Snowmelt–Albedo Feedback: How Does It Impact Antarctic Surface Melt Rates?

Stan Jakobs[1], Carleen Reijmer[1], Michiel van den Broeke[1], Gert König-Langlo[2], Peter Kuipers Munneke[1], Luke Trusel[3], Willem Jan van de Berg[1], and Melchior van Wessem[1]

[1]Utrecht University
[2]Alfred Wegener Institute Helmholtz-Center for Polar and Marine Research Bremerhaven
[3]Pennsylvania State University

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Abstract

The future mass balance of the Antarctic ice sheet depends for an important part on the stability of the floating ice shelves that surround it, as these buttress the flow of grounded ice. Being situated relatively far north and near sea level, surface melt is a common but otherwise intermittent process on Antarctic ice shelves. Surface meltwater can form meltwater ponds, which can deepen existing crevasses that may eventually penetrate through the entire ice shelf. This process, called hydrofracturing, likely contributed to the recent disintegration of multiple ice shelves in the Antarctic Peninsula, most recently Larsen B ice shelf in 2002. A thorough understanding of surface melt processes is therefore key to improve our ability to predict future ice shelf stability and ice sheet mass loss. The snowmelt–albedo feedback plays a crucial role in Antarctic ice sheet surface melt: when snow melts, meltwater may refreeze in the snowpack, increasing the average grain size and lowering surface albedo. In turn, this enhances the absorption of solar radiation, further increasing surface melt rate. To investigate the importance of the snowmelt–albedo feedback for surface melt in Antarctica, we implemented an albedo parameterization in a surface energy balance model that calculates melt rates. In this parameterization, we can separate the impacts of dry and wet snow metamorphism on albedo evolution and melt rate. This allows us to quantify the snowmelt–albedo feedback, the results of which are presented here. Results for Neumayer Station on the Ekström ice shelf in Dronning Maud Land, East Antarctica, show that the snowmelt–albedo feedback results in a threefold increase in local melt rate compared to calculations in which the effect has been ignored. We also applied this method to weather station data from locations elsewhere in Antarctica. Finally, the same albedo parameterization was implemented in the regional climate model RACMO2. This provides the opportunity to extend this method to the entire Antarctic ice sheet, and to assess the temporal and spatial variability of the magnitude of the snowmelt–albedo feedback.

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C.L. Jakobs[1], C.H. Reijmer[1], M.R. van den Broeke[1], G. König-Langlo[2]
P. Kuipers Munneke[1], L.D. Trusel[3], W.J. van de Berg[1], J.M. van Wessem[1]

1) Institute for Marine and Atmospheric Research Utrecht (IMAU), Utrecht University, the Netherlands
2) Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, Bremerhaven, Germany
3) Department of Geography, Penn State University, University Park, PA, USA

Introduction

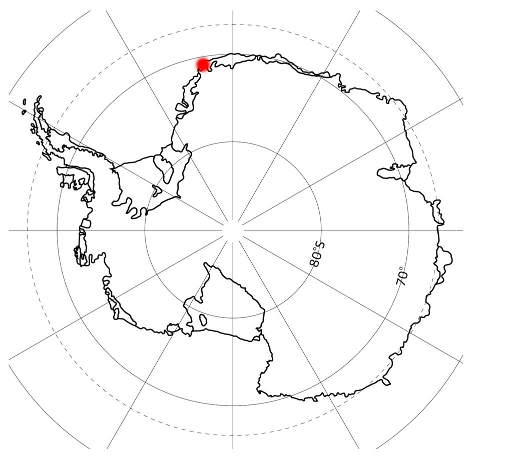

Figure 1: Location of Neumayer station on the Antarctic continent.

Ice shelves are the floating extensions of the ice sheet, present along ~74% of the Antarctic coast (Bindschadler et al., 2011). Surface melt is an extremely important process for ice shelves: surface meltwater can form melt ponds, which are capable of destabilizing the ice shelf and potentially leading to disintegration of the ice shelf. A proper representation of surface melt processes is therefore essential for modeling studies. We have studied the effect of the snowmelt–albedo feedback (SMAF) on surface melt locally, at Neumayer, East Antarctica (Fig. 1), as well as for the entire continent using the regional climate model RACMO2 (Van Wessem et al., 2018).

