Thermodynamic Growth of Sea Ice in the Weddell Sea

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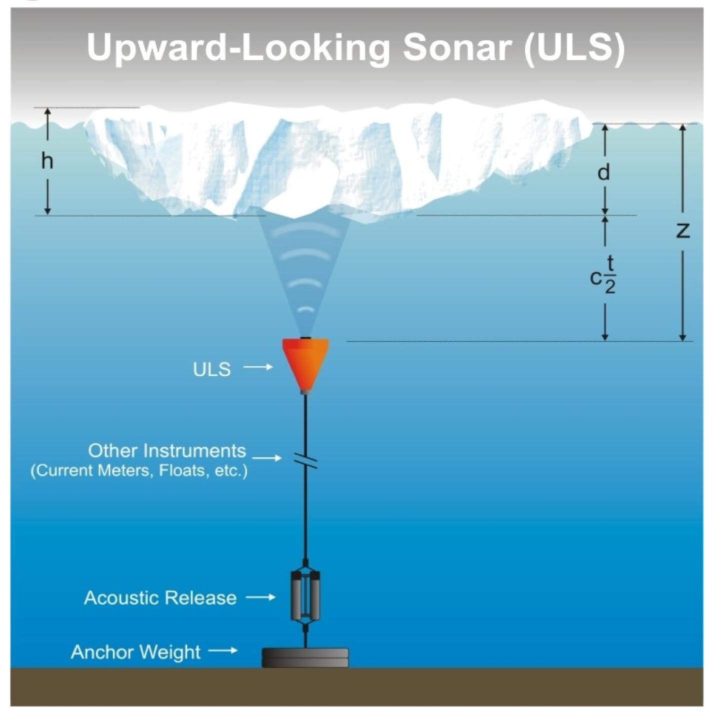
1 Introduction & Objectives



h: Ice Thickness c: Sound Speed
d: Ice Draft t: Signal Travel Time
z: ULS Depth

Fig. 1: ***Mooring arrangement with upward-looking sonar (ULS) [1].***

Thickness measurements of Southern Ocean sea ice are very sparse and satellite altimetry still provides relatively uncertain estimates of ice thickness. The only tool for monitoring sea ice thickness over long periods of time with sufficient accuracy are moored upward looking sonars (ULS). The instruments measure the subsurface portion (draft) of the ice by recording the travel times of sonar signals (Fig. 1).

We present ULS data from the central Weddell Sea, where the sea ice starts forming in April and disappears in January of the following year (length of growth period: ~180 days).

We use the data together with Stefan's Law to estimate the two quantities that limit the maximum thermodynamic ice growth in austral winter to about 1 m: (a) The snow cover on top of the ice and (b) the oceanic heat flux from below.

