Data Descriptor: A global multiproxy database for temperature reconstructions of the Common Era

PAGES2k Consortium

Reproducible climate reconstructions of the Common Era (1 CE to present) are key to placing industrial-era warming into the context of natural climatic variability. Here we present a community-sourced database of temperature-sensitive proxy records from the PAGES2k initiative. The database gathers 692 records from 648 locations, including all continental regions and major ocean basins. The records are from trees, ice, sediment, corals, speleothems, documentary evidence, and other archives. They range in length from 50 to 2000 years, with a median of 547 years, while temporal resolution ranges from biweekly to centennial. Nearly half of the proxy time series are significantly correlated with HadCRUT4.2 surface temperature over the period 1850–2014. Global temperature composites show a remarkable degree of coherence between high- and low-resolution archives, with broadly similar patterns across archive types, terrestrial versus marine locations, and screening criteria. The database is suited to investigations of global and regional temperature variability over the Common Era, and is shared in the Linked Paleo Data (LiPD) format, including serializations in Matlab, R and Python.

| Design Type(s)          | observation design | data integration objective | time series design |
|-------------------------|--------------------|---------------------------|-------------------|
| Measurement Type(s)     | archaeal metabolite| calcification             | glacial ice       |
|                         | calcification      | radiance                  | sediment          |
|                         | stable isotope     | temperature of environmental material | trace metal analysis |
|                         | calcification      | radiance                  | sediment          |
| Technology Type(s)      | data acquisition system |
| Factor Type(s)          | measurement method | environmental material     | geographic location |
|                         | temporal_interval  |                           |                   |
| Sample Characteristic(s)| Democratic Republic of the Congo | lake sediment | Tanzania |
|                         | South Africa       | speleothem                | Antarctica         |
|                         | glacial ice        | borehole                  | United States of America |
|                         | Russian Federation | Canada                    | Greenland          |
|                         | Norway             | Iceland                   | Sweden             |
|                         | Bhutan             | China                     | Indonesia          |
|                         | Japan              | Kyrgyzstan                | Mongolia           |
|                         | Afghanistan        | Thailand                  | Taiwan Province    |
|                         | Viet Nam           | Australia                 | Australia          |
|                         | New Zealand        | Slovakia                  | Romania            |
|                         | Spain              | Germany                   | Estonia            |
|                         | France             | Mexico                    | Atlantic Ocean     |
|                         | marine sediment    | Pacific Ocean             | Indian Ocean       |
|                         | Arctic Ocean       | coral reef                | marine sponge reef |
|                         | Chile              | Argentina                 | Peru               |

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Background & Summary
Since the pioneering work of D’Arrigo and Jacoby1–3, as well as Mann et al.4,5, temperature reconstructions of the Common Era have become a key component of climate assessments6–9. Such reconstructions depend strongly on the composition of the underlying network of climate proxies10, and it is therefore critical for the climate community to have access to a community-vetted, quality-controlled database of temperature-sensitive records stored in a self-describing format. The Past Global Changes (PAGES) 2k consortium, a self-organized, international group of experts, recently assembled such a database, and used it to reconstruct surface temperature over continental-scale regions11 (hereafter, ‘PAGES2k-2013’).

This data descriptor presents version 2.0.0 of the PAGES2k proxy temperature database (Data Citation 1). It augments the PAGES2k-2013 collection of terrestrial records with marine records assembled by the Ocean2k working group at centennial12 and annual13 time scales. In addition to these previously published data compilations, this version includes substantially more records, extensive new metadata, and validation. Furthermore, the selection criteria for records included in this version are applied more uniformly and transparently across regions, resulting in a more cohesive data product.

This data descriptor describes the contents of the database, the criteria for inclusion, and quantifies the relation of each record with instrumental temperature. In addition, the paleotemperature time series are summarized as composites to highlight the most salient decadal- to centennial-scale behaviour of the dataset and check mutual consistency between paleoclimate archives. We provide extensive Matlab code to probe the database-processing, filtering and aggregating it in various ways to investigate temperature variability over the Common Era. The unique approach to data stewardship and code-sharing employed here is designed to enable an unprecedented scale of investigation of the temperature history of the Common Era, by the scientific community and citizen-scientists alike.

Methods
Collaborative model
The database is the product of a community-wide effort, coordinated by PAGES through a network of nine working groups (http://www.pastglobalchanges.org). Calls for participation were disseminated broadly and regional leaders solicited input from scientists with relevant datasets and/or expertise. A provisional database was compiled into a uniform framework, then redistributed to regional groups for quality control and further additions. For this purpose, quality control plots, including basic metadata for each record, were prepared to enable coauthors of this data descriptor to efficiently recognize and correct errors. Examples of these plots are given in the Quality Control section, and the full collection is archived as pdf files in Data Citation 1.

Data aggregation
The PAGES2k community aimed to identify records that are most relevant to understanding temperature evolution over the last 2000 years, while also assembling a uniform global database that can be culled to address a wide range of research questions. Specific criteria were developed to gather all published proxy records that meet five objective and reproducible criteria:

Thermal sensitivity
Proxy records were gathered from archive types for which previous understanding of the proxy system indicated that the records are temperature-sensitive. Records were only included when the original study described the relation between the proxy value and one or more climate variables, including temperature, or when the correlation with nearby instrumental temperature data was high enough to reject the null hypothesis of zero correlation at the 5% level, taking into account both temporal autocorrelation and test multiplicity. Indeed, temporal autocorrelation is well known to reduce the number of degrees of freedom available to reject a null hypothesis14. The test multiplicity problem (aka the ‘multiple comparisons problem’ or ‘look-elsewhere effect’) is the propensity for false positives to arise when multiple hypothesis tests are conducted simultaneously; in this case, testing the null hypothesis at 1,000 grid points with a 5% level would be expected to yield fifty spurious ‘discoveries’15 even in the absence of any link to temperature. Our analysis controls for both effects (see ‘Relationship to temperature’).

In addition, regional and proxy experts who are authors on this data descriptor certified that the records reflect temperature variability and that they meet all other stated criteria (Supplementary Table 1). Note that temperature sensitivity does not preclude the potential for many proxy systems to be secondarily or additionally sensitive to other environmental variables, such as moisture availability.

Record duration
A primary goal of the PAGES2k project is to understand climate dynamics over the entire Common Era. Records of this duration are most commonly accessible from sedimentary sequences that lack annual resolution; a minimum length of 500 years for these records serves as a coarse initial screen. For annually-banded terrestrial records (e.g., varves, glacier ice, tree rings), shorter-duration records that overlap with the instrumental period are important for calibration-validation exercises and for bridging between annually-resolved and lower-resolution records; as a result, annually resolved records from terrestrial archives over 300 years long were also included. Annually resolved records from marine
archives (corals, molluscs) are rarely this long, but provide critical information where instrumental data are often sparse or absent, and were included in the database if they exceeded 50 years in duration.

**Chronological accuracy**
Most records in this database are layer-counted, with a dating uncertainty of a few percent or less, but generally extend back less than 500 years. Other proxy records may span many millennia but some have chronologies that are too uncertain for centennial and finer-scale paleotemperature reconstructions. Recognizing, however, that lake and marine sediments accumulate at approximately constant rates, and considering the goal of building a comprehensive database from which records can be culled as necessary, depending on the scientific question, the initial screen for chronological control was relatively coarse. Once suitable records have been identified, their age-model uncertainty can be quantified using existing statistical procedures, providing a useful basis for including or weighting individual records in paleotemperature reconstructions. Namely, when annual layers cannot be counted, the timelines for records selected for this database were constrained by at least one chronological control point near the most recent end of the record and another near the oldest part of the record, or 1 CE, whichever is younger. Records that are longer than 1,000 years must include at least one additional age approximately midway between the other two. What constitutes ‘approximately’ was open to reasonable interpretation but was typically within two centuries of the mid-point.

**Record resolution**
PAGES2k scientific questions focus on centennial and finer time scales. Terrestrial and lacustrine records were included with average sample resolution of 50 years or finer. However, such records are rare from marine sediments, and thus a minimum average sample resolution of 200 years was accepted for this database. We also included 4 borehole records, although quantifying median resolution is less straightforward in boreholes than in other archives. The borehole records in the database are appropriate for examining decadal to multi-centennial scale variability, depending on the timeframe of interest.

**Public availability**
Proxy records used in the PAGES2k synthesis products are publicly available through previous publications or online data archives, or because their owners made them available for inclusion in this open-access data product. The original data for 49 records are made available for the first time in this data product (specified in Supplementary Table 1). Open access is a critical component of this endeavor, and led us to reject some records that would have been suitable under the other criteria. The focus on annual- to centennial-scale temperature of the past 2000 years led to the exclusion of those paleoclimate records that did not meet the resolution or geochronological control criteria required for meaningful inferences of the temperature history of Common Era.

**Relation to previous release**
The selection criteria for this dataset are specific to the type of proxy archive; for some proxy types, the standards in this version were broadened compared to the criteria used previously by PAGES2k regional groups. In most regions, records have been added that have become available since the publication of PAGES2k-2013, or that were not used in the continental-scale reconstructions because they are not annually resolved and therefore did not conform to the reconstruction method used by a particular regional group. In Antarctica, for example, PAGES2k-2013 included only the longest annually resolved ice cores, whereas the present version includes shorter and decadal-scale-resolution records.

For other proxy types, more stringent criteria resulted in the exclusion of some records. The excluded records are tracked in Supplementary Table 2. In most regions, some records were excluded because they did not meet the stricter standards for the minimum length or temporal resolution (criteria detailed above), or because of ambiguities related to the temperature sensitivity of the proxy, or because they have been superseded by higher-quality records from the same site. Of the 641 records that together comprise the previously published PAGES2k datasets, 177 are now excluded, of which 124 are tree-ring-width series that are inversely related to temperature. To be included in the current database, tree-ring data were required to correlate positively ($P < 0.05$) with local or regional temperature (averaged over the entire year or over the growing season). Trees whose growth increases with temperature (e.g., direct effect of temperature on physiological processes and photosynthetic rates) are more likely to produce a reliable expression of past temperature variability compared to trees that respond inversely to temperature, for which the proximal control on growth is moisture stress (e.g., evapotranspiration demand). Because many trees are more strongly influenced by moisture availability than by growing season temperatures, including only the positive responders reduces the overall number of tree-ring records to a more selective subset (see Supplementary Information, section 1).

