The Cryosphere Discuss., 8, 2923–2956, 2014 www.the-cryosphere-discuss.net/8/2923/2014/ doi:10.5194/tcd-8-2923-2014 © Author(s) 2014. CC Attribution 3.0 License.



This discussion paper is/has been under review for the journal The Cryosphere (TC). Please refer to the corresponding final paper in TC if available.

Seasonal cycle of solar energy fluxes through Arctic sea ice

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Received: 28 April 2014 - Accepted: 19 May 2014 - Published: 5 June 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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Abstract

Arctic sea ice has not only decreased considerably during the last decades, but also changed its physical properties towards a thinner and more seasonal cover. These changes strongly impact the energy budget and might affect the ice-associated ecosys-

- ⁵ tem of the Arctic. But until now, it is not possible to quantify shortwave energy fluxes through sea ice sufficiently well over large regions and during different seasons. Here, we present a new parameterization of light transmittance through sea ice for all seasons as a function of variable sea ice properties. The annual maximum solar heat flux of 30×10^5 J m⁻² occurs in June, then also matching the under ice ocean heat flux. Fur-
- thermore, our results suggest that 96 % of the total annual solar heat input occurs from May to August, during four months only. Applying the new parameterization on remote sensing and reanalysis data from 1979 to 2011, we find an increase in light transmission of 1.5 % a⁻¹ for all regions. Sensitivity studies reveal that the results strongly depend on the timing of melt onset and the correct classification of ice types. Hence,
- these parameters are of great importance for quantifying under-ice radiation fluxes and the uncertainty of this parameterization. Assuming a two weeks earlier melt onset, the annual budget increases by 20%. Continuing the observed transition from Arctic multito first year sea ice could increase light transmittance by another 18%. Furthermore, the increase in light transmission directly contributes to an increase in internal and bottom melt of sea ice resulting in a positive transmittance-melt feedback process.
- ²⁰ bottom melt of sea ice, resulting in a positive transmittance-melt feedback process.

1 Introduction

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The evolution of Arctic sea ice towards a thinner, younger and more seasonal sea ice cover during the last few decades (e.g. Comiso, 2012; Haas et al., 2008; Maslanik et al., 2011, 2007) has a strong impact on the partitioning of solar energy between the atmosphere, the sea ice, and the ocean (e.g. Perovich et al., 2007, 2011; Wang et al., 2014). A general decrease of surface albedo (Perovich et al., 2011), an earlier melt



onset, and a longer melt season (Markus et al., 2009, updated) cause an increase in sea ice and snow melt (Perovich and Richter-Menge, 2009) and lead to higher absorption and transmission of solar irradiance (Nicolaus et al., 2012; Stroeve et al., 2014). Beyond the physical consequences of the observed changes, strong impacts on bio-

Iogical and geochemical processes are expected, like changes in habitat conditions for ice-associated organisms or changes in primary productivity (Arrigo et al., 2012; Deal et al., 2011; Popova et al., 2012).

An increasing number of studies on the interaction of sunlight and sea ice has been performed over the last years. From those studies it was possible to improve our under-

- standing of the effects of snow covers (Perovich et al., 2007), melt ponds (Rösel and Kaleschke, 2012), biological interaction (Arrigo et al., 2012; Mundy et al., 2005, 2007), spatial variability (Perovich et al., 2011), and seasonal changes (Nicolaus et al., 2010a; Perovich and Polashenski, 2012; Perovich et al., 2002). But it was not yet possible to quantify large-scale, multi-seasonal, and inter-annual changes, because all these stud-
- ¹⁵ ies were limited to different regions and/or times of the year. One possible approach to obtain such generalized studies on the in- and under-ice energy budgets in sea-ice covered oceans would be to use a radiative transfer model in combination with surface energy budgets, as obtained by Perovich et al. (2011). However, such a model would require adequate knowledge about the distribution of snow and sea ice (as forcing data)
- to derive the optical properties of sea ice and snow as function of space and time. This kind of information is not available yet, in particular not over decades. An alternative approach is to use existing remote sensing and re-analyses data together with a parameterization of light transmittance through sea ice. This method was developed by Nicolaus et al. (2012) and (2013) to calculate Arctic-wide radiation fluxes through sea
- ²⁵ ice for August 2011, the month when comprehensive transmittance measurements are available (Nicolaus and Katlein, 2013). For this approach a parameterization of light transmittance through sea ice is needed for different sea ice types over the course of the year.



Here we present all seasons and multi-year radiation transfer through Arctic sea ice based on the work by Nicolaus et al. (2012) and (2013). We extend and generalize their up-scaling method by a new parameterization of light transmittance through various types of sea ice over the annual cycle. We also include the temporal and spatial variability of melt ponds by the application of melt-pond concentrations by Rösel et al. (2012). The timing of different seasons is derived from melt and freeze onsets from Markus et al. (2009, updated). In order to judge the reliability of the method and to obtain a measure of uncertainty, the calculated fluxes are compared to in-situ observations during the Tara drift (Nicolaus et al., 2010a) and sensitivity studies are performed. Finally, it was possible to derive trends for the years from 1979 to 2011 for radiation transfer through Arctic sea ice.

