SUNLIGHT, SEA ICE, AND THE ICE ALBEDO FEEDBACK IN A CHANGING ARCTIC SEA ICE COVER

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LONG-TERM GOALS

The overarching goal of this work is to develop a quantitative understanding of the partitioning of solar radiation by the Arctic sea ice cover and its impact on the heat and mass balance of the ice and upper ocean. Particular emphasis is placed on the Chukchi and Beaufort Seas, where there have been large changes in ice conditions in recent years.

OBJECTIVES

1. Synthesize relevant data from reanalysis products, satellite observations, previous field campaigns, and the ongoing Arctic Observing Network.
2. Calculate the partitioning of spectral solar radiation between reflection to the atmosphere, absorption within the ice, and transmission to the ocean.
3. Determine the relative impact on solar partitioning of changes in i) incident solar radiation, ii) ice concentration, iii) ice age, and iv) onset dates of melt and freeze up.
4. Assess the magnitude of the contribution from ice-albedo feedback to the observed decrease of sea ice in the Chukchi and Beaufort Seas.
5. Relate solar heat input to the ice and ocean to surface, bottom, lateral, and internal melting of the ice cover.
6. Determine spatial distribution and temporal evolution of solar heat absorbed in the upper ocean.

7. Transfer results from this study to the sea ice prediction and modeling community to improve the treatment of solar radiation and the ice-albedo feedback. This transfer will take the form of publications and direct input to parameterization development.

APPROACH

The central element of our approach is synthesis. We are synthesizing remote sensing observations, reanalysis products, field observations, autonomous in situ observations, and process models. Our study area is the Arctic Ocean and surrounding seas, with particular emphasis on the Chukchi and Beaufort Seas. Some of the largest changes to the sea ice cover are occurring in the Chukchi and Beaufort where there are many ongoing research efforts affording opportunities for synergy and collaboration. Our analysis is done on a 25 x 25 km equal area scalable grid. The use of this grid facilitates integration and synthesis of observations from different datasets and the export of our results to potential users. This work builds on earlier studies of the impact on albedo evolution by changes in ice concentration and melt and freeze up onset dates by i) examining the impact of the shift from multiyear to seasonal ice; ii) determining heat absorbed in the ice, transmitted through the ice, and deposited into the ocean; and iii) taking a regional focus with extensive data assimilation.

This work is directed at improving our ability to predict the state of the ice cover in the Chukchi and Beaufort Seas over scales from weeks to years to decades. Integration, synthesis, and collaboration are key elements of this project. We are integrating our efforts with ongoing research in the Chukchi and Beaufort Seas including the ONR-DRI on Emerging Dynamics of the Marginal Ice Zone, the Sea Ice Outlook, the Arctic Observing Network projects, the NSF SUB-ICE field experiment, and the NASA-sponsored projects Icebridge and Icescape (Impacts of Climate change on the Eco-Systems and Chemistry of the Arctic Pacific Environment). These projects have generated extensive datasets on ice conditions and ice mass balance, biological, and oceanographic conditions in the Chukchi and Beaufort Seas. We are also coordinating our work with other ONR sponsored research on melt ponds (Golden et al.), ice morphology from satellites (Polashenski et al), and floe size distribution (Richter-Menge et al.)

WORK COMPLETED

We have completed the assembly of a dataset to examine solar partitioning from the local scale to the basin scale.This dataset includes information on incident solar radiation, ice concentration, ice type, and melt and freezeup onset dates on a 25 x 25 km equal area scalable grid from 1980 to 2014. We have added sea ice thickness information from the PIOMAS model [*J. Zhang*], melt pond coverage from MODIS [*Rösel et al.*, 2012], and ice-age estimates [*Maslanik et al.*, 2011] to this dataset.

We have also completed a synthesis of existing field observations of the apparent and inherent optical properties of sea ice, including the many forms of first-year and multiyear ice including snow-covered, bare, and ponded ice. We are using this synthesis in our modeling efforts and it is being documented in a book chapter on the optical properties of sea ice.