**Metadata**
The current database includes a large number of metadata fields to facilitate the intelligent reuse of the data. Table 1 (available online only) lists a subset of information in a single-page format. Supplementary Table 1 includes additional metadata fields with critical information to convey the appropriate use of each dataset, namely: the PAGES2k identifier assigned for this data product, the identifier used in previous PAGES2k
products by the Ocean2k working group\textsuperscript{12,13}, or by PAGES2k-2013, whether the record is superseded by another in this version, the archive type, the primary publication citation, its associated digital object identifier (DOI; if one exists), the secondary publication citation and DOI, the URL link to where the data were archived by the original author, the associated data citation, the geographic coordinates (latitude, longitude, elevation), the name of the site, the ISO 3166-1 standard name of the country/ocean basin where it is located, the earliest and latest years covered by the record, the resolution of the time series (median spacing between consecutive observations), the type of proxy observation, the name of the variable used as the temperature-sensitive time series and its units, the physical feature whose temperature is sensed by the proxy (e.g., surface air temperature, sea-surface temperature), the part of the seasonal cycle recorded by the proxy, the direction of the relationship between the proxy and temperature (positive or negative), quality control (QC) comments, initials of PAGES2k Consortium author who performed QC certification, and a permalink to the dataset’s page at the NCEI-Paleo/World Data Service for Paleoclimatology.

**Annualization**

Annualization is necessary to compare proxies of varying sampling resolution with instrumental observations or with each other. Records with a superannual resolution were interpolated to annual resolution via nearest-neighbor interpolation. Interpolating records may alter their spectral content\textsuperscript{24}, but permits comparison of information on a common time grid and for shared spectral resolutions.

Seasonally-resolved proxies (e.g., most corals) were averaged to produce annual (ANN: Jan-Dec), DJF (December January February) and JJA (June July August) anomalies. Some records from glacier ice have a sampling resolution finer than 1 year. However, diffusion smoothes subannual signals, such that the shortest recoverable periodicity is generally no shorter than 1 year\textsuperscript{25,26}. Such records were therefore annualized to a Jan-Dec window.

The vast majority of records in the database are annually-resolved, and are not affected by this processing. We note, however, that many such records subsample part of the annual cycle (e.g., for tree rings, the growing season). For this purpose it is instructive to compare such records to annual (Jan-Dec), DJF and JJA averages of the HadCRUT4.2 temperature field (Technical Validation). The annualized data are archived alongside the original data, so either may be used in subsequent analyses.

**Code availability**

The Matlab code (https://www.mathworks.com/products/matlab.html) necessary to reproduce the figures of this descriptor is available at https://github.com/CommonClimate/PAGES2k_phase2 under a free BSD license.

**Data Records**

**Proxy dataset**

The PAGES2k temperature database (Fig. 1, Supplementary Fig. 1) includes 692 records (Data Citation 2 to Data Citation 477) from 49 countries and 11 distinct types of archives: 415 from trees (ring width and density), 96 from corals (e.g., isotopes, elemental composition, calcification rate), 58 from marine sediments (e.g. geochemistry, floras and faunal assemblages), 49 from glacier ice, 42 from lake sediments (e.g., floral and faunal assemblages, sediment accumulation, geochemistry), 15 from documentary sources, 8 from scleractinian corals, 4 from speleothems, 3 from boreholes, 1 from bivalves, and 1 hybrid (tree/borehole) record. Each of these archives bears the imprint of a proxy system responding to temperature changes, with the signal recorded in one or more of the archive's chemical, physical, or biological properties\textsuperscript{27}. The details behind the collection, analysis and interpretation of each of the records in the database are beyond the scope of this data descriptor, and we refer readers to the original publications for that information.

The records cover a wide range of time spans, from a minimum of 52 years to a maximum of 2000 years. The average length is 760 years, the median 547 years, not counting the duration of any record beyond 2000 years; temporal resolution ranges from biweekly to centennial, with a majority of annual records. As seen in Fig. 1, many proxy records spanning the last 2000 years are not annually resolved, and in some regions, most of the available records of any length lack annual resolution. The mean resolution of non-tree archives is 11 years, the median 1 year. For sedimentary archives the mean and median resolutions are 25 and 18 years, respectively. A list of sites comprising the database, along with basic metadata, is presented in Table 1 (available online only), an expanded version of which is in Supplementary Table 1. Note that some sites include more than one proxy temperature record.

The majority (59%) of the records are based on tree rings because they are annually resolved, precisely dated, and geographically widespread, especially in the mid-latitudes of the Northern Hemisphere (Supplementary Information, section 1). The PAGES2k collection is unique among previous efforts in the amount of paleoclimate evidence from sources other than tree rings, such as lake and marine sediments, corals, glacier ice and speleothems, thus expanding the geographic and temporal coverage of the database, as well as mitigating potential issues regarding the use of tree rings for temperature reconstructions\textsuperscript{28}.

While the vast majority of the records gathered herein were layer-counted, there are 87 sediment (marine or lake) datasets whose chronologies are derived from radiometric methods. For 41 of those datasets (47%), Data Citation 1 includes the primary geochronological information needed for a formal treatment of time uncertainty using various age-modelling techniques\textsuperscript{19,29,30}. Additionally, 30 records...
(overlapping, but not exclusively, with the 41 above) include chronology ensembles from the Arc2k 1.1.1 dataset. These include both sedimentary records with age ensembles derived via BACON, and ice and varved records with age ensembles derived via BAM.

For comparison, Fig. 2 displays the spatiotemporal distribution of proxy archives in the databases of Mann et al., hereafter M08, and PAGES2k-2013. While the M08 database contains 75% more records than this collection, these records are overwhelmingly land-based, from the Northern Hemisphere, and relatively short. Indeed, the M08 database is disproportionately composed of tree rings from North America, many of which start after 1000 CE, so that fewer than 100 records reach beyond this date. In contrast, the present collection contains 176 records out to 1000 CE, most of which are not tree-based. While the PAGES2k-2013 effort had succeeded in diversifying the network prior to 1200 CE, it focused on terrestrial sites, and was dominated by tree-based records after 1200 CE. The proportion of records from the Southern Hemisphere is comparable between all three databases (15% in M08, 12% in PAGES2k-2013, 16% in this study), but the number of records from Antarctica has steadily improved between databases (8 in M08, 9 in PAGES2k-2013, 26 here). The present dataset therefore constitutes a major leap in terms of the diversity and duration of records, as well as oceanic and polar coverage. The present compilation also marks an unprecedented effort at rigorously assessing their quality as temperature indicators (Technical Validation). While the overall quantity of records has declined with respect to M08, this is largely the result of more selective inclusion criteria (Methods).
Indeed, a unique aspect of the PAGES2k effort is the richness of the metadata annotating each record. In Supplementary Table 1, all proxy records are accompanied by information about their paleotemperature interpretation, including where the proxy senses temperature (e.g., surface-air temperature, sea-surface temperature), the sign of this relationship (positive or negative), and the part of the annual cycle that is preferentially recorded (e.g., May June July). Some of the records from marine sediments were processed for additional quality control as described by ref. 12. The 'QC Notes' column of Supplementary Table 1 specifies data processing that was done, and explains modifications relative to the original data citation. In addition to the metadata in Supplementary Table 1, which are complete for every record, Data Citation 1 includes additional metadata for some records. The type of additional information depends on the proxy record and some of the information is missing for some records. For example, when available, the basis for the temperature interpretation is stated (e.g., calibration or first principles). Some records that were calibrated to temperature (e.g., ref. 35) include the native data from which the temperature series was derived, as well as a description of the calibration (equation, reference, uncertainty, units). This metadata structure follows the Linked Paleo Data (LiPD) structure, and the interested reader is referred to the associated publication36 for a full exposition of the format.

Accordingly, the database is primarily encoded as LiPD36 files: a structured, machine-readable format for paleoclimate data based on Javascript Object Notation (JSON) that accommodates the wide diversity of information comprising this database (PAGES2k_v2.0.0_LiPD.zip, Data Citation 1). Serializationes are also available in the Python (PAGES2k_v2.0.0-ts.pklz, Data Citation 1), Matlab (PAGES2k_v2.0.0.mat, Data Citation 1) and R (PAGES2k_v2.0.0.Rdata, Data Citation 1) languages. Utilities for interacting with LiPD files in Matlab and Python are available at http://github.com/nickmckay/LiPD-utilities. Utilities in R are forthcoming.

**Instrumental temperature dataset**

The ability of the proxy network to capture temperature information is assessed with respect to the instrumental HadCRUT4.2 dataset37, covering CE 1850–2014. The dataset merges surface air temperature over land (CRUTEM4) and sea-surface temperature over ocean regions (HadSST3). We use the Cowtan & Way version38 of the dataset, which corrects for missing values and incomplete post-1979 Arctic coverage via the use of satellite observations. Even with the correction, the HadCRUT4.2 dataset is incomplete, with about 60% of the monthly values missing, so the remaining missing values were infilled via the GraphEM39 algorithm. The graph was chosen via the graphical lasso40 using a sparsity parameter of 0.7%, which was chosen by cross-validation as the minimizer of the expected prediction error (HADCRUT4_median_GraphEM.mat, Data Citation 1).

The global (area-weighted) mean from this dataset is charted in Fig. 3. We note that this dataset may result in temperature variations whose amplitude is biased downwards in regions of poor observational coverage, hence potentially distorting proxy-temperature correlations. Regionally-specific temperature datasets (e.g., ref. 41 for Antarctica) would therefore be more appropriate in regional applications.
Technical Validation
A unique challenge for technical validation of paleoclimatological datasets is that the target, here, site-local temperature over the Common Era, is unknown. Addressing this issue is an important objective of the current study. Our approach to validation includes comparison with the instrumental data for annually-resolved records, subsampling the dataset to assess reproducibility among proxy types and other subsets based on different screening criteria, and coarse-graining the time series to different extents to address issues related to combining records of different resolution and age certainty. Evidence that the records in the database reflect past temperature variability can be found in the original publications associated with each record. In addition, each series incorporated in the dataset was examined by one or more regional experts, who certified that each proxy record included in the database was accurate and related to temperature (Supplementary Table 1). This level of expert elicitation is unique among existing paleoclimate syntheses covering the last two millennia, and is a key value proposition of the PAGES2k crowd-curation process.