2 Methods

Solar short-wave radiation fluxes (250 to 2500 nm, here also referred to as "light") through sea ice are calculated for the entire Arctic (north of 65° N) daily from 1 Jan-¹⁵ uary 1979 to 31 December 2011. Starting from the method and parameterization by Nicolaus et al. (2012) and (2013) the parameterization of light transmittance through sea ice has been extended for all seasons. Transmittance is calculated as a function of sea ice type, surface (snow) melt/freeze state, and melt pond concentration. The new parameterization was merged with satellite observations of daily sea ice concen-²⁰ tration and surface solar irradiance to calculate fluxes. All data sets are interpolated to a 10 km polar stereographic grid. Although daily fluxes are calculated and available, monthly means are shown and used to discuss the findings of this study, because we aim for seasonal changes and long-term trends.

2.1 Input data sets

²⁵ The following satellite and re-analyses data sets were used (Table 1):



1. Sea ice concentration was obtained from the Special Sensor Microwave Imager (SSMI/S) provided through the Ocean and Sea Ice Satellite Application Facilities (OSI SAF, product ID: OSI-401, Andersen et al., 2007). For this study, the combination of reprocessed data (1979 to 2007) and operational data (2008 to 2011) was used. Both data sets have systematical differences due to the processing with a different set of tie point statistics for the ice concentration algorithm (Lavergne et al., 2010). However, within the documented uncertainties both data sets build the best available and consistent time series of sea ice concentration.

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- 2. For sea ice age, we used the updated data product by Maslanik et al. (2007) and (2011). It is based on satellite data and a Lagrangian tracking since 1979. Although this data product distinguishes the age of the ice from 1 to 10 years, here we only distinguish FYI and MYI (2 years and older), because all MYI is assumed to have similar optical properties. All data points with a sea ice concentration > 0 but without sea ice age were treated as FYI. Vice versa, all data points with sea ice concentration < 15% but with an age tag were treated as open water. Such modifications were necessary to obtain consistent data products from the different sources, indicating partially varying sea ice extents.</p>
 - 3. The downward surface solar radiation was obtained four times per day from the European Centre for Medium-Range Weather Forecast (ECMWF) Era Interim reanalyses (Dee et al., 2011). The data (four values per day) were averaged to daily means and are available since 1979.
- 4. Sea ice surface characteristics were categorized by melt and freeze onset dates from passive microwave data (1979 to 2012) (Markus et al., 2009, updated). The data set distinguishes between the first occurrence of a melt event (early melt onset, EMO), the following continuous melt (melt onset, MO), the first occurring of freeze-up conditions (early freeze onset, EFO), and the day of persistent freezing conditions (freeze onset, FO).



 Melt pond fraction was used from Rösel et al. (2012). But since this data set is only available since 2000, melt pond fractions from 1979 to 1999 were set to constant summer values of 26% on FYI and 29% on MYI as observed in August 2011 (Nicolaus et al., 2012). For consistencies with the surface characteristics, all melt pond fractions before EMO are set to zero.

2.2 The up-scaling model

Solar heat input through sea ice into the ocean $(E_T(t, x, y))$ is calculated as the product of the downward solar radiation (E_d) , the sea ice concentration (C_i) , and the total transmittance of pond covered sea ice (τ_i) for each grid cell for each day from 1 January 1979 to 31 December 1999:

$$E_{\mathsf{T}}(t, x, y) = E_{\mathsf{d}}(t, x, y) \times C_{\mathsf{i}}(t, x, y) \times \tau_{\mathsf{i}}$$

with time t and position (x, y).

Since 1 January 2000, when satellite derived melt-pond concentrations are available, the solar heat input through sea ice into the ocean (E_T) is calculated as the sum of fluxes through bare ice (E_B) and melt ponds (E_P):

$$E_{T}(t, x, y) = E_{B}(t, x, y) + E_{P}(t, x, y)$$

$$E_{T}(t, x, y) = E_{d}(t, x, y) \times C_{i}(t, x, y) \times [1 - C_{p}(t, x, y)] \times \tau_{b} + E_{d}(t, x, y)$$

$$\times C_{i}(t, x, y) \times C_{p}(t, x, y) \times \tau_{p}$$
(2)

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with the transmitted solar radiation at the bottom of the ice E_T , downward solar radiation E_d , sea ice concentration C_i , melt pond fraction C_p , transmittance of bare sea ice τ_b , transmittance of melt ponds τ_p , time *t* and grid cell (*x*, *y*).

To obtain the total solar heat input per unit area for a certain time period ($Q_T(x, y)$), the heat flux is calculated for each grid cell and then integrated over the given time (Δt)

$$Q_{\mathsf{T}}(x,y) = \sum E_{\mathsf{T}}(t,x,y) \Delta t.$$



(1)

(3)

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Spatial integration over the entire Arctic Ocean (north of 65° N), reveals the Arctic-wide total solar heat input Q_{T} .

2.3 Seasonality of surface properties and transmittance of Arctic sea ice

To calculate solar heat fluxes under Arctic sea ice for an entire year, the main challenge is to parameterize the seasonal evolution of $\tau_{\rm b}$ (*t*, *x*, *y*). This is mainly achieved by merging the sea-ice age information (Maslanik et al., 2007, 2011) with the melt/freeze status (Markus et al., 2009, updated) into six surface types.