Snowmelt–albedo feedback

When snow melts, the meltwater can refreeze in the snowpack, resulting in significantly larger snow grains. Larger grains absorb more radiation than smaller grains, therefore refreezing leads to a lower surface albedo. This lower albedo increases radiation absorption, further lowering the surface albedo. This is known as the snowmelt–albedo feedback. By implementing an albedo parameterization in a surface energy balance, we are able to isolate the contribution of refrozen snow to surface albedo.

Model description

To quantify SMAF for Neumayer, we use a surface energy balance (SEB) model. This solves the SEB equation:

$$\mathrm{SW}_{\mathrm{net}} + \mathrm{LW}_{\mathrm{net}} + Q_{\mathrm{S}} + Q_{\mathrm{L}} + Q_{\mathrm{G}} = M,$$

where $\mathrm{SW}_{\mathrm{net}}$ and $\mathrm{LW}_{\mathrm{net}}$ are the net shortwave and longwave radiation fluxes, Q_{S} and Q_{L} are the turbulent fluxes of sensible and latent heat, Q_{G} is the ground heat flux and M is the resulting energy available for melt (Reijmer et al., 1999, Jakobs et al., 2019).

- Temperature, wind speed, pressure and radiation fluxes taken from observations (König-Langlo, 2017)
- Turbulent fluxes calculated with Monin-Obukhov similarity theory
- Ground heat flux modeled by a multilayer snow model
- Albedo parameterisation based on Kuipers Munneke et al. (2011)
  - Grainsize-dependent base albedo, modified by snow impurities, solar zenith angle, and cloud optical thickness
  - Grain sizes for new snow and refrozen snow are obtained by minimizing the deviation of daily averaged albedo
  - Precipitation timing taken from a regional climate model (RACMO2.3)

The contribution of refrozen snow to surface albedo can be switched off, allowing us to investigate its effect on surface melt.

Regional climate model

We use RACMO2 to model SMAF for the entire continent

- Dynamics of HIRLAM model, physics of ECMWF-IFS
- Assumes hydrostatic balance, 40 vertical levels
- Multilayer snow model for melt, refreezing, percolation and runoff of meltwater
- Drifting snow scheme that simulates the redistribution and sublimation of suspended snow particles
- Same albedo parameterisation as SEB model

Similar to the local SMAF quantification study, we have performed a run in which the contribution of refrozen snow to surface albedo is switched off.