Quality control
To facilitate quality control of individual records within the database, dashboards displaying raw data, their annualized version and the extent to which they may be informative of annual, JJA or DJF temperature were created. These figures are grouped by region or globally and included on the FigShare repository associated with this publication (Global_QCfig_bundle.pdf, Data Citation 1).

Fundamentally there are two ways to infer past temperatures from paleoclimate records. They can be calibrated using either:

1. direct (in-time) calibration; or:
2. indirect (space for time) calibration.

In the first approach, the record must overlap with the instrumental period (here: 1850–2014), and this period of overlap must contain enough points for a statistical calibration to an instrumental temperature product such as HadCRUT4 to be meaningful. In the second approach, one often uses transfer functions or laboratory-based culture experiments. Accordingly, summary plots for all records are divided into two categories, described below. The instrumental overlap threshold requirement is set at $n = 20$ based on sensitivity tests (not shown). This parameter may be changed in the code associated with this dataset (see Code Availability).
Records that can be calibrated in time
Record Ocn_114 (ref. 42) (Fig. 4) is one such example. The top panel shows the (monthly) raw data as gray circles and an annualized curve whose color code matches that of Fig. 1a. The three bottom plots depict correlations with temperature grid points taken within a 2,000 km radius. The bottom left plot shows correlations with mean annual temperature (MAT), with insignificant correlations (as per an isospectral test 43, 1,000 surrogates, 5% level) denoted by hatching. The local correlation is −0.59 and its bold font weight indicates statistical significance, also at the 5% level. Similar plots are shown for boreal summer (JJA, center) and boreal winter (DJF, right). Essential textual metadata are displayed on the right hand side. Similar plots follow identical conventions.

Records that cannot be calibrated in time
If a record has too coarse a resolution, or ends too early, to contain 20 points over the 1850–2000 interval, it belongs to this category. One such record is Ocn_015, a foraminifera Mg/Ca record from the Caribbean35 (Fig. 5). This record was independently calibrated to temperature, as reflected in the ordinate of the time series plot (top left). The bottom left plot shows correlations with mean annual temperature (MAT), with insignificant correlations (as per an isospectral test 43, 1,000 surrogates, 5% level) denoted by hatching. The local correlation is −0.59 and its bold font weight indicates statistical significance, also at the 5% level. Similar plots are shown for boreal summer (JJA, center) and boreal winter (DJF, right). Essential textual metadata are displayed on the right hand side. Similar plots follow identical conventions.

Relationship to temperature
Here we examine the extent to which the database as a whole captures the observed temperature variability at local and regional scales. We do so via correlation analysis, which makes the common assumption that the relation between the proxy value and temperature over the twentieth century is representative of the entire record (stationarity). Unstable or multivariate associations between proxies and local temperature would represent a significant challenge to this assumption; however, this problem
is not unique to paleoclimatology within the Earth sciences. The approach also assumes that the observational temperature time series itself is accurate and unbiased for each proxy site, which may not be true in areas of sparse coverage or complex topography.

The relationship between the current proxy database and the global temperature field is quantified via Pearson’s linear correlation coefficient (R) between proxy values and temperature averages (ANN, JJA, DJF). Statistical significance is established via a non-parametric, isospectral test, which accounts for the loss of degrees of freedom due to large serial correlations common to proxy time series. Again, we restricted correlation analyses to records comprising a minimum of 20 samples over the instrumental era (CE 1850–2014), which limits the pool of proxies that may be evaluated in this way (n = 597).

Regional screening. First, we search for significant correlations (P < 0.05) within a search radius r_s, ensuring that correlations are local to regional. Compared to a global search, this limits the extent to which spurious correlations may arise, for instance, due to strong trends. Since spatial correlations are non-uniform and highly anisotropic, using a distance-based criterion that is uniform over the globe represents an oversimplification. No single distance is likely to be globally optimal, so its choice reflects a compromise between various factors: autocorrelation in land versus ocean temperatures, annual versus longer resolution, or seasonal biases. With r_s = 2,000 km, 411 records show significant correlations with annual temperature—their absolute values are shown in Fig. 6a and their locations are shown in Supplementary Fig. S3. Results change modestly depending on the value used for r_s.

Regional screening adjusted for the false discovery rate. Searching for potentially hundreds of suitable correlations within such a search radius runs the risk of false discoveries. The problem of multiple hypothesis tests has long been known to statisticians and several solutions exist. We use a method based on the false-discovery rate (FDR), adapted to the climate context. In all, 277 records passed this test with annual data (Supplementary Fig. 4).

Local screening. The search may be further restricted to the nearest HadCRUT4.2 grid point. The results of this evaluation are mapped in Fig. 6b. In some cases this may be problematic because sites may sit at the boundary between grid cells. For sites located in the vicinity of frontal zones with large spatial temperature gradients, choosing the most appropriate neighbor can be particularly difficult. Gridded temperature data may represent observations from a range of elevations or
environments, and therefore may not be representative of the archive’s actual location. Furthermore, the nearest grid point can in some instances be located thousands of kilometers from a site, because of the incomplete coverage of HadCRUT4. This limitation is particularly acute for Antarctic records, because of poor instrumental coverage over the Southern Ocean and Antarctic continent. A total of 181 records passed this test with annual data, including 5 from Antarctica, versus 9 in the regional+FDR case (Supplementary Fig. 5).

**Seasonal effects**

The extent to which proxies are informative of annual temperature depends, sometimes very strongly, on the portion of the annual cycle which they preferentially sample. Thus, before using seasonally-dependent proxies to reconstruct mean-annual temperature, one must ascertain the relationship between seasonal averages and the annual mean.

Supplementary Fig. S6 explores how much of the mean annual temperature (MAT) signal can be explained by boreal summer (JJA, top) versus winter (DJF, bottom) averages in the HadCRUT4.2 dataset. Correlations are generally very high (>0.8) in the tropics, where the MAT range is small, and low in the extra-tropics, particularly over northern hemisphere continental interiors for JJA, where the MAT range is large and dominated by winter synoptic variability. This means that proxies that preferentially record summer conditions may be adequate predictors of the annual mean if they are located in the tropics, but (all other things being equal) less so if they are located on Northern Hemisphere continents. Extratropical winter variability is known to dominate the annual average, so correlations to the MAT primarily reflect winter conditions in those regions.

Table 2 summarizes the result of the aforementioned correlation-based screening for the three approaches (regional, regional with FDR control, and local), as well as the part of the year that goes into the annual average: ANN (calendar year), DJF, JJA, or April-March (AMA). The results make it clear that some proxy records are sensitive to JJA temperature, but not to DJF or annual temperature. The vast majority are tree-ring records from the Northern Hemisphere.
Relationship to other proxies
A total of 95 proxies could not be directly correlated to MAT, either because they ended prior to 1850 or because they featured too few samples after this date. As an alternate validation method, we searched for significant correlations among the 10 closest neighbors from within the proxy dataset that can be correlated with HadCRUT4 (colored dots on Fig. 6a), and reported these significant correlations, along with their magnitude, in Fig. 6c. To minimize issues related to correlating time series with very different resolutions, the time series of proxy neighbors were smoothed to match the resolution of the target proxy. In regions where proxy-record density is high, this is a reasonable approach to assess the mutual consistency between various series; in sparsely sampled regions, this approach implies that proxy series that cannot be directly correlated to instrumental temperature must look like those that can, even if they belong to different climate settings. Moreover, despite the precautions taken with the isospectral test, correlations between a low-resolution record and its high-resolution neighbors are often driven by trends, even if no geophysical connection is present. Correlations between high- and low-resolution records must therefore be interpreted with caution. With these caveats in mind, 54 of the 95 proxies showed a significant correlation to neighboring high-resolution proxies.

Grid-based spatial correlations
An alternate way to evaluate the extent to which variability in the global temperature field is captured by a heterogeneous network of paleoclimate proxies is to quantify the correlation between each grid cell’s instrumental temperature time series and that of all the proxy series within the radius $r_{50}$. Viewed in this manner, the statistical relationship between the regular grid and the irregular proxy network provides information about the extent to which different regions of the global temperature target field are represented by the paleoclimate data, and the strength of that relationship. The results of this evaluation are shown in Fig. 6d. It shows that surface temperature over 73% of the planet is significantly correlated to a proxy time series within a 2,000 km radius—about twice as great an area as covered by the previous PAGES2k compilation.

Global trends
Having quantified the degree to which proxy records from this dataset respond to temperature, we now synthesize the largest-scale thermal signal embedded therein. We do so by use of composite time series, which efficiently summarize the global trends captured in this large and diverse collection. Composites allow us to readily compare signals contained in various subsets of the database; these comparisons, in turn, are an essential check on the mutual consistency of the temperature proxies across regions, geographic settings, and proxy archives.

Our focus here is purposefully general, centered on multidecadal to centennial time scales and ignoring the spatial features. This simple approach is intended as a preliminary estimate of global mean temperature fluctuations over the past 2000 years, and sets the stage for future community endeavors. Indeed, several PAGES2k working groups are currently working to generate spatially resolved reconstructions of annual or seasonal temperature fluctuations at regional to global scales, as well as cross-validated estimates of global mean surface temperature using a variety of statistical approaches. The composites allow this database to be placed in the context of past reconstruction efforts, and to serve as a benchmark for future ones.

Following recent compilations, we average all records (scaled to unit variance) into a composite. We do so at a coarse resolution by applying a simple binning procedure. Compositing makes two implicit assumptions:

(i) all proxy records are linearly related to global, mean-annual temperature.
(ii) all proxy records are equally representative of global mean-annual temperature at any given time, and are thus given equal weight.