2.3.1 Definition of sea ice types

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Figure 1 shows the annual cycle of these six sea ice classes together with surface
properties of Arctic sea ice. Those classes are introduced to avoid abrupt changes in the optical properties during the transition from spring to summer as well as from summer to fall. After EMO, *melting FYI* and *melting MYI* are introduced for sea ice not surviving summer melt. Therefore, it is necessary to calculate for each cell whether it is becoming ice free (sea ice concentration less than 15%) or not. If so, the last day of melting is stored for later calculations. According to Maslanik et al. (2007) and (2011), *FYI* surviving the summer melt turns into *new MYI* after week 36 of the year, and furthermore into *MYI* at the end of the year. As soon as sea ice concentration is getting higher than 15% *new FYI* is formed.

In the following, the composition of bare sea ice and melt ponds is called pond covered sea ice.

2.3.2 Transmittance of pond covered sea ice

The seasonal evolution of surface properties and transmittance of Arctic sea ice is divided into six different phases (note the difference of ice types and seasonal phases). The timing of these phases is based on the melt and freeze onset data set by Markus et al. (2009, updated). Our parameterization of seasonal variations of light trans-



mittance considers the transmission through both, sea ice and snow and is mostly based on measurements from Heat Budget of the Arctic Ocean experiment (SHEBA) from 1997 to 1998 (Perovich, 2005) and the drift of Tara in 2007 (Nicolaus et al., 2010a). In addition, analyses from previous observations by Perovich (1996), Perovich

⁵ et al. (1998), and Nicolaus et al. (2010b) are used. Figure 2a shows the seasonal total transmittance of pond covered sea ice (τ_i) for constant pond concentrations of 26 and 29% for FYI and MYI, as it was used from 1979 to 2000. This composition of a given mixture of ponds and bare ice was used to develop the seasonal cycle of transmittance, as described in the next paragraphs. All transmittances of the different phases are compiled in Table 2.

Phase I: winter (from FO + 60 days to EMO)

Winter conditions are characterized by snow covered sea ice without melt ponds. The snow cover is assumed to be cold, dry and optically thick. It determines the optical properties. Thus, radiative fluxes through sea ice are small. The best available trans-

¹⁵ mittance observations for such conditions are those measured during the first days of the Tara drift, although it was early April already. Hence transmittance was accordingly set to 0.002 (Nicolaus et al., 2010a).

Phase II: early melt (from EMO to MO)

EMO denotes the first significant change in optical properties. Snow depth decreases ²⁰ whereas temperatures of the surface and sea ice increase. Consequently, snow is no longer optically thick and is getting wet and first melt ponds might occur. Here we assume a linear increase of τ_i until MO. However, at MO, the surface albedo of FYI is only about half that of MYI (Perovich and Polashenski, 2012). Since Nicolaus et al. (2010a) calculated a transmittance of 0.02 for MYI for the day of MO, the transmittance of FYI is assumed as 0.04 following the albedo evolution

 $_{\rm 25}$ $\,$ is assumed as 0.04 following the albedo evolution.

Melting FYI and melting MYI

After EMO, it is considered that the annual sea ice retreat in summer strongly impacts the light transmittance. Thus, melting FYI and melting MYI is separated in the parameterization of τ_i . The rapid increase in transmittance of seasonal sea ice can be



described as roughly exponential (Perovich, 1996). Since melting has an approximately inverse effect on transmittance compared to albedo, we use a transmittance of 0.4 for the last existing sea ice (< 10 cm) and fit an exponential increase between EMO and the last day of melting for the according pixel.

Phase III: continuous melt (from MO to MO + 14 days)

After MO, snow is assumed to melt completely within 14 days (Nicolaus et al., 2006) and pond cover fraction increases rapidly until the maximum pond cover is reached at the end of this phase. The transmittance continues increasing linearly until begin of summer (MO + 14 days) (Nicolaus et al., 2006).

¹⁰ Phase IV: summer (from MO + 14 days to EFO)

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During this phase the sea ice surface is characterized by strong sea ice melt and culminates in the Arctic sea ice extent minimum. The surface consists of a mixture of bare ice and melt ponds with comparably small changes. Hence, τ_i is assumed to be constant for sea ice that survives summer melt. Based on observed transmittances

of solar radiation through FYI and MYI during TransArc 2011 (Nicolaus et al., 2012), we use summer transmittances of 0.04 of bare FYI, 0.01 of bare MYI, 0.087 of pond covered FYI, and 0.05 of pond covered MYI. Those numbers are then weighted with melt pond fractions (Rösel and Kaleschke, 2012).

Phase V: fall freeze-up (from EFO to FO)

²⁰ Air and surface temperatures drop below 0 °C resulting in first surface freezing. Subsequently, snow accumulation may start and former melt ponds refreeze but may still be recognized through the new snow cover. Thus, the transmittance is decreasing rapidly. In analogy to Phase III the transmittance of FYI decreases to 0.04 and for MYI to 0.02 until FO. Additionally, sea ice that survived the summer melt is promoted to one-year-

older ice in week 36/37 according to Maslanik et al. (2007) and new ice forms. The transmittance of new first year ice evolves correspondingly to the melting sea ice surface, described above. From EFO until the begin of winter (FO + 60 days) the strong growth of sea ice, increasing sea ice thickness, results in an exponential decrease in light transmission through newly formed FYI.