Results

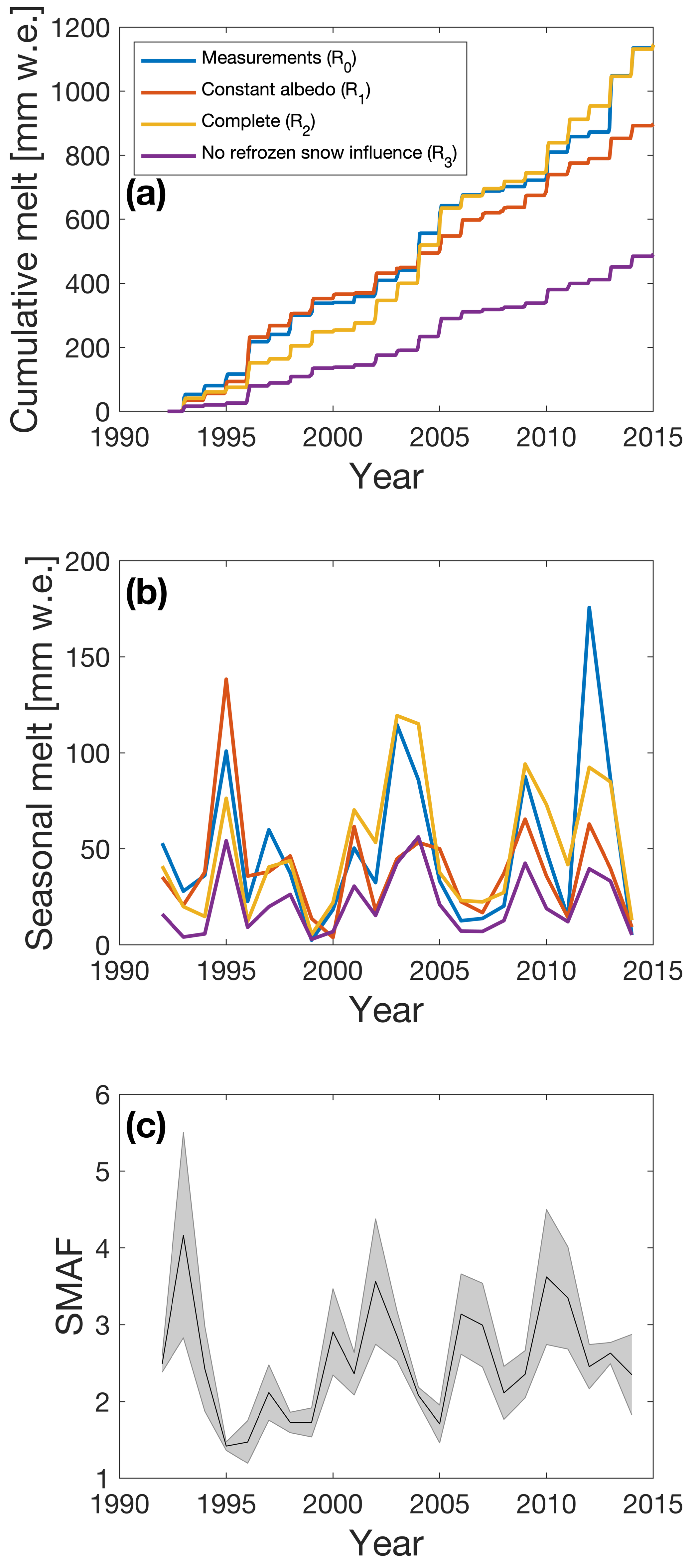

Figure 2: (**a**) Timeseries of modeled cumulative melt for the run with measured albedo (R_0, blue), a constant albedo of 0.84 (R_1, red), a run in which refrozen snow impacts snow grain size (R_2, yellow) and a run in which snow grain size is not influenced by refrozen snow (R_3, purple). (**b**) Same as panel (**a**) but for seasonal melt rates. (**c**) Ratio of modeled surface melt between yellow and purple lines in panels (**a**) and (**b**) (runs R_2 and R_3 respectively). The gray area indicates the uncertainty coming from the uncertainty in the determination of cloud optical thickness, $\pm 5\,\mathrm{W\,m^2}$ measurement uncertainty in SW↑ and the inclusion of shortwave radiation penetration. Figure taken from Jakobs et al. (2019).