Given suitable transformations, (i) may be satisfied for a broad class of proxy records, even very nonlinear ones. Assumption (ii) is more problematic, for three reasons. First, as Fig. 1a shows, the network is dominated by tree rings from the northern midlatitudes, whose temperature sensitivity is

| method | ANN | DJF | JJA | AMA |
|--------|-----|-----|-----|-----|
| reg    | 411 | 396 | 488 | 398 |
| fdr    | 277 | 230 | 318 | 260 |
| loc    | 181 | 114 | 228 | 168 |

Table 2. Number of records retained in the correlation-based screening depending on the method used and the part of the annual cycle selected. ANN: Mean Annual Temperature. DJF: December-January-February. JJA: June July August. AMA: April-March (‘tropical year’) reg: regional screening. fdr: regional screening, controlling for a 5% false discovery rate. loc: local screening. See text for details.
Normalization values point upward (downward) in response to warming (cooling).

Despite assumptions (i) and (ii) above, and their potential violation, we suggest that a simple treatment of the data constitutes an informative appraisal of the largest-scale thermal signal embedded in the dataset. We emphasize, however, that the above concerns are all legitimate, and that more rigorous treatment of these assumptions should and will be applied in formal temperature reconstructions. Compositing involved the following processing steps:

**Sign adjustment.** Records were multiplied by \(-1\) if their values decrease with increasing temperature (i.e., if their `interpDirection` parameter is negative); by \(+1\) otherwise. This step ensures that all proxy values point upward (downward) in response to warming (cooling).

**Normalization.** Records were mapped to a standard normal distribution via inverse transform sampling\(^{51}\), resulting in zero mean and unit variance.

**Binning.** Since the main focus of this composite is on low-frequency (decadal and longer) variability, all records were averaged in bins of 25, 50, and 100 years. Binning also mitigates the effect of age uncertainties, as it is known that even small age offsets between annual records could otherwise cause large spurious trends in composites made from them\(^{32}\).

**Scaling.** Standardized composites were scaled to temperature over identical bins.

**Screening.** For high-resolution records (HR: median resolution finer than 5 years), we applied either no screening (`none`), regional temperature screening (`regional`), or regional screening adjusted for the false discovery rate (`regionalFDR`). For low-resolution records (LR: median resolution coarser than or equal to 5 years), `basicFilter` denotes records that comprise at least 20 values over the Common Era (Supplementary Fig. 2), while `hrNeighbors` denotes records with at least one significantly correlated HR neighbor (see above for the caveats of this approach).

**Bootstrap.** Uncertainties in the composite are quantified via a bootstrap approach\(^{52}\). This assumes exchangeability, and primarily measures sampling uncertainty. We plot 95% confidence intervals derived from an ensemble of 1,000 bootstrap samples; in general, such intervals widen with proxy attrition, as expected.

**Sensitivity analysis**

Figure 7 presents the composites (HR in gray, LR in blue) and the HadCRUT4.2 target (red) scaled to temperature. Cases presented in the left column applied no screening, while the right column explores combinations of screening and binning interval. A striking feature is that in all cases, both HR and LR composites display a long-term cooling trend until the 19th century, after which an abrupt warming takes place, consistent with a very large body of literature\(^{5,8,11,12}\). We also note that temperature variability decreases with increasing bin size, as would be expected for data with random and independent errors.

We find the main results robust to screening choices, with the exception of the case in Fig. 7f (`regionalFDR`, `hrNeighbors`). The latter shows the most discrepancy between HR and LR, mainly because the number of LR proxies is very low (\(n = 22\)) and they have little overlap with the instrumental era, making their temperature calibration unstable. In all cases the HR composites display slightly shallower variations than LR composites. There are two non-exclusive explanations for this. Firstly, it is known that some HR records, particularly the tree-ring chronologies that form the majority of this subset, can be limited in their ability to capture low-frequency variability beyond the mean segment length\(^{53}\). Second, LR records are known to redden climate signals, often exaggerating low-frequency variability at the expense of high frequencies\(^{34}\). Our analysis cannot distinguish between these two possibilities.

It is important to consider whether any of the primary features of the composite series are strongly controlled by a particular subset of proxies, or if they are shared among archive types. There are many potential ways to analyze this dataset. We give but one example in Fig. 8, gathering composites from individual archive types that include 5 or more records among the proxy collection: corals, documentary archives, glacier ice, lake and marine sediments, as well as trees. For this case we apply regional HR screening and basic LR filtering, then average records from coral, documentary, glacier ice, lake sedimentary, marine sedimentary, and tree-ring archives.

Most composites show a strong twentieth century warming trend that emerges above the variability of comparable centennial trends over the last two millennia. This is clearest in the tree- and coral-based
composites, despite very large uncertainties in the latter during the seventeenth century, due to the paucity of records (Figs 1 and 8). An exception to this pattern is in the marine sediment composite (Fig. 8), which shows a cooling trend through most the Common Era. This may be explained by the low resolution of marine sediment records noted earlier, and the process of bioturbation of the sediment archive. These factors diffuse and damp changes occurring over years and decades (e.g., ref. 12), including the most recent warming. Local oceanographic factors may also play a role 12,55.

Uncertainties in these composites include changes in sample size and available data network over time, the potential for non-climatic or non-temperature influences to bias these smaller subsets of the dataset, and the high spatial heterogeneity of subsample networks (Fig. 8). In general, uncertainty bands widen back in time (cf tree composite), with the notable exception of the marine sediment and documentary composites, which show widening bootstrap intervals in the last 2 bins, coincident with a drop in observational coverage in these archives. Note that multidecadal trends present in coral δ¹⁸O records from the eastern tropical Pacific may not be driven by temperature 13,56,57, possibly biasing the trend of this coral composite. The network of lake records is regionally constrained (Fig. 1), and that composite may contain multiple environmental influences beyond temperature. As a result, from the lake subset only, we cannot exclude the possibility of above-modern levels of warmth in the third century CE, though uncertainty bands for early centuries are wide, and the recent rate of warming is clearly unprecedented over the Common Era.

The global composites derived from this dataset, despite their simplicity, supersede the composite-of-opportunity published in the last synthesis 11, which was an average of regional indices obtained by very different means (hence not statistically homogeneous) and did not include the majority of the marine

Figure 7. Global composites for various binning intervals and screening criteria, as indicated in subplot titles. The composites are scaled to temperature for comparison, and the shading denotes 95% bootstrap confidence intervals with 500 replicates, to constrain uncertainties. The cutoff between high-resolution (HR) and low-resolution (LR) records is defined as a median resolution of 5 years. Screening options comprise: no screening (none), regional temperature screening (regional), or regional screening adjusted for the false discovery rate (regionalFDR). For low-resolution records, basicFilter denotes records that comprise at least 20 values over the Common Era (Supplementary Fig. 2), while hrNeighbors denotes records with at least one significantly correlated HR neighbor.
Nevertheless, the present composites share many similarities and some of the same caveats; namely, that a composite tends to give more weight to numerically abundant records (e.g., tree rings), and regions with more abundant observations (e.g., the Northern Hemisphere continents). An in-depth analysis of these composites, along with their climatic interpretation, will be the subject of a companion paper.

Usage Notes
Data Citation 1 gathers data records in multiple digital formats, as well as quality control dashboards for all PAGES 2K regions (Table 3). This collection is the cornerstone of current and future efforts by the PAGES 2K Consortium to better reconstruct surface temperature, attribute its variability to climate forcings, understand its relationship to other components of the climate system, and constrain model simulations. It is appropriate for many purposes, ranging from developing reconstructions of climate indices (e.g., global mean surface temperature, NINO3.4) and fields, to proxy-proxy and proxy-model comparisons, and it was designed to be functional and relatively inclusive so that appropriate records could be selected, depending on the intended purpose, of which some are presently unforeseen.

The 692 temperature-sensitive records described and validated in this manuscript were selected based on the criteria listed above. In addition to these records, Data Citation 1 contains 2,240 ancillary time-series data from the same sites. Most (87%) are associated with tree-ring records from North America, including raw measurements, sample density and expressed population statistics; some are the native observations used to derive the temperature reconstructions included in the restricted group of 692 (e.g., Mg/Ca of foraminifera for sea-surface temperature); others are not directly related to climate but represent environmental changes at the site that might be useful in interpreting the climatic significance of the record (e.g., sedimentary magnetic susceptibility); some are proxy climate records that are sensitive

Figure 8. 50-year binned composites stratified by archive type, for all types comprising 5 or more series. Composites with fewer than 10 available series are shown by a dotted curve, while solid lines indicate more than 10 series. Shading indicates 95% bootstrap confidence intervals with 500 replicates. Gray bars indicate the number of records per bin. The composites are expressed in standard deviation units, not scaled to temperature.
Table 3. Contents of the FigShare repository associated with this descriptor.

| Filename                                      | Contents                                                                 |
|-----------------------------------------------|--------------------------------------------------------------------------|
| LoadData.md                                   | Markdown-style text file explaining how to load the data                 |
| PAGES2k_v2.0.0_LiPD.zip                       | Original records in LiPD format                                          |
| PAGES2k_v2.0.0.mat                            | Matlab-readable data structure                                           |
| PAGES2k_v2.0.0-ts.pklz                        | Python-readable data structure                                           |
| PAGES2k_v2.0.0-RData                         | R-readable data structure                                                |
| HADCRUT4_median_GraphEM.mat                   | Mat file containing the GraphEM-unfilled version of HadCRUT4.2           |
| Africa2k_QCG bundle.pdf                      | Quality-control plots for Africa                                         |
| Ant2k_QCG bundle.pdf                          | Quality-control plots for Antarctica                                     |
| Arc_QCG bundle.pdf                            | Quality-control plots for the Arctic                                     |
| Asia_QCG bundle.pdf                           | Quality-control plots for Asia                                           |
| Aus_QCG bundle.pdf                            | Quality-control plots for Australasia                                    |
| Eur_QCG bundle.pdf                            | Quality-control plots for Europe                                         |
| NAm_QCG bundle.pdf                            | Quality-control plots for North America                                  |
| SAm_QCG bundle.pdf                            | Quality-control plots for South America                                  |
| Ocean_QCG bundle.pdf                          | Quality-control plots for ocean regions                                  |
| Global_QCG bundle.pdf                         | Quality-control plots for all regions                                    |

Several factors stand in the way of the PAGES2k compilation being fully comprehensive: records are continuously being generated and published, while some existing records are not publicly archived. This synthesis represents a major community effort to compile data records and captures a substantial majority of relevant records; it is to be continuously expanded and curated by the PAGES2k community. In addition, the 692 records are easily discoverable in Data Citation 1 (PAGES2k_v2.0.0_LiPD.zip, PAGES2k_v2.0.0.mat, PAGES2k_v2.0.0-RData, PAGES2k_v2.0.0-ts.pklz) by querying the metadata property ‘paleoData_useInGlobalTemperatureAnalysis’, which is set to ‘TRUE’ only for the 692 temperature-sensitive records described here.

