

1 **Internal and external forcing of multidecadal Atlantic climate variability over**
2 **the past 1200 years**

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23 Atlantic Multidecadal Variability impacts the climate around the North Atlantic and in
24 many other parts of the world. There are ongoing discussions on the extent to which
25 Atlantic Multidecadal Variability is driven by external (e.g., solar, volcanic, and/or
26 aerosol) forcing versus internal variability. Here, we provide new evidence for
27 persistent multidecadal variability during AD 800–2010. We produce a summer
28 Atlantic Multidecadal Variability reconstruction using a network of annually-resolved
29 terrestrial proxy records from the circum-North Atlantic region. We find that both
30 large volcanic eruptions and solar irradiance minima induce cool phases of Atlantic
31 Multidecadal Variability and that both forcings together explain approximately 30%
32 of the reconstruction variance (on timescales > 30 years). We define the Atlantic
33 Multidecadal Oscillation as the internally-generated component of Atlantic
34 Multidecadal Variability, and calculate it by empirically removing externally-forced
35 variations. The Atlantic Multidecadal Oscillation reveals persistent multidecadal
36 variability throughout the past twelve centuries, making the largest contribution to
37 Atlantic Multidecadal Variability, and also shows coherence with Northern
38 Hemisphere temperature variations. This attempt to quantify the internally-generated
39 and externally-forced components of Atlantic Multidecadal Variability over more than
40 a millennium supports further understanding of its past behavior and its role in
41 potential decadal-scale climate predictability.

42

43 **Introduction**

44 North Atlantic sea surface temperature (SST) exhibits pronounced variability on
45 multidecadal timescales during the last 150 years, a behavior that is commonly
46 referred to as the Atlantic Multidecadal Oscillation (AMO)¹. Here, we prefer the term
47 Atlantic Multidecadal Variability (AMV) because it does not imply that it is a mode of
48 variability generated solely by internal climate processes. The AMV affects climate of
49 the adjacent continents¹⁻⁴, and also likely Atlantic hurricane activity⁵, African Sahel
50 drought⁶, and Indian summer monsoon strength^{7,8}. AMV also contributes to the
51 multidecadal variability of Northern Hemisphere (NH) temperatures during the past
52 150 years^{9,10}, particularly in the early to mid-20th century¹¹. Studies based on
53 sea-level observations suggest that AMV is an internal mode of climate variability and
54 is dominantly controlled by ocean circulation, primarily the Atlantic Meridional
55 Overturning Circulation (AMOC)¹². This is supported by model studies in which
56 AMV-like variability can be reproduced in the absence of radiative (i.e., external)
57 forcing and caused by the AMOC^{13,14}. In contrast, other studies relegate the role of
58 internal variability, and instead suggest that external (e.g., solar^{15,16}, volcanic^{15,16} and
59 aerosol¹⁷) forcings can modulate or even drive AMV. Even so, in those simulation
60 studies much of the AMV-like variability, especially in the early-20th century, cannot
61 be explained by external forcing^{11,17}.

62 Previous studies of AMV were based either on instrumental data or on climate
63 model simulations with potential deficiencies, which limit our understanding of the
64 long-term AMV behavior and the role of external drivers in the past. Our approach
65 here is to first reconstruct AMV regardless of its cause, and then to subtract an
66 empirical estimate of the externally-forced component, leaving a residual variance
67 that may be considered to arise solely from internal variability^{11,18}. It is this residual
68 series that we define here as the AMO^{11,19,20}.

69

70 **Reconstructing the AMV over the past 1200 years**

71 We use 46 annually-resolved terrestrial proxy records from the circum-North
72 Atlantic-Arctic region, Eastern North America and Europe, to reconstruct the

73 extended summer (May–September) AMV index since AD 800 (Methods). The
74 reconstruction was produced using a nested principal component regression (PCR)
75 method²¹ and validated using a sliding window approach for calibration and
76 verification (Methods, Fig. 1f, Supplementary Table S2) and additionally with
77 model-based pseudoproxy experiments (Supplementary Methods, Figs. S8–S11). A
78 number of sensitivity tests suggest that the reconstruction is, in principle, insensitive
79 to moderate changes in the reconstruction method or in the proxy dataset composition
80 (Supplementary Methods). For instance, alternative reconstructions, using a reduced
81 proxy network selected specifically or randomly (Supplementary Figs. S2, S3, S6),
82 varying the length of instrumental calibration period or fitting to a different seasonal
83 target (Supplementary Figs. S4, S5), or without using a nesting approach
84 (Supplementary Fig. S7), produce multidecadal variability that is very similar to our
85 final reconstruction.

