Influence of snow depth and surface flooding on light transmission through Antarctic pack ice

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Introduction

Snow on sea ice alters the physical properties of the sea-ice cover as well as associated physical and biological processes at the interfaces between atmosphere, sea ice and ocean. The Antarctic snow cover persists during most of the year and contributes significantly to the sea-ice mass budget due to the widespread surface flooding and related snow-ice formation. Snow also enhances the sea-ice surface reflectivity of incoming shortwave radiation and determines therefore the amount of light being reflected, absorbed, and transmitted to the upper ocean.

Study side and measurements

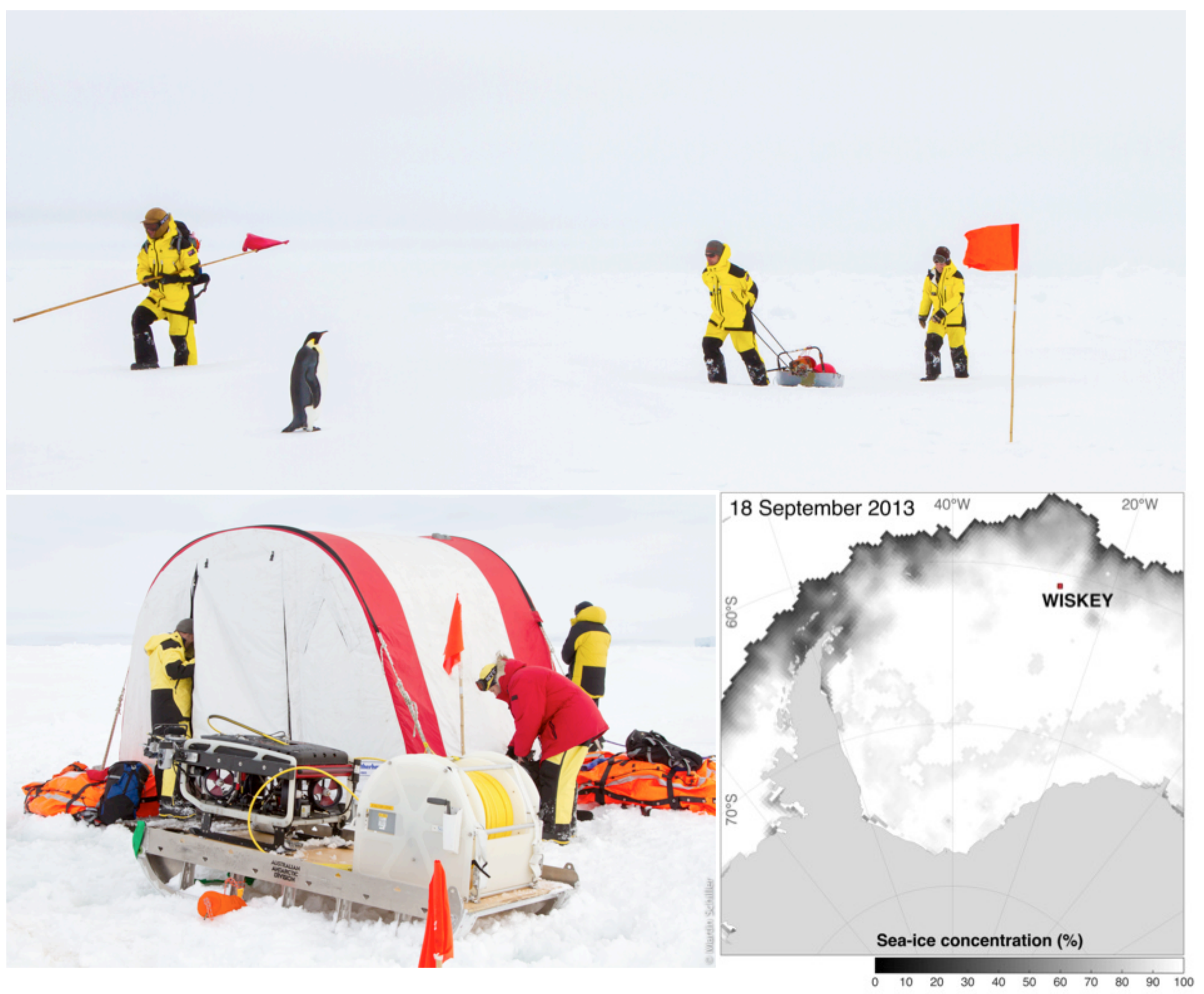


Figure 1: Ice-station sampled during voyage ANT-29/7 (WISKEY) with R/V Polarstern in the Weddell Sea from 18 to 26 September 2013. The lower left picture shows the Remotely Operated Vehicle system to obtain under-ice information. The background image of the lower right image shows the sea-ice concentration on 18 September 2013 provided by www.meereisportal.de. Photo credit to Martin Schiller (AWI).