Our versioning scheme is as follows: the version number for a data compilation is of the form C1.C2.C3, where C1 is a counter associated with a publication of the dataset (e.g., ref. 1), C2 is a counter updated every time a record is added or removed, and C3 is a counter updated every time a modification is made to the data or metadata in an individual record. The dataset published here is thus v2.0.0 of the PAGES2k proxy temperature dataset. Future versions of the dataset, along with a change log that specifies the modifications associated with each new version, will be posted at http://wiki.linked.earth/PAGES2k. This versioning applies only to the temperature-sensitive records in Data Citation 1; changes to ancillary time series are not tracked.

In addition, an archival version of the dataset is available on the website of NCEI-Paleo/World Data Service for Paleoclimatology (https://www.ncdc.noaa.gov/paleo/study/21171), in both the LiPD format and the WDS ASCII template format developed in conjunction with the PAGES2k consortium, which will be updated and versioned as the dataset continues to evolve.

References
1. Jacoby, G. C. Jr & D’Arrigo, R. Reconstructed Northern Hemisphere annual temperature since 1671 based on high-latitude tree-ring data from North America. Climatic Change 14, 39–59 (1989).
2. D’Arrigo, R. D. & Jacoby, G. C. Secular trends in high northern latitude temperature reconstructions based on tree rings. *Climatic Change* **25**, 163–177 (1993).

3. D’Arrigo, R., Jacoby, G., Free, M. & Robock, A. Northern Hemisphere temperature variability for the past three centuries: treering and model estimates. *Climatic Change* **42**, 663–675 (1999).

4. Mann, M. E., Bradley, R. S. & Hughes, M. K. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* **392**, 779–787 (1998).

5. Mann, M. E., Bradley, R. S. & Hughes, M. K. Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophysical Research Letters* **26**, 759–762 (1999).

6. Jones, P. & Mann, M. Climate over past millennia. *Reviews of Geophysics* **42** (2004).

7. Jones, P. et al. High-resolution palaeoclimatology of the last millennium: a review of current status and future prospects. *The Holocene* **19**, 3–49 (2009).

8. Mason-Delmotte, V. et al. Information from Paleoclimate Archives In, Stocker T. F. et al. (eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* 383–464 (Cambridge University Press 2013).

9. Smerdon, J. E. & Pollack, H. N. Reconstructing Earth’s surface temperature over the past 2000 years: the science behind the headlines. *Wiley Interdisciplinary Reviews: Climate Change* **7**, 746–771 (2016).

10. Wang, J., Emile-Geay, J., Guillot, D., McKay, N. P. & Rajaratnam, B. Fragility of reconstructed temperature patterns over the common era: Implications for model evaluation. *Geophysical Research Letters* **42**, 7162–7170 (2015).

11. PAGES2k Consortium. Continental-scale temperature variability during the past two millennia. *Nature Geoscience* **6**, 339–346 (2013).

12. McGregor, H. V. et al. Robust global ocean cooling trend for the pre-industrial Common Era. *Nature Geoscience* **8**, 671–677 (2015).

13. Tierney, J. E. et al. Tropical sea surface temperatures for the past four centuries reconstructed from coral archives. *Paleoceanography* **30**, 492–495 (2015).

14. Yule, G. U. Why do we sometimes get nonsense-correlations between time-series—a study in sampling and the nature of time-series. *Journal of the Royal Statistical Society* **89**, 1–63 (1926).

15. Holm, S. A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics* **6**, 65–70 (1979).

16. Bronk Ramsey, C. Radiocarbon calibration and analysis of stratigraphy: The oxcal program. *Radiocarbon* **37**, 425–430 (1995).

17. Hassell, J. & Parnell, A. A simple monotone process with application to radiocarbon-dated depth chronologies. *Journal of the Royal Statistical Society: Series C (Applied Statistics)* **57**, 399–418 (2008).

18. Blauw, M. Methods and code for ‘classical’ age-modelling of radiocarbon sequences. *Quaternary Geochronology* **5**, 512–518 (2010).

19. Blauw, M. & Christen, J. A. Flexible palaeoclimate age-depth models using an autoregressive gamma process. *Bayesian Analysis* **6**, 457–474 (2011).

20. Anchukaitis, K. & Tierney, J. Identifying coherent spatiotemporal modes in time-uncertain proxy paleoclimate records. *Climate Dynamics* **41**, 1291–1306 (2013).

21. Orsi, A. O., Cornuelle, B. D. & Severinghaus, J. P. Little Ice Age cold interval in West Antarctica: Evidence from borehole temperature at the West Antarctic Ice Sheet (WAIS) Divide. *Geophysical Research Letters* **39**, L09710 (2012).

22. Cook, E. R. et al. Tree-ring reconstructed summer temperature anomalies for temperate East Asia since 800 C.E. *Climate Dynamics* **41**, 2957–2972 (2012).

23. St George, S. An overview of tree-ring width records across the Northern Hemisphere. *Quaternary Science Reviews* **95**, 132–150 (2014).

24. Rehfeld, K., Marwan, N., Heitzig, J. & Kurths, J. Comparison of correlation analysis techniques for irregularly sampled time series. *Nonlinear Processes in Geophysics* **18**, 389–404 (2011).

25. Cuffey, K. M. & Steig, E. J. Isotopic diffusion in polar firn: implications for interpretation of seasonal climate parameters in ice-core records, with emphasis on central Greenland. *Journal Glaciology* **44**, 273–284 (1998).

26. Küttel, M., Steig, E. J., Ding, Q., Monaghan, A. J. & Battisti, D. S. Seasonal climate information preserved in west antarctic ice core water isotopes: relationships to temperature, large-scale circulation, and sea ice. *Climate Dynamics* **39**, 1841–1857 (2012).

27. Evans, M. N., Tolwinski-Ward, S. E., Thompson, D. M. & Anchukaitis, K. J. Applications of proxy system modeling in high resolution palaeoclimatology. *Quaternary Science Reviews* **76**, 16–28 (2013).

28. National Research Council. *Surface Temperature Reconstructions for the Last 2,000 Years*. The National Academies Press, (2006).

29. Ramsey, C. B. Deposition models for chronological records. *Quaternary Science Reviews* **27**, 42–60 (2008).

30. Parnell, A. C., Buck, C. E. & Doan, T. K. A review of statistical chronological models for high-resolution, proxy-based Holocene palaeoenvironmental reconstruction. *Quaternary Science Reviews* **30**, 2948–2960 (2011).

31. McKay, N. P. & Kaufman, D. S. An extended arctic proxy temperature database for the past 2,000 years. *Scientific Data* **1** (2014).

32. Comboul, M. et al. A probabilistic model of chronological errors in layer-counted climate proxies: applications to annually banded coral archives. *Climate of the Past* **10**, 825–841 (2014).

33. Mann, M. E. et al. Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. *Proceedings of the National Academy of Sciences* **105**, 13252–13257 (2008).

34. Mann, M. E. et al. Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science* **326**, 1256–1260 (2009).

35. Lund, D. C. & Curry, W. Florida current surface temperature and salinity variability during the last millennium. *Paleoceanography* **21**, PA0209 (2006).

36. McKay, N. P. & Emile-Geay, J. Technical note: The Linked Paleo Data framework—a common tongue for paleoclimatology. *Climate of the Past* **12**, 1093–1108 (2016).

37. Morice, C. P., Kennedy, J. J., Rayner, N. A. & Jones, P. D. Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set. *Journal of Geophysical Research: Atmospheres* **117**, D08101 (2012).

38. Cowtan, K. & Way, R. G. Coverage bias in the Hadcrut4 temperature series and its impact on recent temperature trends. *Quarterly Journal of the Royal Meteorological Society* **140**, 1935–1944 (2014).

39. Guillot, D., Rajaratnam, B. & Emile-Geay, J. Statistical paleoclimate reconstructions via Markov random fields. *Annals of Applied Statistics* **324–352 (2015).*

40. Friedman, J., Hastie, T. & Tibshirani, R. Sparse inverse covariance estimation with the graphical lasso. *Biostatistics* **9**, 432–441 (2008).

41. Nicolas, J. P. & Bronwich, D. H. New reconstruction of antarctic near-surface temperatures: Multidecadal trends and reliability of global realanalyses. *Journal of Climate* **27**, 8070–8093 (2014).

