Ocean temperature impact on ice shelf extent in the eastern Antarctic Peninsula

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The recent thinning and retreat of Antarctic ice shelves has been attributed to both atmosphere and ocean warming. However, the lack of continuous, multi-year direct observations as well as limitations of climate and ice shelf models prevent a precise assessment on how the ocean forcing affects the fluctuations of a grounded and floating ice cap. Here we show that a +0.3-1.5 °C increase in subsurface ocean temperature (50-400 m) in the north-eastern Antarctic Peninsula has driven to major collapse and recession of the regional ice shelf during both the instrumental period and the last 9000 years. Our projections following the representative concentration pathway 8.5 emission scenario from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change reveal a +0.3 °C subsurface ocean temperature warming within the coming decades that will undoubtedly accelerate ice shelf melting, including the southernmost sector of the eastern Antarctic Peninsula.

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he Antarctic Peninsula has been one of the most rapidly warming regions of the world during the twentieth century where ~75% of the ice shelves have already retreated over the past 50 years. This retreat durably affects the stability of the regional glaciers and the ice sheet mass balance, which ultimately contributes to the eustatic sea-level rise. Specifically, in the eastern Antarctic Peninsula (EAP), the rapid warming observed since the 1970s have had marked consequences on regional glaciers and ice shelves. One of the first major events occurred in 2002 when the Larsen B ice shelf in eastern Antarctic Peninsula (EAP) (Fig. 1) collapsed and lost an area of ~3250 km² by calving huge icebergs to the ocean. A series of smaller—but significant—events occurred earlier in the northern part of the EAP with the collapse of the Larsen A and the Prince Gustav ice shelves in 1995, as well as that of the Larsen Inlet in 1989 (Fig. 1). Since 2010, a giant crack has continuously incised the Larsen C ice shelf until it broke off in 2017 to form a massive iceberg of ~6000 km² (~9–12% of the total ice shelf), thus drawing the premise of unprecedented major collapses in the near future.

Such successive events were initially hypothesized to have been mainly driven by Antarctic surface warming. Indeed, a surface air temperature (SAT) increase of 2–3 °C has been observed between the 1960s and the late 1990s, which may have directly impacted surface melt, increased hydrofracturation, and indirectly glacier acceleration via enhanced precipitation. However, an increase in the ocean heat content can also substantially reduce the ice sheet extent through basal and frontal melting, ice shelves thinning, and iceberg calving. Although the oceanic impact remains difficult to quantify due to the lack of observational data, recent studies suggested that the effects of subsurface ocean warming could have contributed to more than 50% of the total ice loss in some Antarctica areas during the last few years, especially in the EAP region.

Indeed, the intrusion of relatively warm Circumpolar Deep Waters (CDW) onto the Antarctic shelf has been shown to promote ice shelf basal melting around Antarctica. The warm deep water is upwelled across the continental shelf and channeled toward the grounding ice line through cavities and troughs. In the Weddell Sea, the CDW enters as a coastal current from the east and circulates clockwise as Warm Deep Water (WDW) along the EAP shelf. However, the recent and past activity of this warm water mass, including its temperature change and modification along its pathway to the continental shelf by mixing with shelf waters, is not well known, nor its impact on the ice shelf extent. In particular, variations in the intensity and position of the circumpolar Southern Westerly Winds (SWW) along the EAP may strongly modulate the upward transport of WDW onto the shelf through Ekman pumping.

Here we combine recent and geological records spanning the past 9000 years to investigate the variability of environmental conditions of the EAP on multiannual-to-millennial timescales and its effect on the ice shelf boundaries. Our results suggest that the ocean thermal forcing, tied to the circulation of the relatively warm WDW, has played a central role on the regional ice shelf instability during both the instrumental period and Holocene; a slight ocean warming contributing to substantial ice shelf collapse and regression. When extrapolating these results to the most pessimistic Intergovernmental Panel on Climate Change (IPCC) emission scenario, we show that a slight subsurface ocean warming will further accentuate the current erosion of the EAP ice shelf by the end of the twenty-first century.