86 The reconstructed summer AMV index shares 45% of the observed variance
87 during the period 1856–2010 (Fig. 1b), increasing to 72% on decadal (>10 years) and
88 to 88% on multidecadal (>30 years) timescales (Fig. 1c, d). The reconstructed AMV
89 index shows cool phases in the 9th, early-14th, late-15th and 16th–19th centuries with
90 respect to the 1856–1967 mean. Warm phases are reconstructed in the 10th–13th,
91 early-15th and mid-late-20th centuries (Fig. 1e). The reconstructed warm phases of
92 the AMV during the 10–13th centuries are consistent with the estimate in ref.²² that
93 describes the AMV as an important driver of medieval mega-droughts in the
94 American Southwest. The reconstructed AMV exhibits multidecadal variability with
95 dominant periodicities ranging from 64 to 88 years (Supplementary Fig. S12).
96 Wavelet analysis²³ shows that multidecadal variability persisted throughout the past
97 twelve centuries, with particularly strong power in the 12th–15th and 20th centuries
98 (Fig. 2).

99 Our reconstruction shares similar multidecadal behaviour with two published
100 reconstructions of the AMV^{24,25} (Supplementary Figs. S13, S15), but reveals stronger
101 and more persistent multidecadal variability (Supplementary Fig. S14). The
102 differences between these reconstructions can be related to differences in the

103 reconstruction method (e.g., data extracted from the climate field reconstruction
104 approach in Mann et al.²⁴ versus composite-index reconstruction data as used in our
105 study and in Gray et al.²⁵), and because of the precise composition of the proxy
106 networks. The reconstruction of Gray et al.²⁵ is based on a sparse tree-ring network,
107 completely independent of our predictors; it has precise dating control, but its smaller
108 network (only 12 sites) may compromise its representation of AMV if the centers of
109 climate impact of AMV shift through time (also see the discussions in ref.¹⁶). The
110 multi-proxy-based reconstruction of Mann et al.²⁴ has a good spatial coverage of
111 proxies, partly independent of those in our network; however their inclusion of some
112 proxy records with only decadal resolution and the separate calibration of
113 low-frequency (<0.05 cycles/year) components reduces the degrees of freedom
114 available for a robust calibration and verification. Our new reconstruction is based on
115 a large number of annually-resolved, updated proxy records from the circum-North
116 Atlantic and is validated and tested for methodological robustness using statistical and
117 pseudoproxy tests.

118

119 **External forcing and internal variability of the AMV**

120 We performed superposed epoch analysis (SEA; Supplementary Methods, Table S3)
121 to determine the AMV anomalies caused by solar and volcanic forcing. A superposed
122 composite of the 15 largest volcanic eruptions^{26,27} shows significant ($p < 0.05$)
123 negative anomalies of the AMV occur during the decade following an eruption (Fig.
124 3a, b). To focus on multidecadal variability, we performed similar composites but
125 using 30-year low-pass filtered data (Fig. 3c, d). The results suggest that large
126 volcanic eruptions were followed by about two decades of negative AMV anomalies,
127 though the smaller sample size for the multidecadal composite yields greater
128 uncertainties. Our result shows long-term (up to two decades) impacts of volcanic
129 eruptions on North Atlantic SST that may be associated with interactions between
130 atmosphere circulation, ocean circulation and sea ice^{28,29}. However, an important
131 caveat regarding the interpretation of long-term volcanic cooling in our analysis is the
132 biological memory effects in many tree-ring width data³⁰ might lead to an

133 overestimate of the persistence of volcanic cooling and an underestimate of its
134 amplitude (this is the most numerous proxy type in our network, Supplementary Table
135 S1). Compositing multidecadal responses to solar forcing^{31,32} shows negative
136 anomalies of AMV for about three decades following periods with weak solar forcing
137 (Fig. 3e, f), with maximum cooling at ~17 years lag. These results suggest that the
138 large volcanic eruptions and solar irradiance minima may both cause cool AMV
139 phases on multidecadal timescales during the past 1200 years. However, some strong
140 volcanic events coincide with solar minima during the past twelve centuries, further
141 complicating the interpretation.