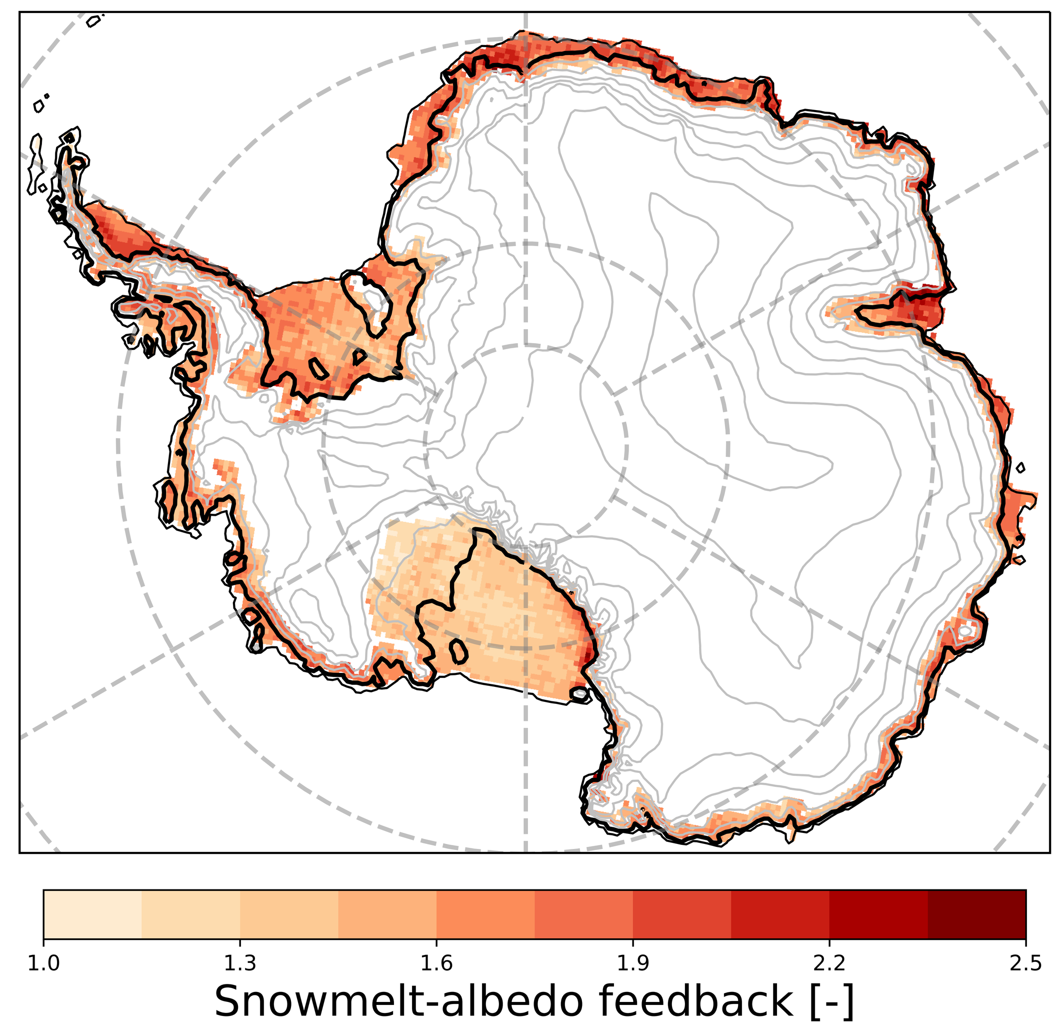

Figure 3: Nov–Mar average values of SMAF obtained with the RACMO2 climate model for Antarctica. The thin black line indicates the 10 m height contour (~ shelf edge), the thick black line indicates the 150 m height contour (~ grounding line), gray lines indicate 500 m height contours.