We are using this extented dataset to build a climatology of the partitioning of solar heat between reflection to the atmosphere, absorption in the snow and sea ice, and transmission to the ocean. The work includes:

1. Testing the albedo parametrizations [*Perovich et al.*, 2002; *Perovich and Polashenski*, 2012] as broadly as possible,
2. Assessing the consistency of approaches for treatment of solar partitioning by ponded ice,
3. Entraining modeled ice thickness data in estimates of light transmittance through sea ice,
4. Exploring differences in solar partitioning between first-year and multiyear ice.

RESULTS

Assessment of changing partitioning

There is a major shift in the Arctic sea ice cover from predominantly multiyear ice to predominantly first year ice. We examined the impact of this shift on the seasonal evolution of albedo and solar radiation partitioning for standard first year and multiyear ice conditions (Figure 1). When the ice is snow covered there is little difference in albedo and partitioning between first year and multiyear ice. Once the snow melts there is significant divergence in the evolution of albedo, with first-year albedos decreasing much more than multiyear values due to the greater coverage of ponds on first-year ice. Much more solar heat is deposited on the first year ice at this time, since this occurs when the incident irradiance is large. The albedo of first year ice is consistently smaller than multiyear ice throughout the remainder of summer. In this example 32% more solar energy was deposited into first year ice than multiyear ice.

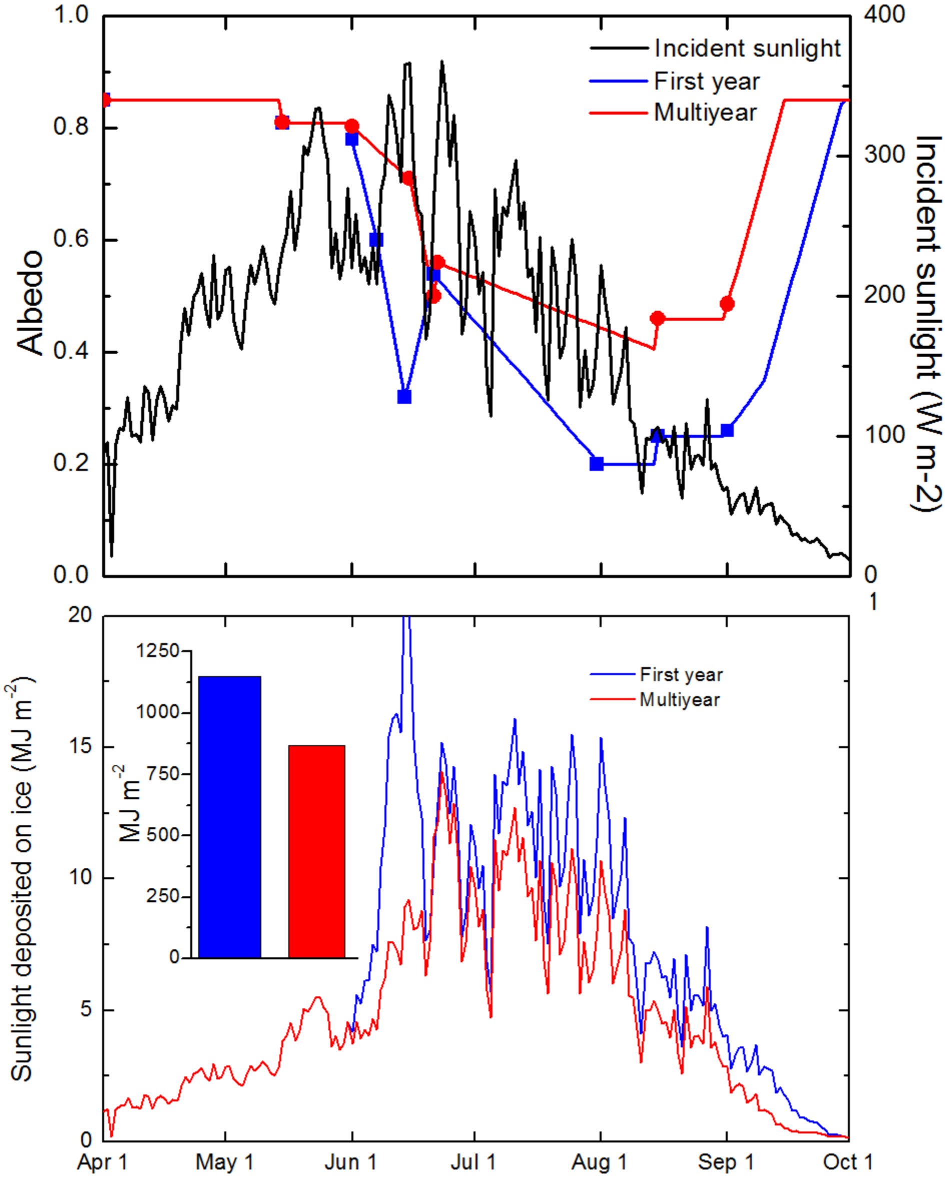

Figure 1. Albedo evolution and solar heat input for multiyear (MY) and first year (FY) ice in the Beaufort Sea.