Here, we present results of a case study of spectral solar radiation measurements (320 to 950 nm) under Antarctic pack ice with an instrumented Remotely Operated Vehicle (ROV) in the Weddell Sea in September 2013. In order to identify the key variables controlling the spatial distribution of the under-ice light regime, we exploit under-ice optical measurements in combination with simultaneous characterization of surface properties, such as sea-ice thickness and snow depth.

Total sea-ice thickness (sea-ice thickness plus snow depth) was measured with a ground-based multi-frequency electromagnetic induction instrument (GEM-2). A GPS-equipped Magna Probe was operated simultaneously in order to obtain snow depth along the snow track. Sea-ice thickness was then calculated as the difference of total sea-ice thickness and snow depth.

Surface flooding as a key parameter

For the ice-covered Southern Ocean, two typical states of sea ice must be distinguished, one with the snow/ice interface above the sea level (positive freeboard, Figure 2a), and the other with the snow/ice interface below the sea level (negative freeboard, Figure 2b). The latter is referred to as flooded snow (slush) and is assumed to have the same density as sea ice.

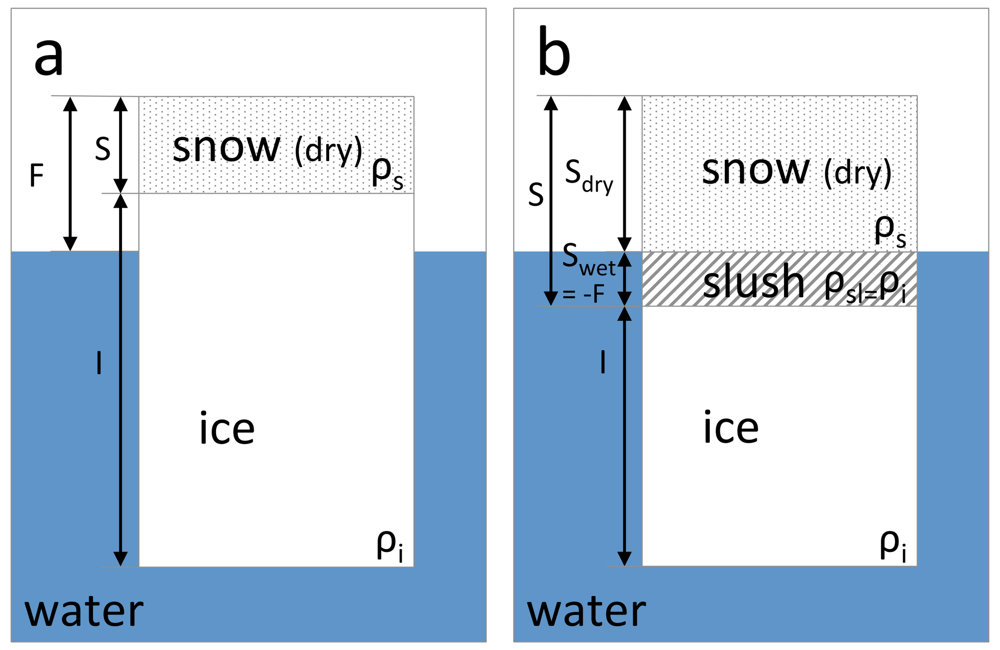


Figure 2: The two states of Antarctic sea ice: (a) Positive freeboard, and (b) negative freeboard. The ice freeboard, F, is controlled by the the density of sea ice, ρ_i, the density of seawater, ρ_w, and the sea-ice thickness, I, and the snow load, which is calculated from the density of snow, ρ_s, and the snow depth, S [Lange et al., 1990; Sturm and Massom, 2010]. In this study, constant densities for seawater, sea ice and snow of 1023.9, 915.1 and 300 kg m^{-3} are assumed, respectively [*Yi et al.*, 2011].