**Results**

**Ocean impact on recent ice shelf collapse.** Using reanalysis data, we first computed the variations of the Ekman pumping along the EAP margin since 1986, the recent crack of the Larsen C since 2010, the study site (JPC-38) (63.717°S, 57.411°W, 760 m water depth) (blue star) and the JRI ice core (black star). The arrows show the circulation of the CDW (orange) and WDW (light brown) around the Peninsula. Reanalyzed data and model simulations have been computed along the EAP margin (i.e., in the gray area). Dark and light blue lines correspond to the bathymetry at 2000 and 1000 m depth and delineate the continental shelf from the abyssal Weddell Sea basin.
fields. As such, dominant SWW, offshore winds would have favored the upward transport of deeper water masses.

Reanalyses\textsuperscript{18,19} concomitantly document a sharp increase in subsurface ocean temperatures (SOT) (50–400 m water depth) on the continental shelf reaching up to +0.6 °C, thus sharing a similar pattern with the computed Ekman pumping during the same period of time. Nevertheless, a certain time lag is sometimes observed between SOT and Ekman pumping variations, especially in the early 2000s. The subsurface temperature should quickly respond to variations in wind-driven upwelling of warmer deep ocean water. However, we suggest that the response is slowed down because of heat exchange between the upwelled water and the much colder atmosphere and surface waters. Other factors like a significant change in the temperature of the deep-water masses\textsuperscript{27} may also have participated to the delay between the two records. We therefore argue that the SOT increase and associated warming of the EAP shelf resulted from two synergistic processes: (i) the enhanced penetration of warm deep waters on the shelf due to intensified wind-driven upwelling linked to a regional or global shift of the surface wind fields\textsuperscript{27} (Fig. 2b), and (ii) the warming of Southern Ocean subsurface waters\textsuperscript{20,22} and CDW during the last century\textsuperscript{23,24}.

We also find that the most rapid and abrupt SOT warming reconstructed around the EAP ice shelf over the last centuries concurred with the Larsen B ice shelf collapse, thus strongly suggesting that a slight SOT increase, in concert with atmospheric warming, has been pivotal in controlling the Larsen B ice shelf instability. While we miss robust observation data prior the 1970s, the continuous SOT increase during phases of smaller collapses may imply that SOTs have potentially contributed to other smaller ice shelf collapses along the EAP and around Antarctica. Comparatively, cold SOTs as observed in the early 2000s, probably due to a dominant downwelling forcing, during a period of pronounced SAT cooling\textsuperscript{25,26} likely prevented further large ice shelf to collapse. Our results suggest that both the ocean (through wind-driven circulation and off-shelf water temperature changes) and atmosphere (through SAT and wind stress changes) forcing have closely acted together over the last decades to either strongly destabilize the EAP ice shelves or, inversely, to limit their dislocation.

Ocean-driven ice shelf regression throughout the Holocene. Beyond the observational period, there is only one available regional SAT record in the EAP\textsuperscript{27} (Fig. 3a), situated in James Ross Island (JRI), and no SOT records so far. Based on water stable isotopes calibrated to recent air temperatures\textsuperscript{7,27}, the reconstructed mean annual SAT documents a 1.5 °C cooling over the Holocene occurring in two steps between 10,000 and 6000 years before present (BP), and 3500 and 500 years BP. The Holocene cooling was interrupted by a slightly warmer period. The first main cooling episode corresponds to a phase of major EAP ice shelf retreat reported in the literature\textsuperscript{28–31}. Indeed, marine sedimentological data indicate that the northern JRI ice shelf initiated a transition from grounded to floating ice ~8000 years BP ago\textsuperscript{30}, which coincided with the early deglaciation of the Prince Gustav Channel and the Ulu Peninsula ice shelves, northwest of JRI\textsuperscript{29}. This deglaciation preceded an ice free-regime that characterized the Vega drift and surrounding areas from ~7000 to 5000 years BP\textsuperscript{30,32–34}. The Larsen A ice shelf was probably destabilized at least as early as ~6300 years BP\textsuperscript{35}, while evidence show that the Larsen B ice shelf experienced a continuous and significant shrinkage throughout the Holocene\textsuperscript{28}. Hence, the EAP ice shelves underwent a major retreat mostly between ~8000 and 6000 years BP.