Phase VI: continuous freeze (from FO to FO + 60 days)

Continuous freezing and an increasing snow accumulation towards an optically thick snow layer and the gradual disappearance of melt ponds characterize this phase. Beyond new sea ice formation, the existing sea ice is getting thicker and older and de-

⁵ formation is increasing. The transmittance is decreasing back to 0.02 until winter. It is assumed that at the end of the freezing phase (FO + 60 days) the surface properties of all newly formed FYI can be considered as equivalent. Afterwards, the accumulated optically thick snow layer dominates the optical properties of FYI and MYI again (Phase I).

10 2.3.3 Transmittance of bare ice and ponds

After 2000, when melt pond products are available from Rösel and Kaleschke (2012), the transmittances of bare ice ($\tau_{\rm b}$) and ponds ($\tau_{\rm p}$) are treated separately (Fig. 2b). The modal transmittance of melt ponds is constant over the entire melt season. It is set to 0.22 for FYI and 0.15 for MYI, as measured during TransArc 2011 (Nicolaus et al., 2012). The seasonal evolution of transmittance of bare ice ($\tau_{\rm b}$) follows the transmittance for pond covered sea ice ($\tau_{\rm i}$):

$$\tau_{\rm b}(x,y) = \tau_{\rm i}(x,y) \times \frac{\tau_{\rm b}({\rm summer},x,y)}{\tau_{\rm i}({\rm summer},x,y)}$$
(4)

The values of τ_{b} (summer, x, y) and τ_{i} (summer, x, y) are the constant values during summer as given in Table 2. The scaling factor is constant for MYI (0.2) and FYI (0.46). Finally, those transmittances are scaled with the pond concentration, as given in Eq. (2).

2.4 Deriving trends

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Based on the results of our calculations of the solar heat input through sea ice into the ocean, trends are analyzed from 1979 to 2011. The trends (monthly and annual)



are calculated by a linear least-squares fit of the total mean (monthly or annual) heat flux for each grid cell ($Q_T(x, y)$). In order to exclude artifacts of the general changes in sea ice concentration, all trends have been corrected with the trend in sea ice concentration. Trends were only calculated for the area of the mean (annual or monthly) sea ice covered area in 2011 (sea ice concentration > 15%). All regions that were not ice covered at any time in 2011 are excluded from the analysis and discussion.

3 Results

3.1 Seasonality of solar radiation under Arctic sea ice

Based on the availability of all input data sets and the seasonality of transmittances, the solar heat input through sea ice into the ocean is analyzed from 1979 to 2011. 10 Figure 3 shows the monthly mean heat input $(Q_T(x,y))$, Eq. 3) under Arctic sea ice (ice covered areas only) from January to December 2011. The example of 2011 was selected to ease comparisons with the results for August 2011 by Nicolaus et al. (2012) and Nicolaus et al. (2013). From October to March the monthly mean solar radiation under sea ice was smaller than 0.2×10^5 J m⁻² with an Arctic-wide total under-ice heat 15 flux (Q_T) of up to 0.4 × 10¹⁹ J. Since this represents less than 1 % of the annual Arcticwide heat flux of 53.3×10^{19} J, those months are neglected for further analyses and discussion. In April the mean heat flux increased to $0.4 \times 10^5 \, \text{J m}^{-2}$ with a maximum of 7 to 8×10^5 Jm⁻² in the marginal ice zone East of Spitsbergen. The transmittance triples from 0.005 in April to 0.015 in May, and together with increasing surface fluxes, 20 the $Q_{T}(x,y)$ increased from $1. \times 10^{19}$ J to 5.5×10^{19} J during this time. The Barents Sea showed averaged transmitted heat fluxes up to 25×10^5 J m⁻² with a mean of 2.2×10^5 Jm⁻² in May. From May to June, the most pronounced increase was found for $Q_{T}(x,y)$ (to 9.3×10^{5} J m⁻²) and the transmittance (0.054). The maximum $Q_{T}(x,y)$ was about 30×10^5 J m⁻². June was the month of the highest Q_T (20.9 × 10¹⁹ J) associated 25 with the highest solar surface irradiance over the entire Arctic Ocean (851 × 10¹⁹ J). That



increase was linked with the beginning of the melt phase (mean MO on 30 May 2011) and the associated strong snow melt. During this time, the difference between thin melting sea ice on the sea ice edge and the persistent sea ice cover became most obvious, e.g. in the Chuckchi and Beaufort Seas. In July, $Q_T(x, y)$ reached its maximum of 9.8×10^5 Jm⁻² resulting from a maximum mean transmittance of 0.089. The maxi-5 mum $Q_T(x, y)$ reached still about 28×10^5 J m⁻² with a Q_T of 18.4×10^{19} J. The different impact of MYI and FYI, becomes most obvious in July. Also continuation of sea ice melt along the ice edge becomes more important for the under-ice heat fluxes. The August decrease of $Q_{T}(x,y)$ by more than 50% to $4.4 \times 10^{5} \,\mathrm{Jm^{-2}}$ along with only a slight reduction of transmittance to 0.084 is mainly caused by the strong decrease in solar 10 surface irradiance $(679 \times 10^{19} \text{ J})$. These surface fluxes are only half of those during the previous months. Maximum $Q_T(x, y)$ reached up to 19×10^5 J m⁻². In September the $Q_{T}(x,y)$ decreased further to 0.6×10^5 J m⁻² related to a low transmittance of 0.039 and $Q_{\rm T}$ was 0.7 × 10¹⁹ J.