Physical properties of the ice floe

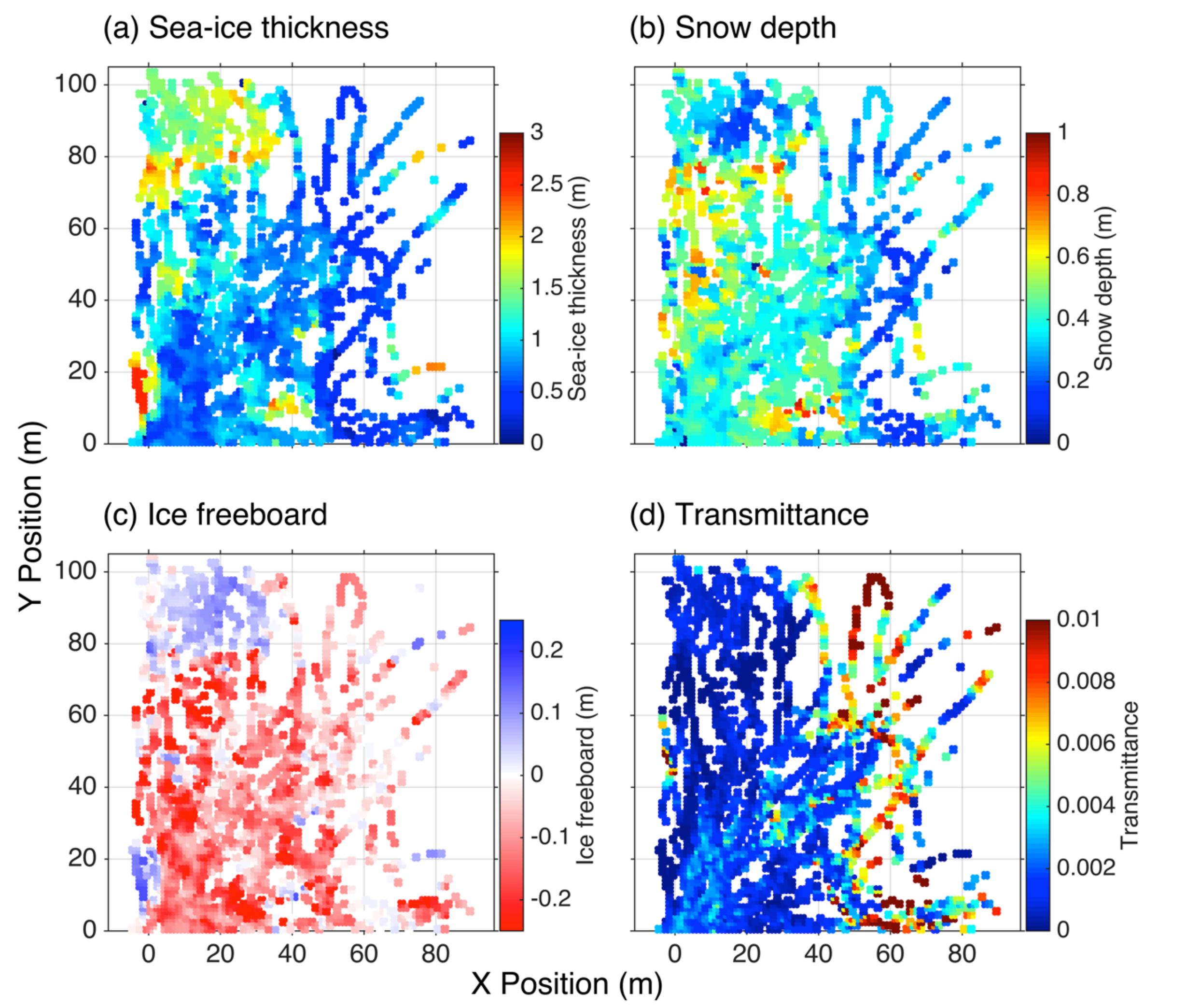


Figure 3: Physical properties of the ice floe with the Remotely Operated Vehicle (ROV) survey area. (a) Sea-ice thickness derived from the ground-based multi-frequency electromagnetic induction instrument (GEM-2). (b) Snow depth measured with the Magna Probe. (c) Estimated ice freeboard. (d) Light transmittance derived as the ratio of measured and transmitted irradiance and incoming solar irradiance above surface. Sea-ice thickness and snow depth measurements as well as ice freeboard are interpolated to the ROV transect lines. All data are gridded to a 2m-by-2m grid.