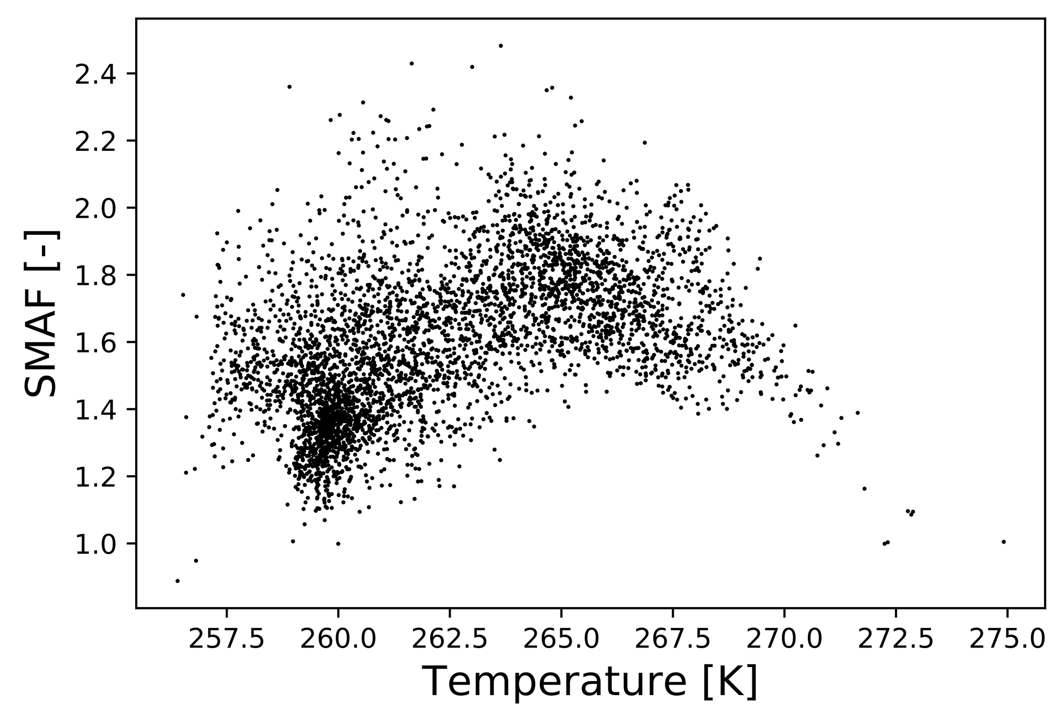

Figure 4: Average Nov–Mar temperature vs. average SMAF for all points in Fig. 3 at which melt is modeled by RACMO2.

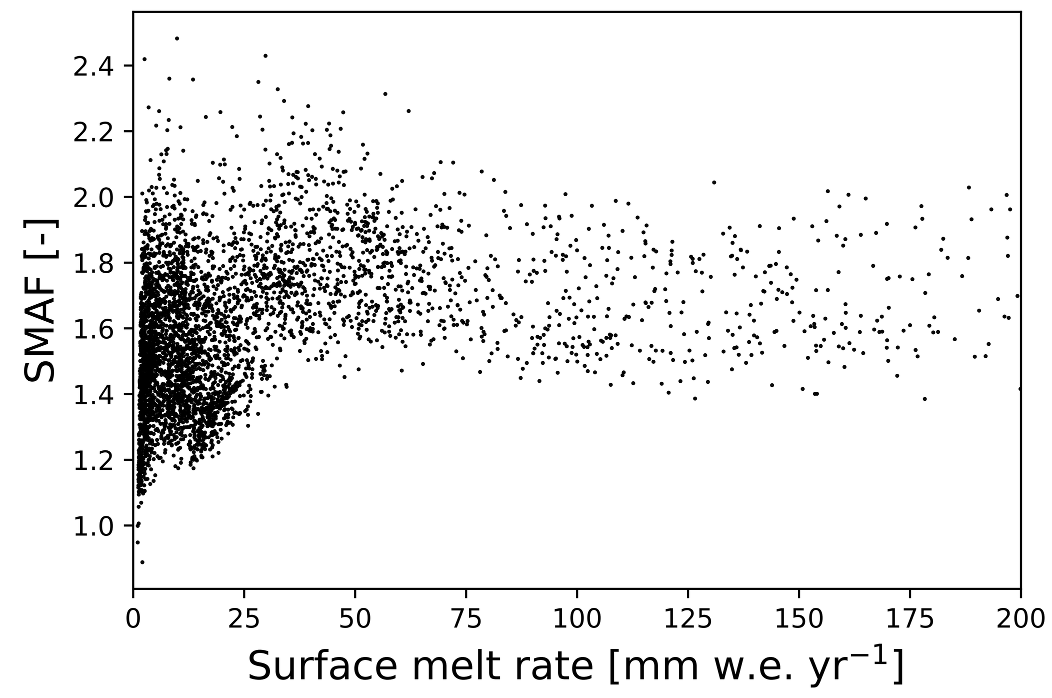

Figure 5: Same as Fig. 4 for average Nov–Mar cumulative surface melt.

Discussion

The results are presented in Fig. 2-5, the main findings are summarised below.

- At Neumayer, the run with parameterized albedo reproduces surface melt well (Fig. 2a+b)
- SMAF enhances surface melt by a factor of 2.5 at Neumayer (Fig. 2c)
- Across Antarctica, SMAF varies from 1–2.5 (Fig. 3)
- Highest SMAF values are encountered in regions with moderate average Nov–Mar temperature (Fig. 4)
- In low-melt regions, SMAF is sensitive to average surface melt rates (Fig. 5)

Outlook

We show that SMAF is highly variable in Antarctica, reaching maximum values in regions with intermittent melt, e.g. coastal Dronning Maud Land and Amery ice shelf. Some questions remain unanswered:

- What is the effect of precipitation and synoptic patterns on spatial variability of SMAF?
- How well does Fig. 3 compare to in-situ SMAF estimates, derived from AWS data across Antarctica?

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