3.2 Light transmission from 1979 to 2011

The new data set of $Q_T(x, y)$ allows quantification of annual budgets, regional differences, and decadal trends. Figure 4a illustrates the strong regional variability of the total solar heat input through sea ice into the ocean ($Q_T(x, y)$) ranging from 20 to 100 MJ m⁻² for the given period. The mean total solar heat input per grid cell in the area of the mean sea ice extent was 46 MJ m⁻². The maximum $Q_T(x, y)$ occurs at the edge of the marginal ice zone in the Canadian Arctic Archipelago (up to 110 MJ m⁻²) and the East Siberian Sea and Chukchi Sea (up to 80 MJ m⁻²). In contrast, excluding ice edge effects, the minimum $Q_T(x, y)$ was found in the Central Arctic, a MYI dominated region of low transmittance.

The mean trend of $Q_T(x, y)$ was $1.5 \% a^{-1}$ (excluding sea ice edge effects) with a maximum of $+4\% a^{-1}$ in the East Siberian Sea and southern part of the North American and Russian Arctic Basin (Figs. 4b and 5a). The reason is likely the prolongation



of the melt season in these regions. Over the entire Arctic, the mean MO was 4 days earlier, shifting from day 145 (24 May) to day 141 (20 May), according a linear regression from 1979 as in 2011. The strongest trend of $4.8 \times 10^{18} \text{ J a}^{-1}$ was found for June followed by May and July with $1.8 \times 10^{18} \text{ J a}^{-1}$. August shows a comparably weak negative trend of $-0.2 \times 10^{18} \text{ J a}^{-1}$, due to a lower solar surface irradiance. Assuming an identical sea ice extent in 1979 and 2011, the increase in the annual mean solar heat

- flux through sea ice (Q_T) amounts to 22.5 × 10¹⁹ J in the Arctic over the entire period. This means an averaged increase by 33%. Over all, 94% of the total annual solar heat input through Arctic sea ice was observed during the four key months: May to August.
- ¹⁰ Furthermore, heat flux time series (annual, June, July) show an increasing variability after 1999, which is likely due to a larger variability of the summer sea ice cover.

4 Discussion

4.1 Seasonality and trends of transmitted fluxes

The total annual solar radiation under Arctic sea ice amounted to 53.3 × 10¹⁹ J in 2011.
Based on this, May to August are the most important months for the basal energy budget of Arctic sea ice. During this time, 96% (51.2 × 10¹⁹ J) of the total annual solar heat input is transmitted through the sea ice. Including April and September in addition, 99% (52.9 × 10¹⁹ J) of the total annual flux is transmitted, within only one third of the year. Generalizing the monthly fluxes, the annual cycle may be summarized in three phases: (1) the heat input through snow and sea ice into the ocean is negligible between October and March, (2) solar surface radiation dominates the under-ice light conditions from April to June, because transmittance increases only slowly, while surface irradiance determines most of the observed changes and variability, (3) during summer (July to September), energy fluxes depend mainly on the sea ice type, showing large differences in transmittance between EXI and MXI

²⁵ showing large differences in transmittance between FYI and MYI.



Comparing our results to the development of the solar heat input into the ice presented by Perovich et al. (2011, Fig. 2), a weaker trend in the contribution of solar heat input to the ocean (up to $1.5 \% a^{-1}$) compared to the one of solar heat input through sea ice (up to $4\% a^{-1}$) is evident. This difference might be an indication of an increasing bottom and internal melt during the last decades and thus, affecting the sea ice mass balance. An increasing light absorption of Arctic sea ice due to more seasonal and less multi year ice was also found by Nicolaus et al. (2012).

The trend towards more light transmission through sea ice, does not only impact the light conditions right at the bottom of the sea ice, but also affects the horizontal and vertical light field in the ice covered ocean. More light at the bottom of sea ice will

- and vertical light field in the ice covered ocean. More light at the bottom of sea ice will deepen the euphotic zone, as more light penetrates deeper into the ocean (Frey et al., 2011; Katlein et al., 2014). It contributes to an increase in mixed layer temperature, and provides more energy for primary production and biogeochemical processes in and beneath the sea ice. However, it has to be noted that an increase in light availability does
- ¹⁵ not necessarily increase biological activity, but might also be harmful (Leu et al., 2010). Consequently, sea ice bottom and internal melt are likely to become more important for sea ice mass balance (Nicolaus et al., 2012), which again might result in an additional increase in transmittance. That feedback process can be trigger a transmittance-melt feedback.
- Our calculated trends are based on constant pond fractions before 2000. Speculation of even less ponds, might even increase the trends. The increasing melt pond fraction on Arctic sea ice between 2000 and 2011 has been also shown in Rösel and Kaleschke (2012).