142 The cross-correlation analyses show a lagged relationship of AMV with solar and
143 volcanic forcing (Supplementary Fig. S17), consistent with the SEA results but with
144 stronger significance. On multidecadal timescales, the maximum correlation between
145 the reconstructed AMV and solar forcing^{31,32} is ~0.35–0.46 ($p < 0.05$) when the AMV
146 lags by 8–12 years, close to the lag found between solar forcing and NH temperature
147 reconstructions³³ (also see Supplementary Figs. S18, S19). The AMV also
148 significantly correlates with volcanic forcing^{26,27} ($r \approx -0.29$ – -0.36 , $p < 0.05$) with
149 approximately 6–7 years lag. Such a lagged relationship between the AMV and
150 external forcing is consistent with climate model simulations¹⁵ and proxy-based
151 reconstruction¹⁶ studies. Multiple linear regression (similar to refs^{16,34}; Supplementary
152 Methods) using these lagged relationships suggests that solar and volcanic forcing
153 together can explain ~28% ($r = 0.53$) of the AMV variance on multidecadal timescales
154 (Supplementary Fig. S20). The inclusion of anthropogenic (e.g., CO₂ concentration)
155 forcing does not improve the regression skill (Supplementary Fig. 20c, d). These
156 results indicate that changes in both solar and volcanic forcing have affected AMV,
157 but their linear impact contributes less than one-third of the AMV variance during the
158 past twelve centuries.

159 The relationship between the AMV and external forcing might be somewhat
160 overestimated in our reconstruction owing to our compilation of temperature-sensitive
161 proxies, which may respond more directly to changes in external forcings. However,
162 the response of the NH temperature to solar and volcanic forcings exhibits somewhat

163 different patterns compared with the AMV shown in our study (see Fig. 5.8 in ref.³⁵).
164 Moreover, a recent study³⁶ suggests the dominant role of atmosphere and ocean
165 circulation in controlling temperature variability in areas surrounding the North
166 Atlantic. Thus, at least part of the impact of solar and volcanic forcing on the AMV
167 suggested by our reconstruction may be dynamically driven (see later discussion of
168 the difficulty in separating the internal variability from the forced component), but the
169 internal variability and forced components are not significantly correlated ($r = 0.06$)
170 during the past twelve centuries, adding credence to our separation of these
171 components.

172 Similar to the approach of refs^{11,19}, we estimate the AMO by removing the
173 externally-forced component from the reconstructed AMV (Supplementary Methods
174 and Fig. S20e). The residual AMO time-series retains persistent multidecadal
175 variations over the past twelve centuries (Fig. 2f), similar to those of the reconstructed
176 AMV. This implies that internal processes have generated multidecadal variability of
177 North Atlantic SST throughout the past twelve centuries, similar to the results
178 obtained in control simulations with climate models^{13,14}. Such a persistent mode of
179 internal variability (i.e., the AMO) might be associated with ocean circulations such as
180 the AMOC¹²⁻¹⁴, or atmospheric circulations such as the North Atlantic Oscillation
181 (NAO)³⁷⁻³⁹. However, significant multidecadal variability found in the AMO is absent
182 in the millennium-length AMOC reconstruction⁴⁰, and the slowdown in the 20th
183 century found in the AMOC⁴⁰ is absent in our AMO reconstruction, implying that the
184 AMO may not be linearly associated with the AMOC.

185

186 **The AMV/AMO and the NH temperature**

187 Our new reconstruction offers an opportunity to examine the association of AMV with
188 climate in a long-term context. We compared the reconstructed AMV with a
189 composite of NH summer temperature-sensitive tree-ring records, using a subset from
190 the records in ref.⁴¹, excluding all those used in our AMV reconstruction
191 (Supplementary Methods), and found strong support for a significant association
192 between AMV and NH temperature at multidecadal and centennial timescales (Fig. 4).