While the ice core-derived SAT were overall warmer throughout the Holocene than during the last two millennia and could have hence favored the EAP ice shelf surface melting during the entire period, the slow and gradual atmospheric cooling trend can hardly explain the initiation of the EAP ice shelf regression and its rapid disintegration between 8200 and 6000 years BP. Therefore,
other mechanisms must be investigated. A good candidate is an ocean warming at depth over the Holocene, as observed for the most recent times. To investigate such a potential link, we provide the first EAP SOT record spanning the last 9000 years at a 100-year resolution. We use the well-dated marine 20-m-long Jumbo Piston core NBP99-03-38 (JPC-38) drilled within the Vega Drift in the northern Prince Gustav Channel (Fig. 1). The stratigraphy\(^{36}\) is based on recent sediment using multi-core sections and strategic \(^{14}\)C ages situated at each major SOT shifts, thus giving us confidence on the timing of the main changes.

Being only located 56 km north of the JRI ice core, it offers a unique opportunity to compare both oceanic and atmospheric evolutions at secular-to-millennial timescales and therefore to identify the primary forcing controlling the regional ice shelf dynamics. We apply the \(\text{TEX}_{86}\) proxy (TetraEther Index of tetraethers with 86 carbons) for low temperatures that reflect mean annual SOT\(^{37-39}\). We mostly discuss here the \(\text{TEX}_{86}\)-converted temperature record in terms of trends and amplitudes rather than absolute values (see Methods).

Our record reveals a sharp SOT increase from ~8200 to 7000 years BP, followed by a continuous and slow ocean warming of +0.3 °C over the course of the mid-to-late Holocene (Fig. 3b), which is supported by diatom census counts in the same core\(^{36}\). A similar warming has been recorded over the nearby South Orkney Plateaus, in the northeast of the Powell Basin, where diatom assemblages reveal a pronounced decline in winter sea-ice cover possibly associated with a warming ocean between ~8200 and 4800 years BP\(^{40}\). In contrast to the SAT, which started to cool ~10,000 years BP ago, the abrupt ocean warming recorded at the JPC-38 core site occurred synchronously with the inferred retreat of the EAP ice shelves. Several studies reported an intensification and southward migration of SWW during the same period of time\(^{41-43}\), as illustrated for instance by pollen records in Patagonia\(^{41}\), South America (Fig. 3c). Building on modern observations, we suggest that this reorganization in the wind fields, including the strengthening and poleward displacement of the convergence zone between the SWW and the northward winds, promoted the upwelling and intrusion of warm deep waters on the EAP continental shelf. We propose that the increase in SOT initiated the ice shelf regression in the northeast EAP through enhanced basal/frontal melting and possibly iceberg calving. Our assumption is consistent with some recent findings in the Amundsen Sea, in southwestern Antarctic Peninsula, where the ice shelf shrinkage during the early Holocene has been similarly attributed to CDW shoaling driven by a more southern position of the SWW during the early Holocene\(^{44}\).

The long-term SOT increasing trend at the JPC-38 core site was punctuated by up to 1.5 °C warm events at the centennial scale, while cold events dwarfed over the course of the Holocene (Fig. 3b). Most of the gradual Holocene EAP ice shelf thinning and shrinking may be explained by the long-term subsurface ocean warming inferred from the \(\text{TEX}_{86}\) record in core JPC-38, likely driven by enhanced warm deep water penetration towards the ice shelf. Moreover, episodic peaks in SOT throughout the Holocene, resulting from additional supply or warming (or both) of deep water, which may have prevented the ice shelf from re-expanding during colder atmospheric phases, thus causing its progressive disintegration.

Estimating the impact of such an ocean warming on the ice shelf basal melting throughout the Holocene is not straightforward as it depends on many complex processes. Nevertheless, an order of magnitude including large uncertainties can be obtained using a simple parameterization\(^{45}\). We assume a linear relationship between basal ice shelf melting and ocean temperature\(^{45}\). We consider an ice shelf front with a typical length of 250 km, i.e., the length of the Larsen A, B and Prince Gustav Channel ice shelf fronts before collapse (i.e., 1970s), which is shorter to the early-to-mid Holocene period given the large extension of the ice shelves in the northern part of the EAP at this time. As SOT constraints, we used a +0.3 °C (Holocene trend) and +1.5 °C (early Holocene) warming.