All findings are based on results that were corrected for the trend in sea ice con-²⁵ centration. However, to point towards the future importance of such heat fluxes, it is important to consider that those sea ice concentration trends differ significantly for different months. While the trend is $-0.1 \% a^{-1}$ for September, it is only $-0.06 \% a^{-1}$ for June, the months when the largest impact on absolute fluxes is observed. In April and May, when the most significant relative changes are observed, and when the impact



for biological primary production is expected to be largest, the trend in sea ice concentration is even positive with $+0.04 \% a^{-1}$. Hence, the importance for energy fluxes through sea ice, and their future developments, remains highly relevant also for the coming years and in a more and more seasonal Arctic sea ice cover.

5 4.2 Comparisons with in-situ measurements

A validation for the calculated trends and spatial variability is almost impossible as insufficient field data with adequate spatial and temporal coverage are available. However, some comparisons with time series of light transmission from different field studies may be performed to identify major uncertainties.

- Here we compare, surface and transmitted solar irradiance of the presented method with in-situ measurements during the Transpolar Drift of Tara from 29 April to 28 August 2007 (Nicolaus et al., 2010a). Nearest-neighbor grid points within 0.5° of the daily Tara position were extracted from the presented data set and averaged. Figure 6a (red and green lines) shows a comparison of the time series of transmitted solar irradi-
- ance from both data sets. Until 8 June, the transmitted solar irradiance under sea ice varies only little around 0.5 W m⁻² for both, the calculated and the measured time series. Afterwards until end of June, the measured transmitted fluxes increased steadily towards 10 W m⁻², whereas calculated fluxes were highly variable with most values below 4 W m⁻². Hence, the total solar heat input through the sea ice to the ocean from 1
- ²⁰ May to 16 July 2007 was 21.4 MJ m⁻² for the observed Tara data, whereas the calculated data resulted in a 17 % lower total heat flux of 17.7 MJ m⁻². During summer (16 July to 14 August), under-ice fluxes cannot be compared reasonably since the sensor at Tara was strongly influenced by biological processes, causing an increased absorption and reduced transmitted fluxes. After 14 August, the measured transmitted heat flux increased readily to about 6 W m⁻²
- flux increased rapidly to about 6 W m^{-2} , comparable to the calculated one. Finally, the decrease in solar elevation caused decreasing transmitted fluxes in both data sets, resulting in similar heat fluxes of $0.28 \times 10^3 \text{ MJ m}^{-2}$ after 14 August.



Main reason for these differences is the timing of the phases describing the surface characteristics. While both data sets have a coincident EMO on 9 June, large differences are evident for the later phase transitions: the observed MO at Tara was on 21 June whereas the calculated MO for the center position was 17 days later on 8 July.

- ⁵ Taking also the other 8 neighbors in account, mean MO was on 13 June. This shows that there is a difference of 25 days in MO on the 10 km grid. As presented above, the transmitted heat flux strongly depends on the timing of the different melt phases by Markus et al. (2009). EFO was observed on 15 August during Tara, whereas the satellite data maintains summer melt conditions until 14 September. However, the total
- ¹⁰ solar heat input through sea ice was similar for both data sets. Conclusively, the solar radiation flux under Arctic sea ice strongly depends on the timing of EMO and MO, while the timing of EFO and FO seems to be of less importance. The timing of melt onset has also a large influence on the total amount of light absorption, as shown in Stroeve et al. (2014). Consider the ongoing lengthening of the melt season by up to two weeks per decade (by a later EMO), their calculations suggest an albedo increase
- of 9 % per decade.

In a second validation step, the heat fluxes were re-calculated using the onset dates as observed during Tara instead of those by Markus et al. (2009) (Fig. 6, black lines). This eliminated the impact of the onset dates on the results. Nevertheless, the calculated total solar heat input through sea ice was still differing by 18% (25.4 MJ m⁻²)

- ²⁰ culated total solar heat input through sea ice was still differing by 18% (25.4 MJ m⁻²) from the Tara fluxes until 16 July (Fig. 6a) due to an unexpected peak in $Q_T(x, y)$ in July. In addition, the calculated time series showed still a large day-to-day variability, including much higher transmittances than observed at Tara. The main reason for this is the alternation of sea ice types (FYI and MYI), whereas the Tara floe consisted of
- MYI only. Consequently, the strong differences in optical properties of FYI and MYI, as parameterized here, strongly contribute to the overall energy budget. To overcome this problem, FYI/MYI fractions per grid cell (Kwok, 2004) could be used instead of the presented discrete distinction. However, such a data set is not yet available for the given time span.



Hudson et al. (2013) measured heat fluxes and calculated transmittances of Arctic FYI in July/August 2012. However, a direct comparison of energy fluxes, as for the Tara measurements, is not possible, because the melt-pond concentration data set ends in December 2011. August transmittance in our study (0.087) is based on the observations by Nicolaus et al. (2012), which is only half of the 0.16 found by Hudson et al. (2013). Hence, it may be assumed that heat fluxes through sea ice would be larger based on those measurements. Differences between both studies mainly result from differences in sea ice thickness during the respective campaigns as well as the different methods of quantifying transmittance (mean value vs. modal value) (Hudson et al., 2013). Including measured ocean heat fluxes during summer (Hudson et al., 2013), we conclude that the heat flux through the sea ice is of similar magnitude and importance.

Measurements from Ice-Tethered Profilers (ITPs) (Krishfield et al., 2008) could be used as an alternative approach to estimate uncertainties of the new parameterization.