193 The significant correlation arises from common variance on timescales longer than 30
194 years ($r = 0.60$, $p < 0.001$) and is still high even if the centennial timescale variance is
195 previously filtered out (30–90 years, $r = 0.55$, $p < 0.001$). This strong, significant
196 correlation does not solely arise from common external forcings: it is still significant
197 (>30 years, $r = 0.47$, $p < 0.001$; 30–90 years, $r = 0.44$, $p < 0.001$; Fig. 4c, d) between
198 their internal variability components, suggesting that the AMO and NH temperature
199 are associated through internal climate variability over the past 1200 years (also see
200 Supplementary Fig. S23).

201 Running correlations (150-year windows) suggest that this association between
202 the AMV/AMO and NH temperature remains strong over most of the past twelve
203 centuries (Supplementary Figs. S24, S25). This implies a dynamical link between the
204 AMO and NH temperature variability during the past twelve centuries^{9,11,20}, and
205 suggests that the apparent influence of AMV on regional or hemispheric climate, in a
206 long-term context, does not arise solely from common responses to external drivers.

207 The findings presented here have implications for decadal-scale climate
208 predictions, because there may be more decadal predictability in the North Atlantic
209 than in many other regions⁴². Our longer AMV/AMO reconstructions may contribute
210 to facilitating a better understanding of the impacts of the AMV during the
211 pre-industrial period on the climate in North America^{1,2}, Europe^{2,4}, Asia^{7,8}, as well as
212 Greenland inland ice melt³, Atlantic hurricane activity⁵, and African Sahel drought⁶.
213 Future work should consider using climate model simulations²⁰ and a
214 detection/attribution approach⁴³ to complement our simple approach (linear regression
215 against forcing time-series) to separate the internal variability and forced components.
216 Such an approach is beyond the scope of this single paper and requires multiple
217 climate models that can realistically simulate AMV, AMO and the dynamic response
218 of the Atlantic to external forcings on multi-decadal timescales. Our study provides a
219 better understanding of the AMV/AMO and an improved basis for future work based
220 on model evaluation.

221

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337

338 **Author contributions**

339 J.W. and B.Y. conceived the study, carried out the data analysis and wrote the
340 manuscript, with contributions to the design of the study and its experiments from
341 F.C.L., J.L., T.J.O. and K.R.B. E.Z. designed and performed the pseudoproxy
342 experiments. All authors discussed the results, edited and commented on the
343 manuscript.

344

345 **Competing financial interests**

346 The authors declare no competing financial interests.

347

348 **Figure captions**

349 **Figure 1 | Summer AMV reconstruction.** **a.** Location of the 46 proxy records.
350 Colors represent the contribution (beta-weight; Supplementary Methods) of each
351 record to the reconstruction for the most replicated nest 1500–1967 (see
352 Supplementary Table S1 for details of each proxy record). **b.** Comparison between
353 the reconstructed (black line; ± 1 RMSE, gray shading) and instrumental AMV (red
354 line). **c, d.** As **b**, but 10-year (**c**) and 30-year (**d**) low-pass filtered. Correlation
355 coefficient, effective degrees of freedom (N_{eff} ; Supplementary Methods) and
356 significance level during the period 1856–2010 are indicated on each panel. **e.** The
357 AMV reconstruction for the past 1200 years (AD 800–2010), as an annually
358 revolved reconstruction (black line; ± 1 RMSE, grey shading) and 30-year low-pass
359 filtered (red). **f.** Reduction of error (RE) and explained variance (R^2) for each nest. **g.**
360 The number of contributing proxy records from the North Atlantic-Arctic region,
361 Eastern North America and Europe for each nest. In each case, the AMV index is
362 shown as anomalies relative to the 1856–1967 mean (dashed lines). The AMV
363 reconstruction, beta-weight, R^2 and RE are reported as the median value of the 38
364 ensemble members derived by a sliding approach for calibration and verification in
365 each nest.