When considering an average SOT warming of +0.3 °C as observed in our records over the last 7400 years BP, we estimate a minimum net heat flux from the ocean to the ice shelf of ~3 × 10\(^{11}\) J s\(^{-1}\) and a melting rate of ~3 × 10\(^{10}\) m\(^3\) year\(^{-1}\) (or ~1 mSv) (see Methods). This would correspond to a melting of at least
~10 m of ice per year on a surface covering the whole ice shelf front and penetrating 12 km below the ice shelves. If instead we take the surface of the 1970s EAP ice shelves for which we have a reasonable estimate (around 12,300 km² when summing up the Larsen A and B and the Prince Gustav Channel ice shelf area), this would correspond to an average melt rate of the ice shelf of about 2.4 m per year. A +1.5 °C SOT warming as recorded between ~8200 and 7000 years BP in the EAP would imply a five times larger melt rate following the same parameterization. This clearly appears sufficient to have a large impact on ice shelf dynamics, especially as parameterizations using simple linear relations between ocean temperature and melting likely provide a lower estimate.46 Therefore, although both ocean and atmosphere thermal forcing impacts on ice shelf instability, we conclude that, during the ocean warming phases, the SOT must have played a major role on controlling the regional ice shelf retreat.

Future projections. In the light of these new findings, we scrutinize the evolution of the SAT and SOT in projections from 26 climate models in order to anticipate the possible evolution of the ice caps of the Antarctic Peninsula during the next century. We focus on two different IPCC scenarios (referred to as the RCP 2.6 and 8.5), differing by their radiative forcing trajectories throughout the twenty-first century47 and representing two potential evolutions of the future greenhouse gas concentrations (Fig. 4a, b and Supplementary Figure 3). We averaged the results of the different model simulations, thus filtering out most of the model internal variability, which allows to retrieve the forced temperature signal considered as the main response to potential anthropogenic greenhouse gas emissions.

For the RCP2.6 scenario, we find that both SAT and SOT trends for the next century are relatively weak and remains in the range of reconstructed variations over the Holocene period, each of the trends being <+1 °C and +0.1 °C over the next 90 years, respectively (Fig. 4a). Placing these results in a Holocene context, regional temperatures variations suggest that the RCP2.6-forced simulated warming trends may lead to limited ice shelf disintegration in the near future, unless the ongoing warming may determine the ice shelf fate48. In comparison, for the RCP8.5 scenario, projections exhibit regional atmospheric and oceanic warming trends that are three-to-four times higher than in the RCP2.6 scenario (warming by up to +3.5–4.5 °C and +0.3–0.4 °C in the atmosphere and subsurface ocean by 2100, respectively) (Fig. 4b). Such subsurface ocean warming is comparable to the +0.3 °C increase inferred for the last 7400 years BP in core JPC-38 and similar to the SOT trend observed in reanalyses over the last decades.

Given the recent impact of the +0.3 °C warming on the ice shelf as well as during the Holocene, we anticipate an accelerated melting of EAP ice shelves over the next decades due to projected anthropogenic forcing. Together with the simulated +3 °C atmospheric warming, they will probably substantially increase the occurrence of huge collapses if the climatic trend continues to follow the RCP8.5 scenario. Since features such as wind-driven ocean circulation, sea-ice cover or the amount and distribution of the freshwater released to the ocean though ice-melt still need to be improved in climate models, the warming of ocean temperature may be subdued in model projections. Consequently, the impact of changes in the wind forcing17 on the shoaling and further penetration of the warm deep waters on the continental shelf remains potentially underestimated. Thus, the future of the EAP ice shelf may be possibly more marked than projected. If the
warm deep waters were to be redirected toward the continental shelf in the southeasternmost part of the Weddell Sea, enhanced heat content could increase by ~20% the yearly basal ice-melt underneath the Filchner-Ronne ice shelf. Would such a predicted warming affect the whole Weddell Sea region, its impact on the surrounding ice sheets and glaciers would be marked for sea-level rise.