Light attenuation

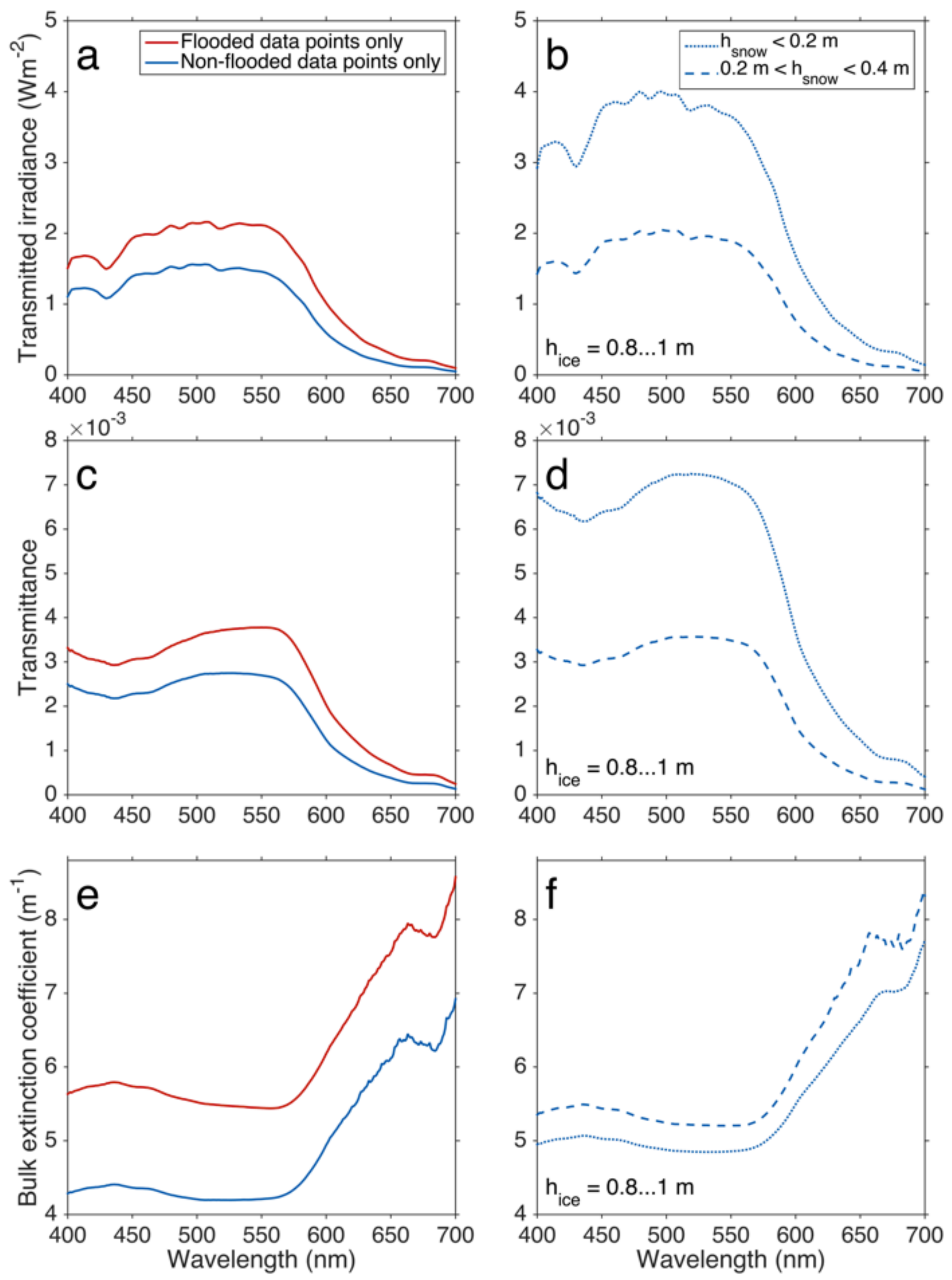


Figure 4: Mean spectral (a,b) transmitted irradiance, (c,d) light transmittance and (e,f) bulk extinction coefficient for (a,c,e) flooded data points only (red), non-flooded data points only (blue) and (b,d,f) non-flooded data points only with a sea-ice thickness between 0.8 and 1 m subdivided into two snow classes: snow depth < 0.2 m (dotted lines) and snow depth > 0.2 m and < 0.4 m (dashed lines).

Table 1: Summary statistics for measured and calculated physical sea-ice parameters for the non-flooded grid cells only (positive freeboard), and flooded grid cells only (negative freeboard) of the WISKEY data set. Reported values are mean values ± its standard deviation or mode values.