366

367 **Figure 2 | Wavelet analysis for the reconstructed AMV during the past twelve**
368 **centuries.** **a.** The annually-resolved AMV reconstruction and **b.** its wavelet power
369 spectrum. **c.** The 30-year low-pass filtered AMV reconstruction and **d.** its wavelet
370 power spectrum. **e.** The internal variability component of AMV (i.e., the AMO),
371 calculated by subtracting the forced component from the reconstruction, also 30-year
372 low-pass filtered (Supplementary Methods and Fig. S20e). **f.** The wavelet power
373 spectrum for the AMO as shown in **e**. In all cases of Gaussian wavelet analysis, the
374 cross-hatched region is the cone of influence, where zero padding has reduced the
375 variance. Black contour is the 90% significance level for a red-noise (autoregressive

376 lag1) background spectrum²³.

377

378 **Figure 3 | The reconstructed AMV response to volcanic eruptions and solar**

379 **variability. a.** Superposed composite of the 15 largest volcanic eruptions during the

380 past 1200 years (AD 800–2000) in the reconstruction of ref.²⁶. **b.** As **a**, but using an

381 alternative volcanic reconstruction²⁷. Multidecadal composites of the 5 strongest

382 volcanic eruptions in the reconstruction of ref.²⁶ (**c**) and of ref.²⁷ (**d**). Multidecadal

383 composites of the 5 solar irradiation minima in the reconstruction of ref.³² (**e**) and

384 ref.³¹ (**f**). The interannual composites were calculated using annually-resolved AMV

385 from 5 years before to 15 years after the event year. The multidecadal composites

386 were calculated using 30-year low-pass filtered AMV from 30 years before to 30

387 years after the event year. In each case, shading indicates the 95% confidence

388 interval for the composite mean. See Supplementary Methods for the superposed

389 epoch analysis (SEA) and Supplementary Table S3 for the selected event years.

390

391 **Figure 4 | Comparison of the AMV and AMO reconstructions with Northern**

392 **Hemisphere (NH) temperature.** The AMV reconstruction (red) compared with a

393 composite of 22 temperature-sensitive tree-ring records (black line, composite mean;

394 gray shading, composite mean ± 1.0 standard error) for timescales >30 years (**a**) and

395 30–90 years (**b**). The 22 tree-ring records are not included in the proxy dataset used

396 in our AMV reconstruction (Supplementary Table S5). **c.** As **a**, but for the internal

397 variability components (AMO and NH internal variability) that were calculated by

398 subtracting the externally-forced components from the reconstructed AMV and NH

399 temperature (Supplementary Methods, Figs. S20e, S22c). **d.** As **c**, except that the

400 variations on timescales >90 years were filtered out. The correlation coefficient with

401 the effective degree of freedom (N_{eff} ; Supplementary Methods) and the significance

402 level for the two compared time-series are indicated on each panel. See

403 Supplementary Fig. S23 for an additional comparison between the AMV and a

404 composite of 13 published NH temperature reconstructions.

405

406 **Methods**

407 **Instrumental AMV index.** We use a summer (May–September, MJJAS) average
408 AMV index, computed as the area-weighted average over the North Atlantic Ocean
409 (0–70°N), from the Kaplan SST dataset⁴⁴ as the instrumental predictand for the
410 reconstruction. Unlike some previous studies^{1,5} we do not linearly detrend this SST
411 index to obtain the AMO index because this may introduce a biased climate signal¹¹.
412 Here we follow the approach of refs.^{11,18} by reconstructing the full variation in
413 Atlantic SST (i.e. the AMV) and then removing an estimated forced component
414 (Supplementary Methods) to leave the internal variability, and call that the
415 reconstructed AMO.

416

417 **Selection of proxy records.** The climate proxy records from the circum-North
418 Atlantic (–100°W–35°E, 20°N–80°N), a region including the North Atlantic-Arctic
419 region, Europe and Eastern North America (which are considered to be the centers of
420 strong climate impacts of AMV¹⁻⁵), were selected as the network dataset. We only
421 retained the climate reconstructions (or proxy records used in published
422 reconstructions) that have an annual resolution and start prior to AD 1500.

423 For the North Atlantic-Arctic region and Europe, temperature records
424 (including tree-ring, ice core and historical document) used by PAGES 2k
425 Consortium⁴⁵ were included, but superseded versions of some records were replaced
426 by new ones, e.g., Torneträsk⁴⁶ and Jämtland⁴⁷ (Supplementary Table S1). However,
427 we did not use any of the tree-ring network used by the PAGES 2k Consortium⁴⁵ for
428 Eastern North America, due to weak and even negative (for part of them)
429 correlations with temperature at annual timescales^{45,48}.

