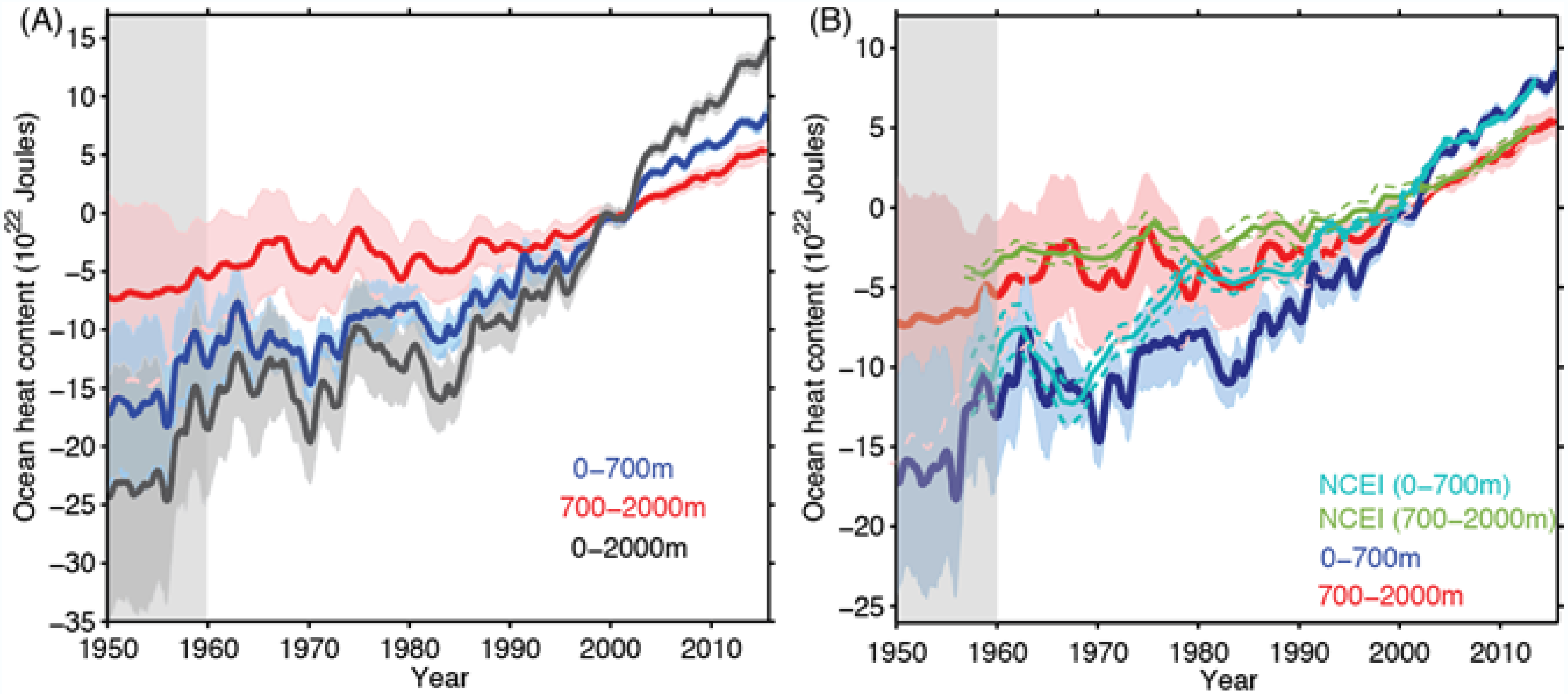
Updates to Full-Depth OHC Rate Changes



Full-depth OHC changes. For models, histograms represent distribution of results with solid line the median and dashed lines the 5-95% valuves. For observations, results are linear trends.

L. Cheng, K.E. Trenberth, M.D. Palmer, J. Zhu, and J.P. Abraham, Observed and Simulated Full-Depth Ocean Heat Content Changes for 1970-2005, *Ocean Sciences*, (in press).