Compilation of a library of sea ice inherent optical properties

A radiative transfer model is needed to generate estimates of light transmission through the ice and absorption within the ice. The fundamental building blocks of such a model are absorption and scattering coefficients. We have compiled a library of these values for different ice conditions. Figure 2 presents scattering coefficients for bare and ponded, first year and multiyear ice at different depths. Summer sea ice can be treated as three optical layers; a surface scattering layer, a drained layer, and the ice interior. Scattering coefficients for the different layers vary over two orders of magnitude. There can also be considerable variability for a particular layer of a particular ice type.

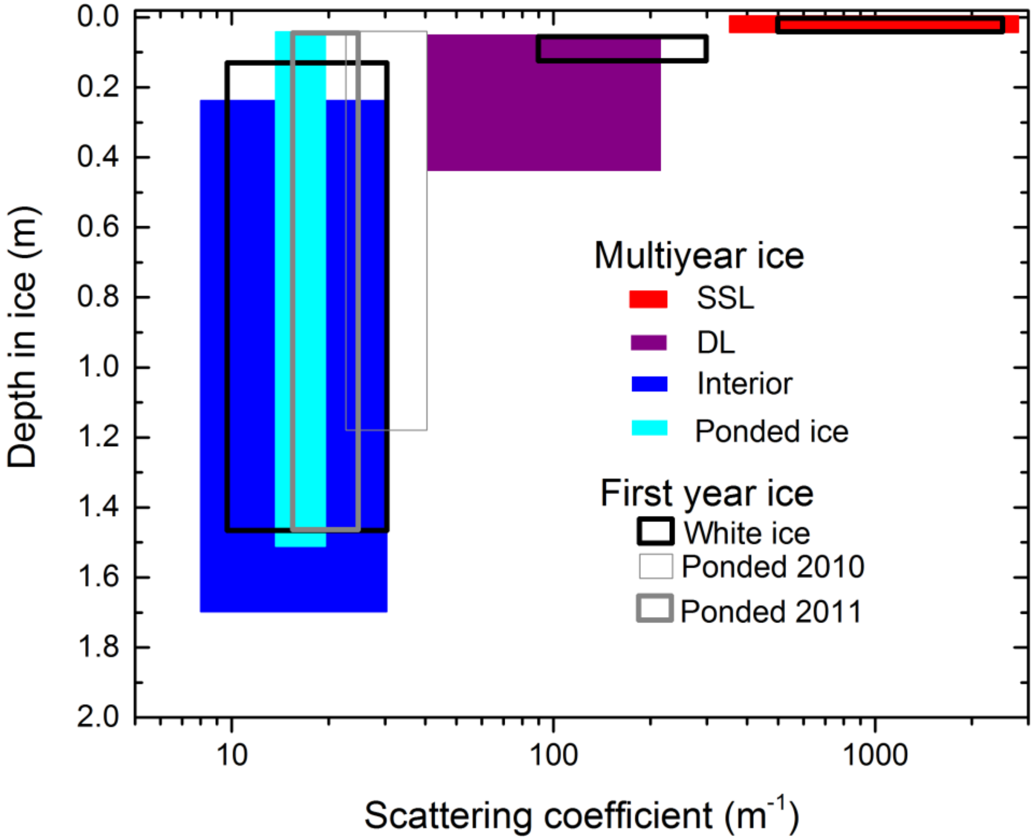

Figure 2. Scattering coefficients for bare and ponded, first year and multiyear ice.