42. Kuhlert, H. et al. A 200-year coral stable oxygen isotope record from a high-latitude reef off Western Australia. *Coral Reefs* **18**, 1–12 (1999).
86. Giles, G. C. et al. Surface air temperature variability reconstructed with tree rings for the Gulf of Alaska over the past 1200 years. *The Holocene* 24, 196–208 (2014).
87. D’Arrigo, R., Wilson, R. & Jacoby, G. On the long-term context for late twentieth century warming. *Journal of Geophysical Research* 111, D03103 (2006).
88. Grootes, P. M. & Stuiver, M. Oxygen 18/16 variability in Greenland snow and ice with 10^4 to 10^5 year time resolution. *Journal of Geophysical Research* 102, 26455–26470 (1997).
89. Haltiäho, E., Saarinen, T. & Kukkonen, M. A 2000-year record of solar forcing on varved lake sediment in eastern Finland. *Quaternary Science Reviews* 26, 678–689 (2007).
90. Hughes, M., Touchan, R., Funkhouser, G., Vaganov, E. & Shiyatov, S. Twentieth-century summer warmth in northern Yakutia in a 600-year context. *The Holocene* 9, 629–634 (1999).
91. Isaksson, E. et al. Climate oscillations as recorded in Svalbard ice core d18O records between AD 1200 and 1997. *Geografiska Annaler, Series A: Physical Geography* 87, 203–214 (2005).
92. Lamoureux, S. F. & Bradley, R. S. A late Holocene varved sediment record of environmental change from northern Ellesmere Island, Canada. *Journal of Paleolimnology* 16, 239–255 (1996).
93. Larsen, D. J., Miller, G. H., Geirsdóttir, A. & Thorardsson, T. A 3000-year varved record of glacier activity and climate change from the proglacial lake Hvitarvatn, Iceland. *Quaternary Science Reviews* 30, 2715–2731 (2011).
94. MacDonald, G. M., Case, R. A. & Szicz, J. M. A 538-year record of climate and treeline dynamics from the lower Lena River region of northern Siberia, Russia. *Arctic and Alpine Research* 30, 334–339 (1998).
95. Moore, J., Hughes, K., Miller, G. & Overpeck, J. Little Ice Age recorded in summer temperature reconstruction from varved sediments of Donard Lake, Baffin Island, Canada. *Journal of Paleolimnology* 25, 503–517 (2001).
96. Osula, A. E. & Alenius, T. 10000 years of interannual sedimentation recorded in the Lake Nautajärvi (Finland) clastic–organic varves. *Palaeogeography, Palaeoclimatology, Palaeoecology* 219, 285–302 (2005).
97. Fischer, H. et al. Little Ice Age clearly recorded in northern Greenland ice cores. *Geophysical Research Letters* 25, 1749–1752 (1998).
98. Thomas, E. K. & Briner, J. P. Climate of the past millennium inferred from varved glacial lake sediments on northeast Baffin Island, Arctic Canada. *Journal of Paleolimnology* 41, 209–224 (2009).
99. Vinther, B. M. et al. A synchronized dating of three Greenland ice cores throughout the Holocene. *Journal of Geophysical Research* 111, D13102 (2006).
100. Vinther, B. M. et al. Synchronizing ice cores from the Renland and Agassiz ice caps to the Greenland ice core chronology. *Journal of Geophysical Research* 113, D08115 (2008).
101. Vinther, B. et al. Climatic signals in multiple highly resolved stable isotope records from Greenland. *Quaternary Science Reviews* 29, 522–538 (2010).
102. Berghorson, P. An estimate of drift ice and temperature in Iceland in 1000 years. *Jokull* 19, 94–101 (1969).
103. Clegg, B. F. et al. Six millennia of summer temperature variation based on midge analysis of lake sediments from Alaska. *Quaternary Science Reviews* 29, 3308–3316 (2010).
104. Clegg, B., Kelly, R., Clarke, G., Walker, I. & Hu, F. S. Nonlinear response of summer temperature to Holocene insolation forcing in Alaska. *Proceedings of the National Academy of Sciences* 106, 19299–19304 (2011).
105. D’Andrea, W. J., Huang, Y., Fritz, S. C. & Anderson, N. J. Abrupt Holocene climate change as an important factor for human migration in West Greenland. *Proceedings of the National Academy of Sciences* 108, 9765–9769 (2011).
106. Fisher, D. A. et al. Effect of wind scouring on climatic records from ice-core oxygen-isotope profiles. *Nature* 301, 205–209 (1983).
107. Fisher, D. A. Penny Ice Cap cores, Baffin Island, Canada, and the Wisconsinan Foxe Dome connection: Two states of Hudson Bay ice cover. *Science* 279, 692–694 (1998).
108. Luoto, T. P., Sarmaja-Korjonen, K., Nevalainen, L. & Kauppila, T. A 700 year record of temperature and nutrient changes in a small eutrophied lake in southern Finland. *The Holocene* 19, 1063–1072 (2009).
109. Luoto, T. P. & Helama, S. Palaeoclimatological and palaeolimnological records from fossil mires and tree-rings: the role of the North Atlantic Oscillation in eastern Finland through the Medieval Climate Anomaly and Little Ice Age. *Quaternary Science Reviews* 29, 2411–2423 (2010).
110. Okuyama, J., Narita, H., Hondo, T. & Koerner, R. M. Physical properties of the P96 ice core from Penny Ice Cap, Baffin Island, Canada, and derived climatic records. *Journal of Geophysical Research* 108, 2090 (2003).
111. Rolland, N., Larocque, I., Francus, P., Pienitz, R. & Laperrière, L. D. G. Frey and E.S. Devee Review 1: Numerical tools in palaeoecology—Progress, potentialities, and problems. *Journal of Paleolimnology* 20, 307–332 (2009).
112. Schneider, L. et al. Revising midlatitude summer temperatures back to A.D. 600 based on a wood density network. *Geophysical Research Letters* 42, 4556–4562 (2015).
113. Melvin, T. M., Grudt, H. & Brufla, K. R. Potential bias in ‘updating’ tree-ring chronologies using regional curve standardisation: Re-processing 1500 years of Tornetrask density and ring-width data. *The Holocene* 23, 364–373 (2012).
114. Zhang, P., Linderholm, H. W., Gunnarson, B. E., Björklund, J. & Chen, D. 1200 years of warm-season temperature variability in central Scandinavia inferred from tree-ring density. *Climate of the Past* 12, 1297–1312 (2016).
115. Opel, T., Fritzsche, D. & Meyer, H. Eurasian Arctic climate over the past millennium as recorded in the Akademii Nauk ice core (Sernovnya Zemlya). *Climate of the Past* 9, 2379–2389 (2013).
116. Björklund, J. A., Gunnarson, B. E., Seifigen, K., Esper, J. & Linderholm, H. W. Blue intensity and density from northern Fennoscandian tree rings, exploring the potential to improve summer temperature reconstructions with earlywood information. *Climate of the Past* 10, 877–885 (2014).
117. Björklund, J. A. et al. Advances towards improved low-frequency tree-ring reconstructions, using an updated *Pinus sylvestris* L. MXD network from the Scandinavian Mountains. *Theoretical and Applied Climatology* 113, 697–710 (2012).
118. McKay, N. P., Kaufman, D. S. & Micheliutti, N. Biogenic silica concentration as a high-resolution, quantitative temperature proxy in Hallet Lake, south-central Alaska. *Geophysical Research Letters* 35, L05709 (2008).
119. D’Andrea, W. J. et al. Mild Little Ice Age and unprecedented recent warmth in an 1800 year lake sediment record from Svalbard. *Geology* 40, 1007–1010 (2012).
120. D’Andrea, W. J., Huang, Y., Fritz, S. C. & Anderson, N. J. Abrupt Holocene climate change as an important factor for human migration in West Greenland. *Proceedings of the National Academy of Sciences* 108, 9765–9769 (2011).
121. McCarroll, D. et al. A 1200-year multiproxy record of tree growth and summer temperature at the northern pine forest limit of Europe. *The Holocene* 23, 471–484 (2013).
122. Divine, D. et al. Thousand years of winter surface air temperature variations in Svalbard and northern Norway reconstructed from ice-core data. *Polar Research* 30, 73–79 (2011).
123. Porter, T. J., Pisaric, M. F., Kokelj, S. V. & deMontigny, P. A ring-width-based reconstruction of June-July minimum temperatures since AD1245 from white spruce stands in the Mackenzie Delta region, northwestern Canada. *Quaternary Research* 80, 167–179 (2013).
124. Kinnard, C. et al. Reconstructed changes in Arctic sea ice over the past 1,450 years. *Nature* 479, 509–512 (2011).
125. Hughen, K. Overpeck, J. & Anderson, R. Recent warming in a 500-year palaeotemperature record from varved sediments, Upper Soper Lake, Baffin Island, Canada. *The Holocene* 10, 9–19 (2000).

126. Briffa, K. R. et al. Reassessing the evidence for tree-growth and inferred temperature change during the Common Era in Yamalia, northwest Siberia. *Quaternary Science Reviews* 72, 83–107 (2013).

127. Panyushkina, I. P., Ovtchinnikov, D. V. & Adamenko, M. F. Mixed response of decadal variability in larch tree-ring chronologies from upper tree-lines of the Russian Altai. *Tree-Ring Research* 61, 33–42 (2005).

128. Magdá, V. N., Block, J., Ödipüpa, O. C. & Vaganov, E. A. Extraction of the climatic signal for moisture from tree-ring chronologies of Altai-Sayan mountain forest-steppes. *Contemporary Problems of Ecology* 4, 716–724 (2011).

129. Ovtchinnikov, D., Adamenko, M. & Panyushkina, I. An 1150-year tree-ring chronology in Altai Region and its application for reconstruction of summer temperatures. *GeoLines* 11, 121–122 (2000).

130. Briffa, K. R. et al. Tree-ring width and density data around the Northern Hemisphere: Part 1, local and regional climate signals. *The Holocene* 12, 737–757 (2002).

131. Cook, E. R. et al. Asian monsoon failure and megadrought during the last millennium. *Science* 328, 486–489 (2010).

132. Cook, E. R. et al. Tree-ring reconstructed summer temperature anomalies for temperate East Asia since 800 C.E. *Climate Dynamics* 41, 2957–2972 (2013).

133. Qin, N. et al. Climate change over southern Qinghai Plateau in the past 500 years recorded in Sabina tibetica tree rings. *Chinese Science Bulletin* 52, 2484–2488 (2008).

134. Yasue, K., Funada, R., Fukazawa, K. & Ohtani, J. Tree-ring width and maximum density of Picea glehnii as indicators of climatic changes in northern Hokkaido, Japan. *Canadian Journal of Forest Research* 27, 1962–1970 (1997).

135. Esper, J., Frank, D. C., Wilson, R. J. S., Büntgen, U. & Treydte, K. Uniform growth trends among central Asian low- and high-elevation juniper tree sites. *Trees* 21, 141–150 (2007).

136. Sano, M., Furuta, F. & Sweda, T. Tree-ring-width chronology of Larix gmelinii as an indicator of changes in early summer temperature in east-central Kamchatka. *Journal of Forest Research* 14, 147–154 (2009).