¹⁵ They allow quantifying the heat content of the uppermost ocean and its changes. However, such comparison would require a significant extension of the presented study, integrating larger depths and including all radiation fluxes through open waters.

4.3 Sensitivity studies

Main reasons for the large discrepancies between the observed and calculated trans mittance and transmitted light were the dating of melt onset and the spatial variability of the ice types. Thus, several sensitivity studies have been performed. Three studies focused on the influence of timing and length of the melt season on the solar heat input to the upper ocean: (1) EMO and MO 7 days earlier (moving the Arctic-wide means to 8 May and 23 May), (2) EMO and MO 14 days earlier (means: 1 May and 16 May), and
 (3) EFO and FO 14 days later (means: 21 October and 2 November) in 2011.

A 7 days earlier EMO and MO affect in most cases the time of high sea ice concentration and large solar surface irradiance. It results in an increase in total annual solar heat input through sea ice to the ocean (Q_T) of 11 % from 53.3 × 10¹⁹ J to 59.2 × 10¹⁹ J for



the entire year 2011. The strongest increase of 33 % compared to the reference melt onset dates was found for May, while the strongest absolute increase of 3.1×10^{19} J was found in June. Shifting the melt season another 7 days backwards, Q_T increases in total by 24 % to about 66.3×10^{19} J for the year. This increase is more than double compared to the 7-day-shift (Table 3). The pronounced increase is most evident in May when 90 % more light transmission was found than in the reference system. The

May, when 90 % more light transmission was found than in the reference system. The strongest absolute increase of 6.2×10^{19} J (transmittance from 0.054 to 0.067) was derived for June. The spatial distribution of the impact of the 14 days earlier EMO and MO showed the largest increase of solar heat input to the upper ocean in the marginal ice zone, adding up to more than 100 % (Fig. 7a).

Experiment 3, extending the melt season by 14 days later EFO and FO, results in a 1% increase of $Q_{\rm T}$ from 53.3 × 10¹⁹ J to 53.9 × 10¹⁹ J (Fig. 7b). Since the surface solar radiation is much less than between April and June, the change in the end of the melt season affects only parts of August and September (increase of 9% from 7.02 × 10¹⁹ J).

In a fourth sensitivity study, the influence of the ice type was quantified. The reference ice cover of 2011 consists e.g. of 56 % FYI and 44 % MYI in August. Assuming that all sea ice in 2011 was MYI, the mean transmitted flux decreased by 34 % to 35.5×10^{19} J. In contrast, assuming that only FYI was present increased that value by 18 % to 62.7×10^{19} J. Hence, the transition from a MYI to FYI dominated Arctic sea ice regime results in a further increase of solar heat flux under Arctic sea ice.

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Beyond those experiments, also other parameters influence the amount and seasonality of solar heat input through the ice to the ocean, in particular surface solar radiation and the melt pond fraction. Increasing the latter by 10%, the annual heat flux

increases by 5 % for the solar heat input to the upper ocean. The effect approximately scales linearly, and increasing the melt pond fraction by 20 % results in an increase of the heat flux by 10 %. Changes in the solar surface radiation as well as in sea ice concentration have also a linear influence on the solar radiation flux under Arctic sea



ice (Eq. 2). The effect of sea ice concentration is not discussed, since all results related to the ice covered parts of the ocean only.

5 Summary and conclusions

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The new parameterization for light transmission through Arctic sea ice in combination
with time series derived from satellite observations and re-analyses allows to quantify solar short-wave radiation fluxes through Arctic sea ice for the entire annual cycle over more than 30 years (1979 to 2011). Therefore, highest fluxes were calculated for June. The presented studies suggest that 96 % of the total annual solar heat input through sea ice occur in only 4 months (May to August). Regarding the time period from 1979
to 2011, an increase in light transmission of 1.5 % a⁻¹ with regional maxima of 4.0 % is found.

The results of our sensitivity studies show that energy fluxes strongly depend on the timing of melt onset and sea ice types (first and multi year ice). Those parameters are the most critical ones for the shown calculations and describe the most critical uncertainties. The calculated trends are affected most of these uncertainties.

All these results consider the fluxes through ice-covered ocean only, which highlights that changes in sea ice properties have a large impact on the energy budget and should not be neglected compared to the obvious effect of sea ice retreat. However, the ongoing retreat of sea ice will cause additional increases in radiation fluxes into

the Arctic Ocean. The access heat will also contribute to an increase of heat stored in the ocean mixed layer and will impact the melt season duration and timing, particularly autumn refreezing.

The additional energy input into the sea ice and the upper ocean will also impact inner sea ice structures as well as internal and basal melting. Comparison with surface radiation trends by Perovich et al. (2011) suggests that the stronger trend in transmission compared to the trend in fluxes into the sea ice surface also induces an additional transmittance-melt feedback mechanism.



More investigations of bio-geo-physical connections will be needed to better quantify the effects of the changing physical environment on the ecosystem and element cycles, and vice versa. Additional work will also be needed to improve Arctic-wide snow depth and sea ice thickness data products. Those products should on a good description of ⁵ surface properties during the spring-summer-transition, when the largest uncertainties were found. Such time series might become available from new data products merging observations from different satellites and sensor types (e.g. SMOS, CryoSat-2, AMSR-E), and potentially also numerical models. The non-existence of such reliable long-term and Arctic-wide data sets was the main reason to develop the presented method, based on available parameters. Otherwise, the application of a radiation transfer model with adequate input (forcing) data would have been an obvious alternative.