Validation of empirical albedo record

The empirical ice albedo record developed by *Perovich et al.* [2002] is an extrapolation from the year long SHEBA dataset that consisely summarizes albedo based on remotely sensed (passive microwave) trigger dates (early melt onset, final melt onset, early freeze up, final freezeup). This empirical record has been invaluable for assessing the surface heat balance of ice at specific locations, but has not been subjected to broad tests or validation. We have now compared estimates of basin-wide intrinsic ice albedo (ice only, does not include areas of open water) for the empirical record developed by *Perovich et al.* [2002, 2012] with the CLARA-SAL dataset [*Riihelä et al.*, 2013]. This comparison is only where the ice concentration remains > 50% for the entire year. Generally for May, June and July, ice albedo differences for the two treatments are smaller than ± 0.1. The difference in August is closer to 0.2 in much of the western Arctic Ocean, where the empirical record appears to assign lower albedo to the surface than the satellite record. However, a key discrepancy in these records appears to be the summer minimum albedo and the average date this minimum albedo occurs. Figure 3 shows maps of the average minimum albedo reached during the summer melt season. The empirical model and the remotely sensed observations yield very similar minimum summer sea ice albedos, which are generally ≤ 0.45 across the basin. The CCSM4 model appears to persistently overestimate minimum summer albedo with values typically ≥ 0.45 across much of the basin.

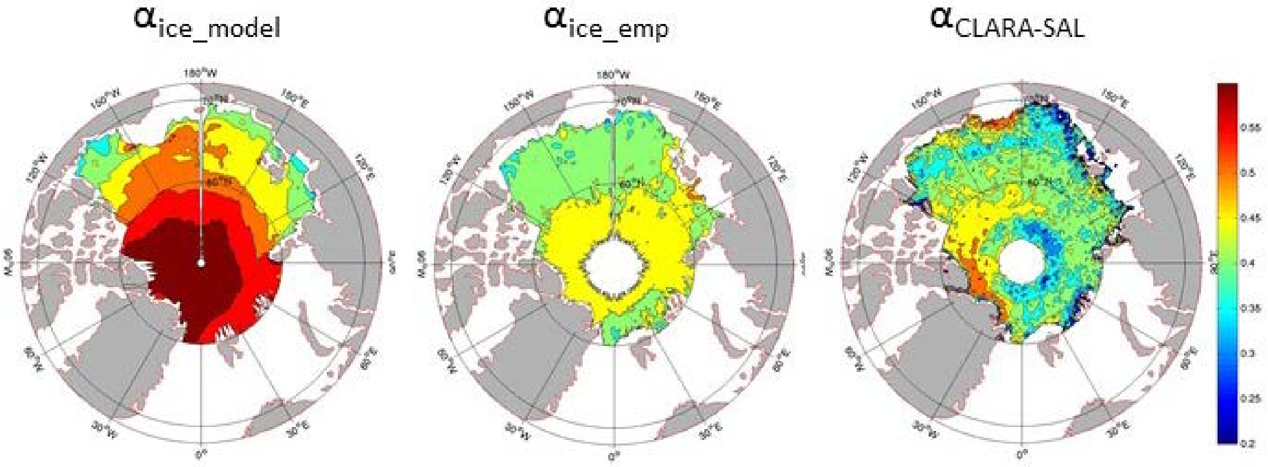

Figure 3. Average minimum summer ice albedo from (a) CCSM4 model, (b) empirical record, and (c) CLARA-SAL record.

Furthermore, the date of average minimum surface albedo for the ice covered portion of all grid cells where ice concentration exceeds 50% is compared for the CCSM4 model output, the empirical record, and the CLARA-SAL remotely sensed record in Figure 4. While it appears that the GCM model agrees approximately with the observational record and that that the empirical record is the outlier, we think that both the GCM model and the satellite record are severely impacted by significant shortcomings and that the empirical record is likely to actually be a better representation of the seasonal evolution of the actual albedo progresssion. In the case of the GCM, shortcomings stem from the issue that many summers remain frozen and do not initiate a melt sequence (consistent with Fig. 3a where the minimum albedos remain relatively high), which is not verified by passive microwave melt onset data. In the case of the remotely sensed record, low light levels and increased solar zenith angles bias the CLARA-SAL ice albedos at the close of summer [*Riihelä et al.*, 2013]. The timing of the lowest albedo should be tightly tied to the date of freeze onset, which is most accurately portrayed in the passive microwave record, and hence in the empirical treatment. Figures 3 and 4, along with related discussion, are presented in *Light et al.* [2015].