**Methods**

**Reanalysis data.** The quality of reanalysis is relatively low before 1979 in the high latitudes of the Southern Hemisphere as few data were assimilated in this region due to the lack of observations. There is no observation data for the sub-super-facial deep waters covering the last decades and century. We acknowledge that the reanalyses data that we use to reconstruct the wind-driven forcing on the SOT in this study are therefore relatively uncertain but should be robust enough to mirror the penetration of the WDW at least over the last decades. The Ekman pumping has been computed along the EAP continental shelf using surface wind velocities coming from the recent twentieth century reanalysis NOAA (20CR) Project version 2, consisting of an ensemble of 56 realizations with 2° × 2° gridded hourly weather data from 1950 to 2010, and from the ERA-Interim version 2 reanalyses (see code in Supplementary file 1). The definition of the Ekman pumping used is:

\[ w_e = \text{curl} \left( \frac{\mathbf{f} \cdot \mathbf{\rho} \partial \mathbf{\rho}}{\rho} \right) \]

where \( \mathbf{r} \) is the wind stress vector, \( \rho_0 \) is a reference density of freshwater, \( f \) is the Coriolis parameter. The unit of Ekman pumping \( w_e \) is m s\(^{-1} \) but here it has been standardized by the standard deviation computed over the whole period of available data.

The SOTs were estimated from both the GLORYS reanalysis and EN4 objective reanalysis, each covering a different time interval. GLORYS produces monthly global ocean reanalysis at eddy-attenuating resolution from 1993 to 2010, while EN4 generates monthly data that covers the period between 1979 and 2010. GLORYS’s reanalysis is based on the ocean and sea-ice general circulation model NEMO in the ORCA025 configuration forced by surface boundary conditions derived from atmospheric ECMWF reanalysis, and on the assimilation of in situ temperature and salinity profiles observations as well as sea surface temperature from satellite measurements and sea-level anomalies obtained from satellite altimetry. EN4 data set is an incremental development of the previous version EN3 and consists of an objective analysis based on the temperature and salinity profiles derived from WOD09, GTSP, Argos, and the ASBO project. SOT were estimated at a 50–400 m water depth range on the continental shelf, where the warm deep waters mix with the continental shelf waters before altering the grounded ice shelf stability (see Supplementary Note 1).

**The \( \text{TEX}^{0.6}_4 \) proxy.** To reconstruct subsurface ocean conditions in the coastal Antarctic regions, we applied the \( \text{TEX}^{0.6}_4 \) (TetraEther Index of tetraethers with 86 carbon) proxy for low temperature polar regions. This proxy is based on the relative distribution of Thaumarchaeotal isoprenoid glycerol dibiphytanyl glycerol tetraether (GDGT) fatty acids for reconstructing SOTs. The analysis of GDGTs was conducted at the Royal Netherlands Institute for Sea Research (NIOZ) as previously described. To convert \( \text{TEX}^{0.6}_4 \) values into sea subsurface temperatures, we used the calibration considering the following equation:

\[ \text{TEX}^{0.6}_4 = \log \left( \frac{\text{GDGT} - 2}{\text{GDGT} - 1 + \text{GDGT} - 2 + \text{GDGT} - 3} \right) \]

where \( \text{SOT} \) is the sea surface temperature (°C) and \( \text{TEX}^{0.6}_4 \) is the multi-proxy GDGT index. The SOT anomalies have been computed by subtracting 1.84 °C to the SOT values, 1.84 corresponding to the mean of the estimated SOT values using Eqs. (1) and (2) for the entire Holocene. To estimate the impact of the SOTs on the ice shelf throughout our record and calculate the corresponding ice melting rate as shown hereafter, we compute a temperature change of +1.5 and +0.3 °C over the early Holocene (8200–7000 years BP) and the Holocene trend (7000–0 years BP), respectively, based on a linear regression.

Given that our study site (760 m water depth), we suggest that the downwind transport is probably relatively fast and the GDGTs compounds are attached to particles, which are produced from the melting of sea ice or ice shelf, liquid pellets or marine snow. We exclude any terrestrial organic matter that could influence the \( \text{TEX}^{0.6}_4 \) as the BIT index (Supplementary Figure 4), based on the marine vs. terrestrial GDGTs, exhibits very low values (<0.1). In the Antarctic Peninsula, the only two studies focusing on GDGT producers have reported that the Thaumarchaeota species mostly reside within the 50–200 m upper ocean layer (Supplementary Figure 1) and reach their highest abundance during the late winter and early spring seasons. Given the relatively shallow water depth of our study site and the seasonality signal generally smoothed out in the sediment, we assume that the \( \text{TEX}^{0.6}_4 \)-derived temperatures predominantly reflect changes in mean annual temperature of the subsurface waters influenced by the WDW. Hence, we use the \( \text{TEX}^{0.6}_4 \) as the BIT index in our analysis.