137. Panyushkina, I., Chang, C., Clemens, A. & Bykov, N. First tree-ring chronology from Andronovo archaeological timbers of Bronze Age in Central Asia. *Dendrochronologia* 28, 13–21 (2010).

138. Davi, N. K., Jacoby, G. C., Curtis, A. E. & Baatarbileg, N. Extension of drought records for central Asia using tree rings: west-central Mongolia. *Journal of Climate* 19, 288–299 (2006).

139. Ahmed, M. et al. The dendroclimatic potential of conifers from northern Pakistan. *Dendrochronologia* 29, 77–88 (2011).

140. Sano, M., Buckley, B. M. & Sweda, T. Tree-ring based hydroclimate reconstruction over northern Vietnam from Fokienia hodginsii: eighteenth century mega-drought and tropical Pacific influence. *Climate Dynamics* 33, 331–340 (2008).

141. Buckley, B. M. et al. Climate as a contributing factor in the demise of Angkor, Cambodia. *Proceedings of the National Academy of Sciences* 107, 6748–6752 (2010).

142. Wang, S., Ye, J. & Gong, D. Climate in China during the Little Ice Age. *Quaternary Sciences* 1, 54–64 (1998).

143. Chiu, G. et al. Seasonal temperature variability during the past 1600 years recorded in historical documents and varved lake sediment profiles from northeastern China. *The Holocene* 22, 785–792 (2012).

144. Thompson, L. G. A high-resolution millennial record of the south Asian monsoon from Himalayan ice cores. *Science* 289, 1916–1919 (2000).

145. Wang, S. & Wang, R. Reconstruction of winter temperature in east China during the last 500 years using historical documents. *Acta Meteorologica Sinica* 48, 108–119 (1990).

146. Zheng, S. Z. Climate in the Little Ice Age and its effects in Guangdong, China. *Chinese Science Bulletin* 27, 302–304 (1982).

147. Zhang, D. Winter temperature changes during the last 500 years in south China. *Chinese Science Bulletin* 6, 497–500 (1980).

148. Thompson, L. G. Tropical climate instability: The last glacial cycle from a Qinghai-Tibetan ice core. *Science* 276, 1821–1825 (1997).

149. Demuzeko, D. Y. & Solomina, O. N. Ground surface temperature variations on Kunashir Island in the last 400 years inferred from borehole temperature data and tree-ring records. *Doklady Earth Sciences* 426, 628–631 (2009).

150. Thompson, L. G. et al. Holocene climate variability archived in the Parusungai ice cap on the central Tibetan Plateau. *Annals of Glaciology* 43, 61–69 (2006).

151. Demuzeko, D. Y. & Golovanova, I. V. Climatic changes in the Urals over the past millennium; an analysis of geothermal and meteorological data. *Climate of the Past* 3, 237–242 (2007).

152. Cook, E. R. et al. Millennium-long tree-ring records from Tasmania and New Zealand: a basis for modelling climatic variability and forcing, past and present and future. *Journal of Quaternary Science* 21, 689–699 (2006).

153. Cook, E. R., Palmer, J. G., Cook, B. I., Hogg, A. & D’Arrigo, R. D. Multi-site palaeoclimatic resource from Lagarostrobus colensoi tree-rings at Oroko Swamp, New Zealand. *Global and Planetary Change* 33, 209–220 (2002).

154. Allen, K. J., Cook, E. R., Francey, R. J. & Michael, K. The climatic response of Phyllocladus asplenifolius (Labill.) Hook. f. in Tasmania. *Journal of Biogeography* 28, 305–316 (2001).

155. Duncan, R. P., Fenwick, P., Palmer, J. G., McGlone, M. S. & Turney, C. S. M. Non-uniform interhemispheric temperature trends over the past 550 years. *Climate Dynamics* 35, 1429–1438 (2010).

156. Buckley, B. M., Cook, E. R., Peterson, M. J. & Barbetti, M. A changing temperature response with elevation for *Lagarostrobus franklinii* in Tasmania, Australia. *Climate Change* 36, 477–498 (1997).

157. Saunders, K., Grosejans, M. & Hodgson, D. A. 950 yr temperature reconstruction from Duckhole Lake, southern Tasmania, Australia. *The Holocene* 23, 771–783 (2013).

158. D’Arrigo, R. D., Buckley, B. M., Cook, E. R. & Wagner, W. S. Temperature-sensitive tree-ring width chronologies of pink pine (*Holocarpus bifurmis*) from Stewart Island, New Zealand. *Palaeogeography, Palaeoclimatology, Palaeoecology* 119, 293–300 (1996).

159. Xiong, L. & Palmer, J. G. Reconstruction of New Zealand temperatures back to AD 1720 using Libocedrus bidwillii tree rings. *Climatic Change* 45, 339–359 (2000).

160. Esper, J. et al. Orbital forcing of tree-ring data. *Nature Climate Change* 2, 862–866 (2012).

161. Büntgen, U. et al. Filling the eastern European gap in millennium-long temperature reconstructions. *Proceedings of the National Academy of Sciences* 110, 1773–1778 (2013).

162. Popa, I. & Kern, Z. Long-term summer temperature reconstruction inferred from tree-ring records from the Eastern Carpathians. *Climate Dynamics* 32, 1107–1117 (2008).

163. Büntgen, U. et al. 2500 years of European climate variability and human susceptibility. *Science* 331, 578–582 (2011).

164. Büntgen, U., Frank, D. C., Nievergelt, D. & Esper, J. Summer temperature variations in the European Alps, A.D. 755–2004. *Journal of Climate* 19, 5606–5623 (2006).

165. Büntgen, U., Frank, D., Neuschwander, T. & Esper, J. Fading temperature sensitivity of Alpine tree growth at its Mediterranean margin and associated effects on large-scale climate reconstructions. *Climatic Change* 114, 651–666 (2012).

166. Dorado Liñán, I. et al. Estimating 750 years of temperature variations and uncertainties in the Pyrenees by tree-ring reconstructions and climate simulations. *Climate of the Past* 8, 919–933 (2012).
167. Dobrovolsky, P. et al. Monthly, seasonal and annual temperature reconstructions for Central Europe derived from documentary evidence and instrumental records since AD 1500. *Climatic Change* **101**, 69–107 (2009).

168. Pla, S. & Catalán, J. Chrysophyte cysts from lake sediments reveal the sub-millennial winter/spring climate variability in the northwestern Mediterranean region throughout the Holocene. *Climate Dynamics* **24**, 263–278 (2004).

169. Helama, S. et al. A palaeotemperature record for the Finnish Lakeland based on microdensitometric variations in tree rings. *Geochronometria* **41**, 265–277 (2014).

170. Larocque-Tobler, I., Grossejain, M., Heiri, O., Trachsel, M. & Kamenik, C. Thousand years of climate change reconstructed from chironomid subfossil preserved in varved lake Silvaplana, Engadine, Switzerland. *Quaternary Science Reviews* **29**, 1940–1949 (2010).

171. Trachsel, M., Grossejain, M., Schnyder, D., Kamenik, C. & Reim, B. Scanning reflectance spectroscopy (380–730 nm): a novel method for quantitative high-resolution climate reconstructions from minerogenic lake sediments. *Journal of Paleolimnology* **44**, 979–994 (2010).

172. Larocque-Tobler, I. et al. A last millennium temperature reconstruction using chironomids preserved in sediments of anoxic Seebergeee (Switzerland): consensus at local, regional and Central European scales. *Quaternary Science Reviews* **41**, 49–56 (2012).

173. Martin-Chivelet, J., Muñoz García, M. B., Edwards, R. L., Turrero, M. I. & Ortega, A. I. Land surface temperature changes in northern Iberia since 4000 yr BP, based on δ18O of speleothems. *Global and Planetary Change* **77**, 1–12 (2011).

174. Mangini, A., Spöl, C. & Verdes, P. Reconstruction of temperature in the Central Alps during the past 2000 yr from a δ34S of stalagmite record. *Earth and Planetary Science Letters* **235**, 741–751 (2005).

175. Lejónhufvud, L. et al. Five centuries of Stockholm winter/spring temperatures reconstructed from documentary evidence and instrumental observations. *Climatic Change* **101**, 109–141 (2009).

176. Tarand, A. & Nordli, P. The Tallinn temperature series reconstructed back half a millennium by use of proxy data. *Climatic Change* **48**, 189–199 (2001).

177. Salzer, M. & Kipfmüller, K. Reconstructed temperature and precipitation on a millennial timescale from tree rings in the southern Colorado Plateau. *USA Climatic Change* **70**, 465–487 (2005).

178. Barclay, D. J., Wiles, G. C. & Calkin, P. E. A 1119-year tree-ring-width chronology from western Prince William Sound, southern Alaska. *The Holocene* **9** (1999).

179. Bunn, A. G., Graumlich, L. J. & Urban, D. L. Trends in twentieth-century tree growth at high elevations in the Sierra Nevada and White Mountains, *USA. The Holocene* **15**, 481–488 (2005).

180. Schweingruber, F. H. & Briffa, K. R. Tree-ring density networks for climate reconstruction, vol. 41 of NATO ASI Series (Series I: Global Environmental Change) 43–66 (Springer Berlin Heidelberg, 1996).

181. Youngblut, D. K. & Luckman, B. H. Evaluating the temperature sensitivity of radial growth patterns from whitebark pine in the western Canadian Cordillera. *Dendrochronologia* **31**, 16–28 (2013).

182. Colenutt, M. & Luckman, B. The dendrochronological characteristics of alpine Larch. *Canadian Journal of Forest Research* **25**, 777–789 (1995).

183. Clague, J. I. et al. Rapid changes in the level of Kluane Lake in Yukon Territory over the last millennium. *Quaternary Research* **66**, 342–355 (2006).

184. Pederson, G. T. et al. The unusual nature of recent snowpack declines in the North American Cordillera. *Science* **333**, 332–335 (2011).

185. Gajewski, K. Late Holocene climate changes in eastern North America estimated from pollen data. *Quaternary Research* **29**, 255–262 (1988).

186. Kipfmüller, K. F. Reconstructed summer temperature in the northern Rocky Mountains wilderness, *USA. Quaternary Research* **70**, 173–187 (2008).