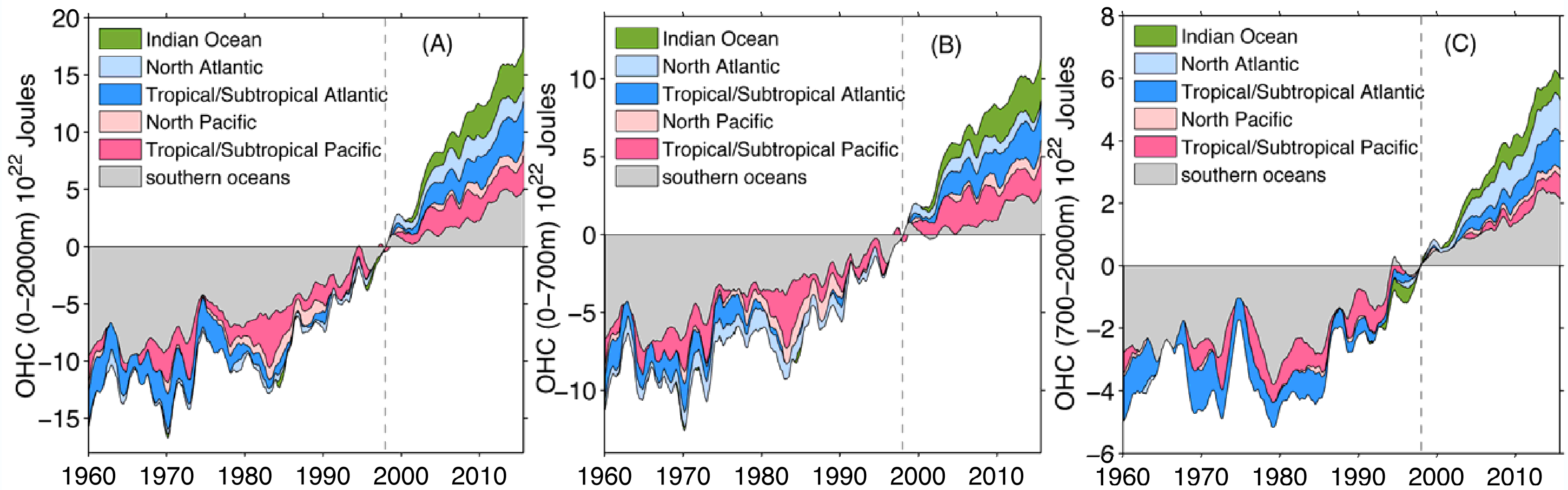
Updates to OHC Rate Changes by Depth



(A) Global OHC changes 0-700m (blue), 700-2000m (red), and 0-2000m (black) from 1955 to 2015 as obtained by this study, and the uncertainty of $\pm 2\sigma$ interval shown in shading. **(B)** Comparison with *Levitus et al.* (NCEI) with its standard error in dashed lines.

L. Cheng, K.E. Trenberth, J. Fasullo, T. Boyer, J. Abraham J. Zhu, Improved Estimates of Ocean Heat Content from 1960-2015, Science Advances (submitted).

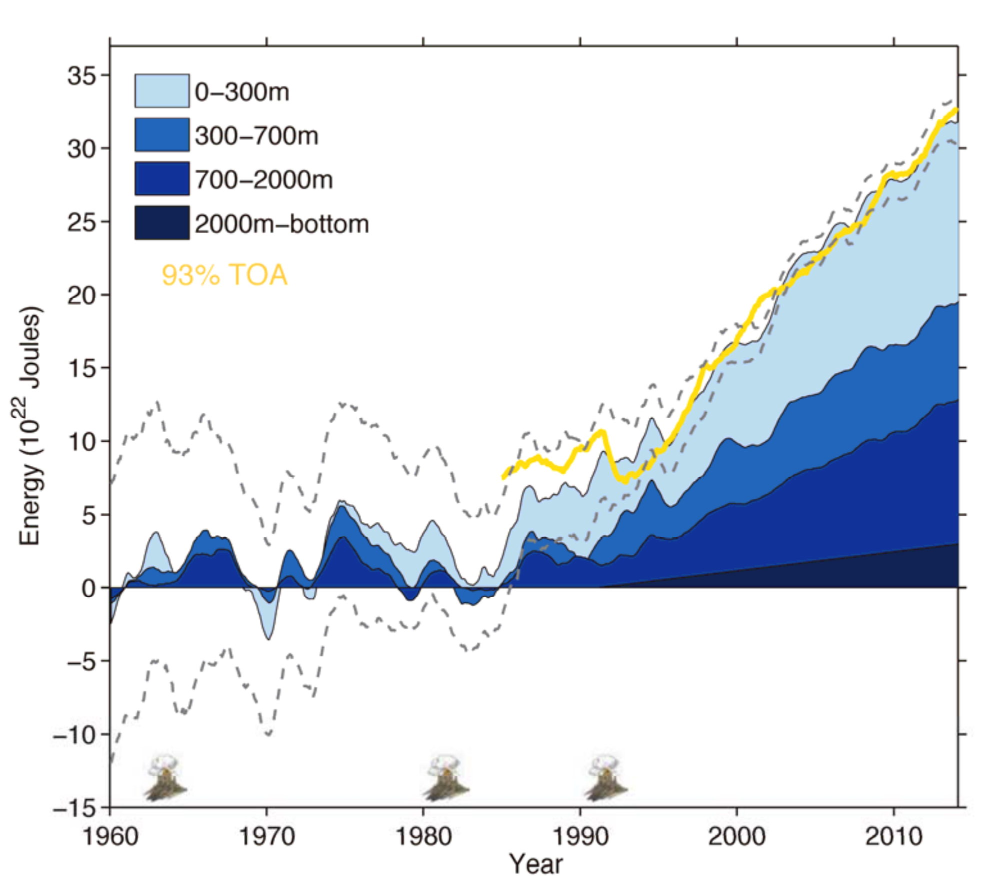
Updates to Basin OHC Rate Changes



Ocean heat content changes from 1960 to 2015 for different ocean basins. (A), for 0-2000m and (B) for 0-700m (C) 700-2000m. All of the time series are relative to the 1997-1999 base period and smoothed by a 12-month running filter.

L. Cheng, K.E. Trenberth, J. Fasullo, T. Boyer, J. Abraham J. Zhu, Improved Estimates of Ocean Heat Content from 1960-2015, Science Advances (submitted).

Updates to Layer OHC Rate Changes



Estimate of the ocean energy budget. The three major volcano eruptions are marked. The energy budgets are relative to 1958-1962 base period. The integrated net radiative imbalance from *Allan et al.* (*63*) observed from the top of atmosphere (TOA) is included in yellow multiplied by 0.93 to be comparable with ocean energy budget. The TOA radiation is adjusted to the value of OHC within 2013-2014.

For 1960-2015:
0-300m = 37%
300-700 m = 20%
700-2000 m= 30%
2000 m-below = 13%

L. Cheng, K.E. Trenberth, J. Fasullo, T. Boyer, J. Abraham J. Zhu, Improved Estimates of Ocean Heat Content from 1960-2015, Science Advances (submitted).

Conclusions

- Simplified method of numerical fluid dynamic model reduces the error in XBT data.
  - Over corrects at depth, under corrects at the surface
- Temperature affects the linear term (*A*) by 2.2% over the range 0 – 30°C
- Computational time and effort is high with the full model, simplified model is still effective.
- New OHC estimates are provided
- Comparison with models show excellent agreement
- OHC should be a fundamental metric to assess models