**Estimated ice melting rate.** Sub-ice shelf melting should ideally be estimated using an ocean model coupled to an ice shelf model in order to represent the ocean circulation in the cavity beneath the shelf, the processes controlling the melting and the feedback between this melt and circulation. This is unfortunately impossible at the scales investigated here, first of all because the precise topography of the ice shelves is largely unknown. We thus rely on a very simple parameterization, used for instance in ice sheet modelling, assuming a basic linear relationship between ice shelf melting and SOT.

\[ \text{Q}_{\text{net}} = \rho c_w \text{w} (\text{SOT} - T_i) \times A_{\text{eff}} \]

where \( \rho \) is the density of seawater (1000 kg m\(^{-3}\)), \( c_w \) is the specific heat capacity of seawater (4000 kg \(^{-1} \) °C\(^{-1}\)), \( T_i \) is the freezing point temperature at the ice base shell, \( A_{\text{eff}} \) is the effective area for melting. The total net melting rate can be then estimated as follows:

\[ \Delta m_{\text{net}} = \text{Q}_{\text{net}} / (\rho / L) \]

where \( \rho_I \) is the density of the ice shelf (920 kg m\(^{-3}\)), \( L_i \) is the latent heat of fusion (334,000 kg °C\(^{-1}\)). We assume \( A_{\text{eff}} \) can be estimated from the length of the ice shelf front before the major collapses (i.e., prior to 1970) and a constant cross-shelf length taken equal to 12 km.

Given that this parameterization tends to underestimates the calculated melting rate, this means that the values provided here, already large in terms of contribution, represents a lower bound. The Holocene warming and the simulated one by the end of the century are of the same order (+0.3 °C). Despite the need to improve such estimation, we strongly believe that the +10 m of ice melting computed for the Holocene could give a good overview for the near future if the current climatic trend continues to follow the RCP8.5 scenario. Moreover, although the Larsen C seems to not be primarily impacted by the summer SOT as recently evidenced, due to the limited impact of the wind forcing (i.e., the Westerlies), we cannot exclude that a combined effect associating its recent collapse and the continuous southward migration of the Westerlies would not promote the WDW shoaling in this area in the future and therefore amplify its disintegration.

**Model projections (present to 2100).** We investigate projections from 26 climate models (Fig. S3) participating in the fifth Coupled Model Intercomparison Project (CMIP5) following two different emission scenarios (RCPs): RCP2.6 and RCP8.5.
Our selection includes the models providing for both scenarios the physical parameters that we analyzed here, i.e., SAT and SOT. The models fulfilling this criterion are the following: bcc-csm1-1-m, bcc-csm1-1, BNU-ESM, CanESM5, CCSM4, CESM1-CAM5, CNRM-CM5, CSIRO-Mk3-6-0, GFDL-s2-0, GFDL-s2, FIO-ESM, GFDL-CM3, GFDL-ESM2G, GISS-E2-H, GISS-E2-R, HadGEM2-OG, HadGEM2-ES, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC5, MIROC-ESM, MPI-ESM-LR, MPI-ESM-MR, MRI-CGCM3, NorESM1-ME, NorESM1-M (Fig. 4 and S3).

Code availability. The code used to characterize the Ekman Pumping can be found as supplementary file.

Data availability

All data produced by this study are available from the corresponding author (johnan.etoourneau@act.u-gris.csi.es).

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Author contributions
J.E. designed and coordinated the study and led the writing. V.W., J.-H.K., L.B., S.S., and J.S. S.D. were responsible for the GDGT data acquisition. G.S. and D.S. analyzed the observation-based reanalysis data and model simulations. H.G. estimated the ice shelf melting. J.E., J.-H.K., X.C., G.S., J.C., H.G., M.N.-H., and D.S. were in charge of the majority of the data interpretation. All authors commented on the manuscript and contributed to the writing.

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