2 Data

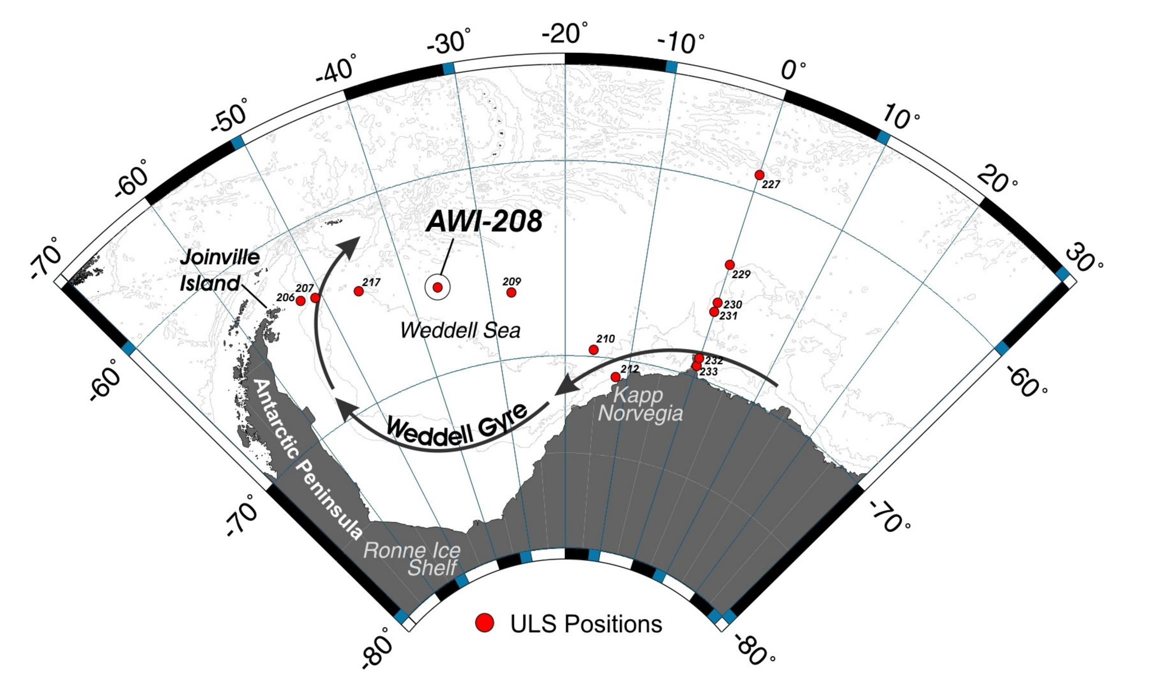


Fig. 2: ***Positions of the AWI mooring array in the Weddell Sea.***

The data for this study are from the ULS attached to mooring *AWI-208* in the centre of the Weddell Gyre (Fig. 2).

The ULS of *AWI-208* measured in 1993-1994 with a lograte of 4 minutes and for three years between 2008-2010 with a lograte of 1 minute. The uncertainty of the ULS data was estimated as ±5-12 cm [1].

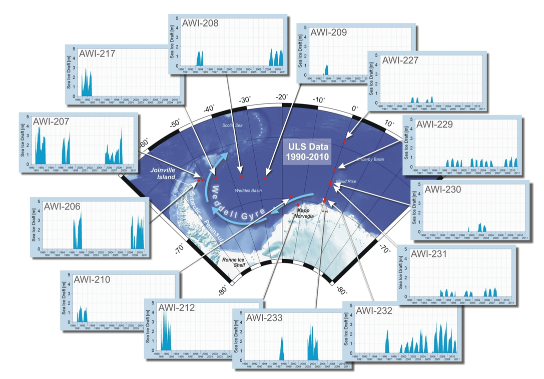
The surface air temperatures for calculating ice thickness using Stefan's Law were taken from the ECMWF Interim reanalysis project.

References

[1] A. Behrendt, W. Dierking, E. Fahrbach, H. Witte (2013) *Sea ice draft in the Weddell Sea, measured by upward looking sonars*, Earth System Science Data, 5, 209-226

[2] Petrich C., H. Eicken (2010) *Growth, Structure and Properties of Sea Ice*, In: Sea Ice (second edition), D.N. Thomas and G.S. Dieckmann (eds.), Blackwell Publishing Ltd.

[3] Fowler C. (2013) *Polar Pathfinder Daily 25 km EASE-Grid Sea Ice Motion Vectors*, Boulder, Colorado USA: National Snow and Ice Data Center. Digital media.



Download the full ULS dataset from the PANGAEA archive:
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3 Stefan's Law

$$H = \sqrt{\frac{2\lambda_i}{\rho_i L_i \left(1 + \frac{\lambda_i}{\lambda_s} r\right)} \int_0^T (T_w - T_a)\,dt + A^2} - A - \frac{1}{\rho_i L_i} \int_0^T F_w \, dt$$

$$A = \left(\frac{\lambda_i}{k\left(1 + \frac{\lambda_i}{\lambda_s} r\right)} \right) \quad \text{and} \quad r = h/H$$

H: Ice Thickness
h: Snow Layer Thickness
ρ_i: Ice Density
L_i: Latent Heat of Ice
$T_{a,w}$: Air/Water Temperature
k: Heat Transfer Coefficient
$\lambda_{i,s}$: Ice/Snow Thermal Conductivity
F_w: Oceanic Heat Flux

Modified form of Stefan's Law with ice-atmosphere coupling (*k*), a snow layer which is assumed to increase linearly with ice thickness (*h* = *r H*) and a constant oceanic heat flux (F_w) [2].