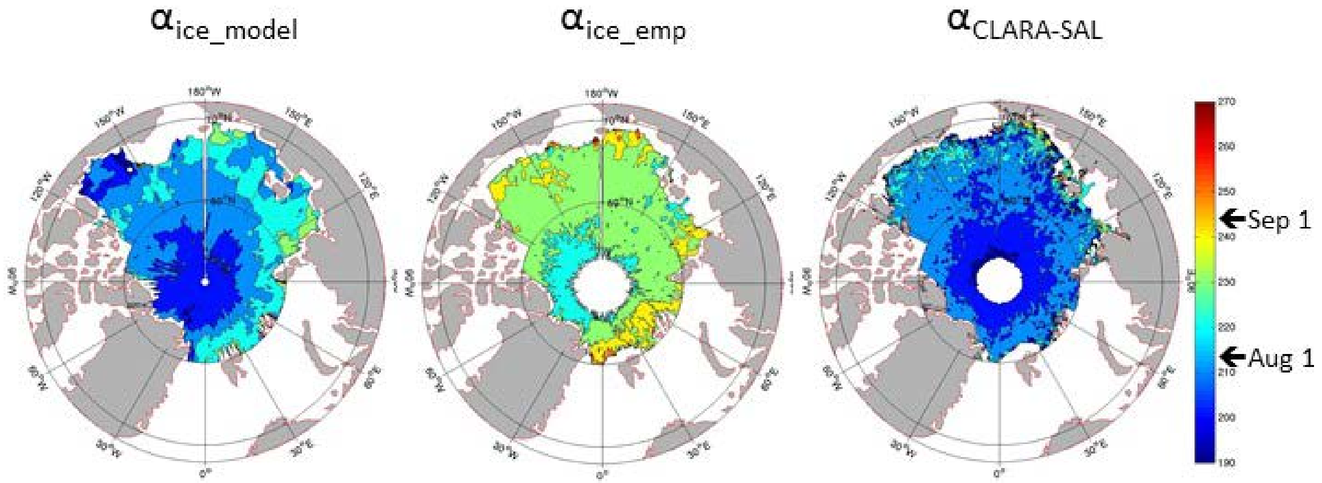

Figure 4. Average day of year for lowest ice albedo from (a) CCSM4 model, (b) empirical record, and (c) CLARA-SAL record.

Assessment of treatment of solar partitioning by ponded ice

The work of *Rösel et al.* [2012] provides remotely sensed estimates of melt pond areal coverage from 2000 to 2011. These data have been regridded for use with our empirical albedo record. We have been investigating the consistency between the melt pond areal fraction product and the remotely sensed albedo product in the context of understanding the surface radiation budget. Particular attention is paid to the infrequent summer observation of the surface and the need to carry out monthly averages. We are also comparing the satellite pond record with in situ observations of melt pond evolution [*Fetterer and Untersteiner*, 1998; *Perovich et al*., 2002; *Polashenski et al.*, 2012].

Estimation of light transmittance through sea ice.

We have regridded ice thickness output from the PIOMAS model and have carried out an assessment of light transmittance through the summer ice cover. This was accomplished by combining our synthesized inherent optical properties library with a simple Beer's Law radiative transfer formulation. Figure 5 shows average accumulated heat [MJ m^{-2}] through July for only the ice covered portion of each grid cell. The three maps represent the last three decades.

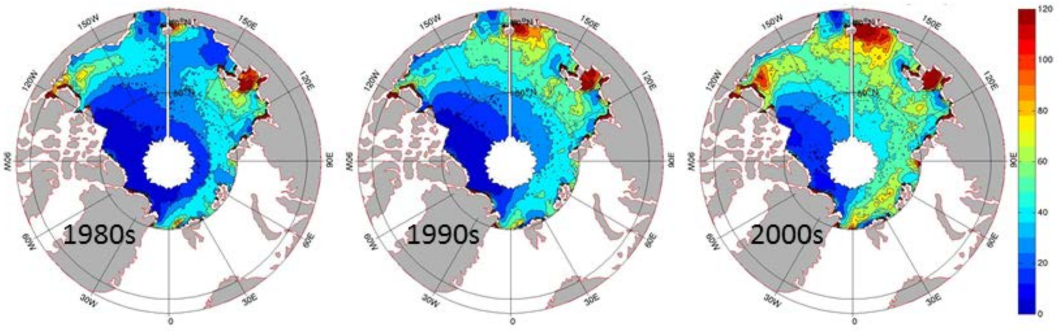

Figure 5. Maps of mean accumulated ocean heat (MJ m^{-2}) transmitted through the ice for the 1980s, 1990s, and 2000s. Significant increases in heating are due at least in part to reduced ice thickness, but may also be due to trends in earlier melt onset and consequent enhanced surface melt ponding.