430 A number of temperature reconstructions around the circum-North Atlantic that
431 were not included in the PAGES2k dataset were also added into our proxy dataset. In
432 addition, a number of hydroclimate (e.g., precipitation, drought and stream flow)
433 reconstructions for these areas were also included (Supplementary Table S1).
434 Although the hydroclimate proxies are expected to have a less stable and more
435 varying relationship with the AMV than the temperature proxies⁴⁹, our

436 reconstruction was not sensitive to the inclusion or exclusion of the hydroclimate
437 proxies (Supplementary Methods).

438 The final dataset comprises 46 proxy records in total, including 19 for the North
439 Atlantic-Arctic region, 18 for Europe and 9 for Eastern North America. Details of the
440 individual proxy records and their correlations with the AMV index are shown in
441 Supplementary Tables S1.

442

443 **AMV reconstruction.** The 46 proxy records, including 35 tree-ring records, 10
444 ice-core records and 1 historical documentary record, were used to reconstruct an
445 extended summer (MJJAS) AMV index. We apply the Nested Principal Component
446 Regression (PCR) methodology²¹ with a sliding window approach for calibration
447 and verification^{36,50} to the reconstruction. The nested PCR calculation was applied as
448 follows.

449 Firstly, all proxy records were normalized to have zero mean and unit Standard
450 Deviation (SD) over their common period (e.g., 1500–1967 for 46 proxy records). A
451 principal components analysis (PCA) was calculated on the proxy predictors that
452 have complete data for the nest period.

453 Secondly, the first n principal components (PCs) with eigenvalues >1 were
454 retained as predictors for Multiple Linear Regression (MLR).

455 Thirdly, MLR was performed to reconstruct the AMV index by regressing the
456 retained PCs of the proxy records against the instrumental AMV index during the
457 calibration interval. Here, a sliding window approach for calibration and verification
458 was used across the period 1856–1967, the maximum overlap period between the 46
459 proxy records and the AMV index. The initial calibration interval extends from 1856
460 to 1930 and was incremented by one year until reaching the final period 1893–1967,
461 deriving an ensemble of 38 plausible reconstruction members. In each calibration
462 step, the 37 years excluded from calibration were used for cross verification.

463 Finally, a nested procedure was applied by repeating the first three steps, but
464 after removing the shortest proxy record each time.

465 The above PCR calculations created backward nests by considering the number of

466 available proxies dropping back in time before AD 1500, and also forward nests by
467 the gradually decreasing number of proxies with data after AD 1967. For each nested
468 subset, the reduction of error (RE) and R^2 were used to assess the skill of each nested
469 model²¹.

470 Our method considered only the regression-based uncertainties associated with the
471 residuals in the verification period. These were calculated as the Root Mean Square
472 Error (RMSE) defined as:

$$473 \quad \text{RMSE} = \sqrt{\frac{1}{n} \sum_{t=1}^n (y_t - y'_t)^2} \quad ,$$

474 where y_t and y'_t are the actual and estimated data in year t of the verification period
475 and n is the number of years during the verification period.

476 In each nest, the AMV reconstruction, proxy weights (Supplementary Methods),
477 RE, R^2 and RMSE statistics (Supplementary Table S2) were then characterized as the
478 median value of the 38 ensemble members derived by the sliding approach for
479 calibration and verification. The final reconstruction was created by splicing together
480 the median reconstruction and estimated uncertainties (± 1 RMSE) of each nest with
481 the maximum number of proxy records. Before splicing, the mean and variance of
482 each nested time-series had been adjusted to be the same as the most replicated 1500–
483 1967 nest. This approach avoids artificial changes in variance and long-term mean
484 due to varying of available number of proxy records in each nested reconstruction^{41,51}.

485 For additional methods, see Supplementary Methods.

486

487 **Data availability.** The AMV/AMO reconstructions together with associated climate
488 proxy data are archived by the National Oceanic and Atmospheric Administration
489 (NOAA) for routine public access and use
490 ([https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/climate-recon](https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/climate-reconstruction)
491 [struction](https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/climate-reconstruction)).

492

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