ρ_i = 0.92 g cm^{-3} L_i = 334 J g^{-1}
λ_i = 2.2 W m^{-1} K^{-1} k = 22 W m^{-2} K^{-1}
λ_s = 0.19 W m^{-1} K^{-1}

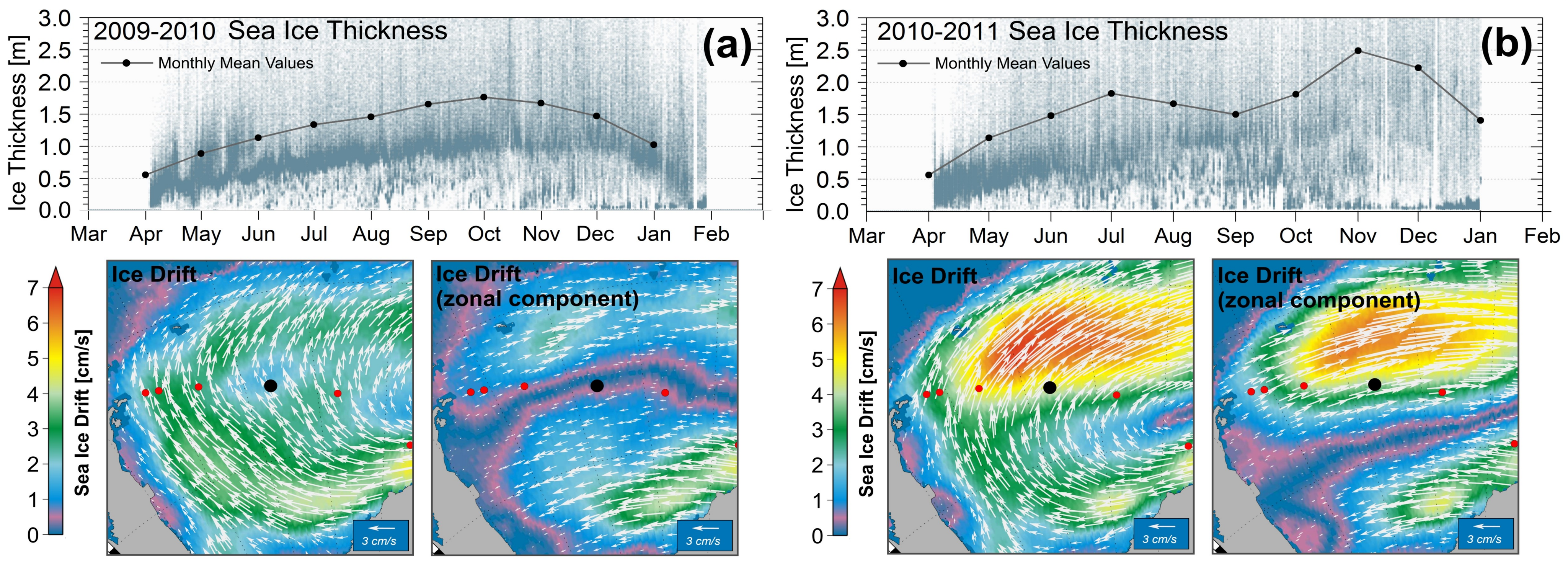

Fig. 3: ***Upper panels: ULS draft data converted into total ice thickness. Each blue dot represents one ULS measurement (>500.000 per year). Lower panels: Average ice drift from microwave satellite sensors [3]. Black dot on drift maps: AWI-208. The drift was averaged for April-December. (a) Ice season 2009-2010. (b) Ice season 2010-2011.***

4 Results & Conclusion

Clear thermodynamic growth/melt cycles are measured at AWI-208 when the zonal ice drift component is small and/or has zero average (Fig. 3a). When the zonal ice drift dominates in eastern direction, the ULS measurements are more determined by deformed ice (Fig. 3b).

To estimate the snow thickness and the oceanic heat flux, the ice draft from ULS was first converted into ice thickness. The thermodynamic growth was determined by calculating the statistical mode of the weekly ice thickness distributions.

The observed ice growth can be reasonably described without assuming an oceanic heat flux (Fig. 4a). A slightly better fit, however, is obtained assuming a thinner snow cover and an additional moderate oceanic heat flux of 7 W m^{-2} (Fig. 4b).

Different combinations of *r* and F_w were calculated using Stefan's Law. Those results showing the smallest RMS deviation of 0.09 m from the ice-thickness mode were taken to derive realistic ranges of snow thickness and oceanic heat flux: **$0 \le r \le 0.06$** (i.e. ~0-6 cm snow) and **$5 \le F_w \le 12$ W m^{-2}** (Fig. 4b). These values are within realistic boundaries for the Weddell Sea. For example, a heat flux of 20 W m^{-2} with r = 0.03 would increase the RMS deviation to 0.47 m.

Conclusions:

The modified form of Stefan's Law provides a reasonable model of thermodynamic ice growth in the Weddell Sea. Variations of the snow parameter and the oceanic heat flux within realistic boundaries suggest that both a snow layer of a few centimetres and a moderate oceanic heat flux limit the thermodynamic ice growth to about 1 m thickness in winter.