Updated estimate of Arctic Ocean heating

Perovich et al. [2007] demonstrated that there have been significant increases in ocean heating over the satellite era. In fact, the largest increases have been centered in the Western Arctic. We have updated this analysis to include ice concentration observations and shortwave radiation estimates through 2014. Figure 6a shows the analysis for 1979 – 2005 (reproduced from Perovich et al., Fig. 2) and Fig. 6b shows the updated analysis for 1979 – 2014. This analysis shows increases in heating are being manifested more dramatically in areas of the Arctic beyond the western basin in the most recent years. Change in trend in the Western Arctic is small, likely because the ice cover now has predictably low late summer concentration, so the heating there has not increased dramatically. Summer heating in other parts of the Arctic ice cover appear to now be accelerating.

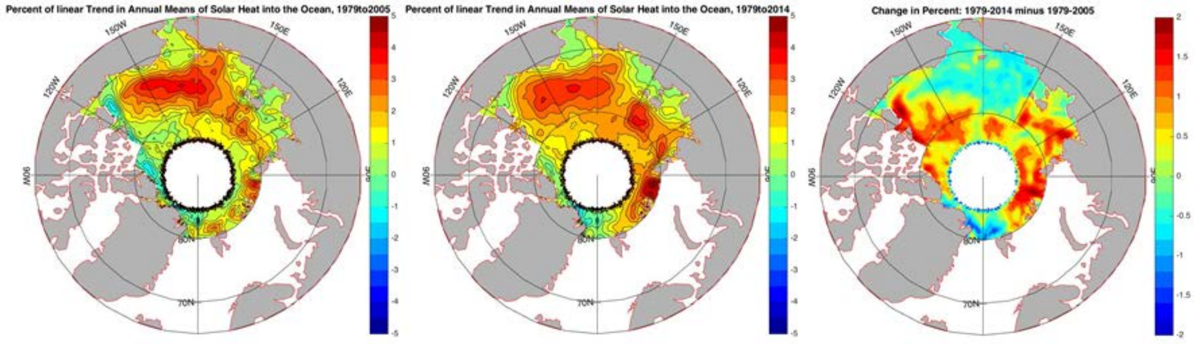

Figure 6. Maps of the linear trend of annual solar heat input to the ocean. (a) is reproduced from Perovich et al., 2007 Fig. 2 and demonstrates the observed trend for 1979 – 2005; (b) is obseved trend updated to include years through 2014; (c) shows the difference in trends between (a) and (b).

IMPACT/APPLICATIONS

Our findings are clarifying the differences in optical behavior between first-year and multiyear ice and ascertaining the effect of changes in seasonal timing of melt and freezeup. These findings indicate that the amount of solar radiation being deposited in the ice-ocean system is increasing.

RELATED PROJECTS

Our work is closely integrated with several other Office of Naval Research projects. Our radiative transfer modeling requires information on sea ice morphology including ice concentration, pond fraction, melt state, snow depth, and ice thickness. We are working with K. Golden on melt pond statistics, J. Richter-Menge on floe size distribution, and C. Polashenski on remote sensing products for sea ice. We are making use of modeled ice thickness fields from the Pan-Arctic Ice-Ocean Modeling and Assimilation System (PIOMAS). We are also integrating our efforts with ongoing research in the Chukchi and Beaufort Seas including the ONR-DRI on Emerging Dynamics of the Marginal Ice Zone, the Sea Ice Outlook, the Arctic Observing Network projects and the NASA-sponsored projects Icebridge and Icescape (Impacts of Climate change on the Eco-Systems and Chemistry of the Arctic Pacific Environment). We are also collaborating with climate modelers (M. Holland) at NCAR.

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14. ABSTRACT

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