Parameters		Non-flooded data points only	Flooded data points only
Sea-ice thickness (m)		1.42 ± 0.51	0.78 ± 0.30
Snow depth (m)		0.30 ± 0.12	0.42 ± 0.12
Ice freeboard (m)		0.05 ± 0.04	-0.12 ± 0.07
Light transmittance	mean	0.0019 ± 0.0025	0.0026 ± 0.0031
	mode	0.0008	0.0008
Extinction coefficients (m^{-1})	ice	1.264 ± 0.133	2.06 ± 0.97
	snow	31.76 ± 0.69	31.22 ± 0.53
	slush	--	6.21 ± 3.23

Arctic vs. Antarctic

Strong surface melt and summer melt ponds

Year-round snow cover and widespread surface flooding

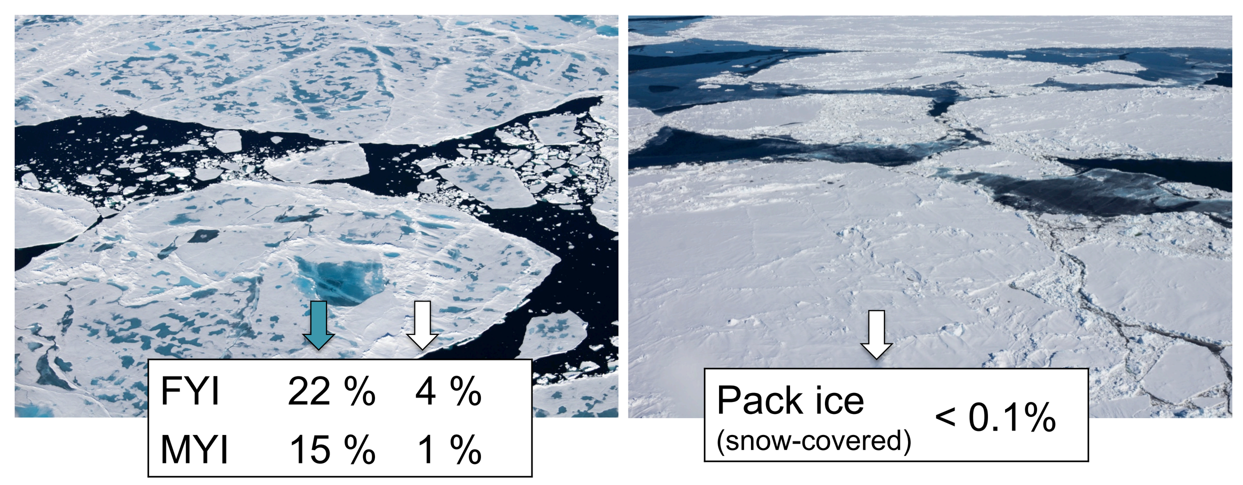


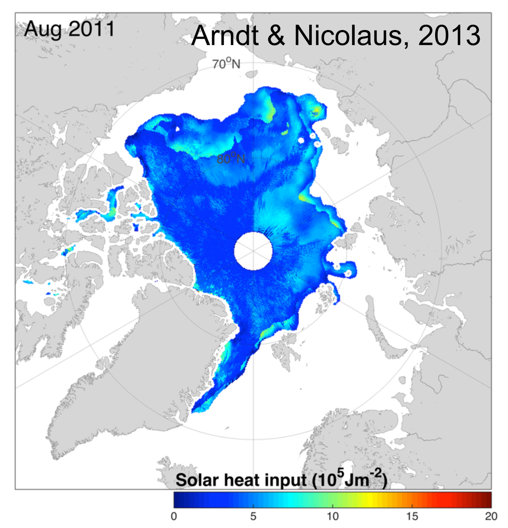
Figure 6: Light transmittance of (bare and pond-covered) Arctic first- and multi-year sea ice, and Antarctic snow-covered pack ice during summer.

Area-wide up-scaling

Input parameters

- Remote sensing data
  Sea-ice type
  Sea-ice concentration
  Melt pond coverage
- Surface properties
  Surface melt state
- Downward surface solar radiation

Arctic-wide under-ice calculations



Needed input parameters

- Remote sensing data
  Temporal evolution of snowpack
  Sea-ice concentration
  Snow depth
  Sea-ice thickness
  Floe size distribution
- Surface properties
  Snow coverage
  Vertical snow structures

So far no Antarctic-wide under-ice calculations possible

Conclusions

- Antarctic pack ice transmits less than 0.1% of the incoming solar radiation during early spring
- Ice freeboard and related flooding at the sea-ice surface and the snow depth distribution dominate the spatial variability of the under-ice light regime
- In contrast to Arctic sea ice, complex surface properties prevent a direct correlation between surface properties and the under-ice light field

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