 Acknowledgements. We are most grateful to Jim Maslanik (University of Colorado Boulder), Thorsten Markus and Jeffrey Miller (both NASA Goddard Space Flight Center), Thomas Lavergne (OSISAF, Met Norway), and Anja Rösel and Lars Kaleschke (both University of Ham burg) for data provision and support through manifold discussions on their data products and processing details. We thank Christian Katlein (Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung) and Martin Claussen (Max Planck Institute for Meteorology) for constructive comments on the manuscript. The study was funded through the Remote Sensing Alliance of the Helmholtz Association and the Alfred-Wegener-Institut Helmholtz-Zentrum für
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Parameter	Time period	Source
Sea ice concentration	1979–2007 2008–2011	OSI SAF, reprocessed data OSI SAF, operated data (Andersen et al., 2007)
Sea ice age	1979–2011	Maslanik et al. (2007, 2011)
Downward surface solar radiation	1979–2011	ECMWF (Dee et al., 2011)
Melt and freeze onset	1979–2005 2006–2010 2011	SSMR AMSR-E SSM/IS (Markus et al., 2011)
Melt pond fraction	1979–1999 2000–2011	Constant fraction as in 2011 ICDC (Rösel et al., 2012)



Table 2. Transmittances of different sea ice and surface types. Abbreviations: FYI: first year ice, MYI: multi year ice, Phase I: winter, MO: melt onset, Phase IV: summer, FO: freeze onset, Threshold: transition from open ocean to sea ice and vice versa.

	Phase I (winter)	At MO	Phase IV (summer)	At FO	Threshold
FYI, pond covered sea ice	0.002	0.04	0.087	0.04	0.4
MYI, pond covered sea ice	0.002	0.02	0.05	0.02	0.4
FYI, bare ice/snow	0.001	0.017	0.04	0.017	0.17
FYI, melt ponds			0.22		
MYI, bare ice/snow	0	0.004	0.01	0.004	0.07
MYI, melt ponds			0.15		
Open ocean			0.93		



Table 3. Annual Arctic-wide solar heat input (and relative changes) under sea ice (Q_T) in 2007
for the reference method and sensitivity studies: changes in melt season duration by (1) 7 day
earlier early melt onset (EMO) and melt onset (MO), (2) 14 days earlier EMO and MO, and (3)
14 days later early freeze onset (EFO) and freeze onset (FO). All numbers in 10 ¹⁹ J.

	Reference system	EMO and MO – 7 days	EMO and MO – 14 days	EFO and FO + 14 days
Apr	1.00	1.19 (+19%)	1.45 (+45 %)	1.00 (0%)
May	5.53	7.35 (+33%)	10.5 (+90 %)	5.53 (0%)
Jun	20.9	24.0 (+15%)	27.1 (+30%)	20.9 (0%)
Jul	18.4	19.1 (+4%)	19.7 (+7%)	18.4 (0%)
Aug	6.33	6.42 (+1%)	6.48 (+2%)	6.68 (+5%)
Sep	0.69	0.69 (0%)	0.69 (0%)	0.97 (+41 %)
Jan-Dec	53.3	59.2 (+11 %)	66.3 (+24%)	53.9 (+1%)





Figure 1. Classification of sea ice **(a)** types and **(b)** surface properties as used in this study. The timing of each phase results from the status of the sea ice. Depending on the season, different sea ice types co-exist. Abbreviations: FYI: first year ice, MYI: multi year ice, EMO: early melt onset, MO: melt onset, EFO: early freeze onset, FO: freeze onset.







Figure 2. (a) Total transmittance of sea ice during each phase (Fig. 1). In this figure, melt pond concentrations of 26% are assumed for first year ice (FYI) and 29% are assumed for multi year ice (MYI). **(b)** Transmittance of bare ice during each phase (see Fig. 1). Transmittances of single ice classes are given in Table 1. Abbreviations: see Fig. 1.



Figure 3. Monthly mean of total solar heat input $(Q_T(x, y))$ under Arctic sea ice (ice covered areas only) for the year 2011.





Figure 4. Annual total solar heat input $(Q_T(x, y))$ through Arctic sea ice. (a) Average and (b) trend from 1979 to 2011. The trend is corrected for the trend in sea ice concentration. Purple shaded areas were not covered with sea ice during the maximum extent in all years.





Figure 5. (a) Arctic-wide total solar heat flux under sea ice (Q_T) (black) and its trend (red) from 1979 to 2011. **(b)** Monthly Arctic-wide solar heat input for May to August and its trend from 1979 to 2011. The data are corrected for the trend in sea ice concentration. Areas that were not ice covered at any time in 2011 or in the certain month in 2011 are excluded from the analyses.





Figure 6. (a) Transmitted total solar heat input and **(b)** total transmittance during the drift of Tara in 2007 (Nicolaus et al., 2010b). Compared are in situ measurements (green) with the presented method (red) and the presented method, but using the observed dates for phase transitions. Between 16 July and 14 August (dotted lines) a comparison is not reasonable since the sensor was strongly influenced by biological processes during Tara.