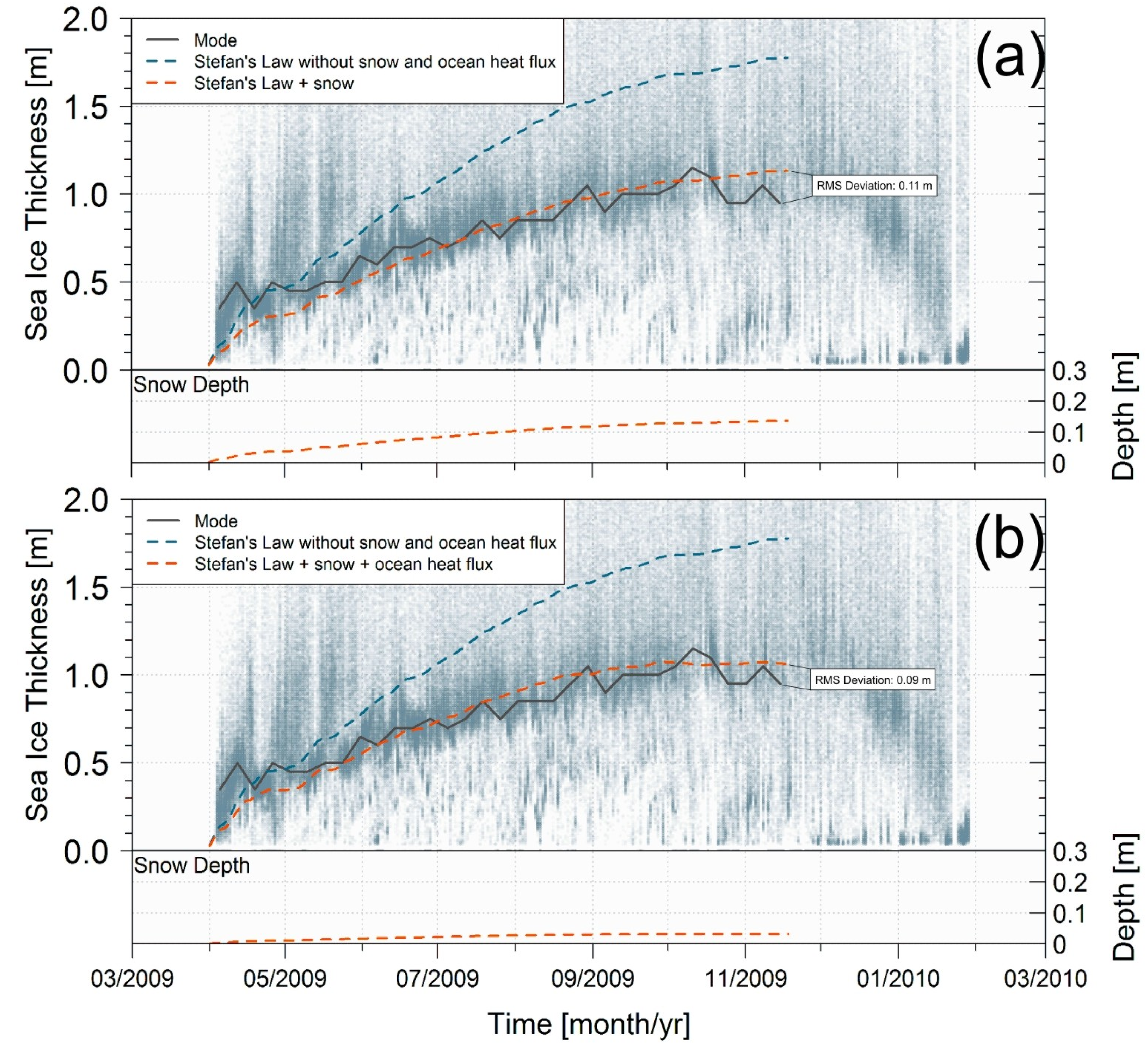

Fig. 4: ***ULS data for 2009-2010, the statistical mode of the weekly ice thickness distributions and estimations from Stefan's Law. Blue lines: results from Stefan's Law without snow and oceanic heat flux. (a) Red line: Model with snow layer and zero oceanic heat flux. (b) Red line: Model with thinner snow cover (~3 cm) and F_w = 7 W m^{-2}. The subplots show the estimated snow layer thicknesses.***