187. Salzer, M. W., Bunn, A. G., Graham, N. E. & Hughes, M. K. Five millennia of paleotemperature from tree-rings in the Great Basin, *USA. Climatic Change* **42**, 1517–1526 (2013).

188. Schiefer, E., Menounos, B. & Slawmaker, O. Extreme sediment delivery events recorded in the contemporary sediment record of a montane lake, southern Coast Mountains, British Columbia. *Canadian Journal of Earth Sciences* **43**, 1777–1790 (2006).

189. Paquetto, N. & Gajewski, K. Climatic change causes abrupt changes in forest composition, inferred from a high-resolution pollen record, southwestern Quebec, Canada. *Quaternary Science Reviews* **75**, 169–180 (2013).

190. St. Jacques, J.-M., Cumming, B. F. & Smol, J. P. A 900-year pollen-inferred temperature and effective moisture record from varved Lake Mina, west-central Minnesota, USA. *Quaternary Science Reviews* **27**, 781–796 (2008).

191. Ersek, V., Clark, P. U., Mix, A. C., Cheng, H. & Lawrence, R. D. Holocene winter climate variability in mid-latitude western North America. *Nature Communications* **3**, 1219 (2012).

192. Kipfmüller, K. F. & Salzer, M. W. Linear trend and climate response of Gennaretti, F., Arseneault, D., Nicault, A., Perreault, L. & Begin, Y. Volcano-induced regime shifts in millennial tree-ring

193. Cropper, J. P. & Fritts, H. C. Tree-ring width chronologies from the North American Arctic. *Arctic and Alpine Research* **35**, 29, 219–228 (2003).

194. Luckman, B. H. & Wilson, R. J. S. Summer temperatures in the Canadian Rockies during the last millennium: a revised record. *Climate Dynamics* **24**, 131–144 (2005).

195. St George, S. & Luckman, B. H. Extracting a paletemperature record from *Picea engelmannii* tree-line sites in the central Canadian Rockies. *Canadian Journal of Forest Research* **31**, 457–470 (2001).

196. Luckman, B. & Kavanagh, T. Impact of climate fluctuations on mountain environments in the Canadian Rockies. *AMBIO: A Journal of the Human Environment* **29**, 371–380 (2000).

197. Bigler, C., Gustin, D. G., Gunning, C. & Veblen, T. T. Drought induces lagged tree mortality in a subalpine forest in the Rocky Mountains. *Oikos* **116**, 1983–1994 (2007).
204. Jiang, H., Eiriksson, J., Schulz, M., Knudsen, K.-L. & Seidenkrantz, M.-S. Evidence for solar forcing of sea-surface temperature on the North Icelandic Shelf during the late Holocene. Geology 33, 3–13 (2005).

205. Sejrup, H., Halldísson, H. & Andrews, J. A Holocene North Atlantic SST record and regional climate variability. Quaternary Science Reviews 30, 3181–3195 (2011).

206. Berner, K. S., Koč, N., Godtliebsen, F. & Divine, D. Holocene climate variability of the Norwegian Atlantic Current during high and low solar insolation forcing. Paleoceanography 26, PA2220 (2011).

207. Newton, A., Thunell, R. & Stott, L. Changes in the Indonesian Throughflow during the past 2000 yr. Geology 39, 63–66 (2010).

208. Nieto-Moreno, V. et al. Climate conditions in the westernmost Mediterranean over the last two millennia: An integrated biomarker approach. Organic Geochemistry 55, 1–10 (2013).

209. Doose-Rolinski, H., Rogalla, U., Scheeder, G., Lückge, A. & von Rad, U. High-resolution temperature and evaporation changes during the Late Holocene in the northeastern Arabian Sea. Paleoceanography 26, PA2206 (2011).

210. Kim, J.-H. et al. Impacts of the North Atlantic gyre circulation on Holocene climate off northwest Africa. Geology 35, 387–390 (2007).

211. McGregor, H. V., Dima, M., Fischer, H. W. & Mulitza, S. Rapid 20th-century increase in coastal upwelling off northwest Africa. Science 315, 637–639 (2007).

212. Black, D. E. et al. An 8-century tropical Atlantic SST record from the Cariaco Basin: Baseline variability, twentieth-century warming, and Atlantic hurricane frequency. Paleoceanography 22, PA4204 (2007).

213. Lea, D. W. Synchrony of tropical and high-latitude Atlantic temperatures over the last glacial termination. Science 301, 1361–1364 (2003).

214. Lamy, F., Rühlmann, C., Hebbeln, D. & Wefer, G. High- and low-latitude climate control on the position of the southern Peru-Chile Current during the Holocene. Paleoceanography 17, PA000727 (2002).

215. Kuhnert, H. & Mulitza, S. Multidecadal variability and late medieval cooling of near-coastal sea surface temperatures in the eastern tropical North Atlantic. Paleoceanography 26, PA4224 (2011).

216. Keigwin, L. D., Sachs, J. P. & Rosenthal, Y. A 1600-year history of the Labrador Current off Nova Scotia. Climate Dynamics 21, 53–62 (2003).

217. Richter, T., Peeters, F. & van Weering, T. Late Holocene (0–2200 years) surface temperature and salinity variability, Fen Drift, NE Atlantic Ocean. Quaternary Science Reviews 28, 1941–1955 (2009).

218. Richey, J. N., Poore, R. Z., Flower, B. P., Quinn, T. M. & Hollander, D. J. Regionally coherent Little Ice Age cooling in the Atlantic Warm Pool. Geophysical Research Letters 36, L21703 (2009).

219. Weldeab, S., Lea, D. W., Schneider, R. R. & Andersen, N. 155,000 years of west African monsoon and ocean thermal evolution. Science 316, 1303–1307 (2007).

220. Sepúlveda, J. et al. Holocene sea-surface temperature and precipitation variability in northern Patagonia, Chile (Jafac Fjord, 44°S). Quaternary Research 72, 400–409 (2009).

221. Isorno, D. et al. The 1500-year climate oscillation in the midlatitude North Pacific during the Holocene. Geology 37, 591–594 (2009).

222. Keigwin, L. D., Sachs, J. P., Rosenthal, Y. & Boyle, E. A. The 8200 year B.P. event in the slope water system, western subpolar North Atlantic. Paleoceanography 20, PA2003 (2005).

223. Calvo, E., Grimalt, J. & Jansen, E. High resolution UTy sea surface temperature reconstruction in the Norwegian Sea during the Holocene. Quaternary Science Reviews 21, 1385–1394 (2002).

224. Linsley, B. K., Rosenthal, Y. & Oppo, D. W. Holocene evolution of the Indonesian throughflow and the western Pacific warm pool. Nature Geoscience 3, 578–583 (2010).

225. Oppo, D. W., Rosenthal, Y. & Linsley, B. K. 2000-year-long temperature and hydrology reconstructions from the Indo-Pacific warm pool. Nature 460, 1113–1116 (2009).

226. Moreno, A. et al. The Medieval Climate Anomaly in the Iberian Peninsula reconstructed from marine and lake records. Quaternary Science Reviews 43, 16–32 (2012).

227. Harada, N., Ahoğan, N., Uchida, M. & Murayama, M. Northward and southward migrations of frontal zones during the past 40 ky in the Kuroshio-Oyashio transition area. Geochemistry, Geophysics, Geosystems 5, Q09004 (2004).

228. Sicre, M.-A. et al. Sea surface temperature variability in the subpolar Atlantic over the last two millennia. Paleoceanography 26, PA4218 (2011).

229. Camer, R. E., Oppo, D. W. & McManus, J. F. Amplitude and timing of temperature and salinity variability in the subpolar North Atlantic over the past 10 kyr. Geology 35, 315 (2007).

230. Wu, W., Tan, W., Zhou, L., Yang, H. & Xu, Y. Sea surface temperature variability in southern Okinawa Trough during last 2700 years. Geophysical Research Letters 39, L14705 (2012).

231. Thornalley, D. J. R., Elderfield, H. & McCave, I. N. Holocene oscillations in temperature and salinity of the subpolar North Atlantic. Nature 457, 711–714 (2009).

232. Saraswat, R., Lea, D. W., Nigam, R., Mackensen, A. & Naik, D. K. Deglaciation in the tropical Indian Ocean driven by interplay between the regional monsoon and global teleconnections. Earth and Planetary Science Letters 375, 166–175 (2013).

233. Zhao, M., Eglinton, G., Read, G. & Schimmelmann, A. An alkene (Uty) quasi-annual sea surface temperature record (A.D. 1440 to 1940) using varved sediments from the Santa Barbara Basin. Organic Geochemistry 31, 903–917 (2000).

234. Leduc, G., Herbert, C. T., Blanz, T., Martinez, P. & Schneider, R. Contrasting evolution of sea surface temperature in the Benguela upwelling system under natural and anthropogenic climate forcings. Geophysical Research Letters 37, L20705 (2010).

235. Zhao, M., Huang, C.-Y., Wang, C.-C. & Wei, G. A millennial-scale UTy sea-surface temperature record from the South China Sea (8°N) over the last 150 ky: Monsoon and sea-level influence. Palaeogeography, Palaeoclimatology, Palaeoecology 326, 39–55 (2006).

236. Mohtadi, M., Romero, O. E., Kaiser, J. & Hebbeln, D. Cooling of the southern high latitudes during the Medieval Period and its effect on ENSO. Quaternary Science Reviews 26, 1055–1066 (2007).

237. deMenocal, P. Coherent high- and low-latitude climate variability during the Holocene warm period. Science 288, 2198–2202 (2000).

238. Abrantes, F. et al. Shallow-marine sediment cores record climate variability and earthquake activity off Lisbon (Portugal) for the last 2000 years. Quaternary Science Reviews 24, 2477–2494 (2005).

239. Stott, L., Zimmermann, A. & Thunell, R. Southern Hemisphere and deep-sea warming led glacial atmospheric CO2 rise and tropical warming. Science 318, 435–438 (2007).

240. Bonnet, S., de Vernal, A., Hillaire-Marcel, C., Radi, T. & Husum, K. Variability of sea-surface temperature and sea-ice cover in the Fram Strait over the last two millennia. Marine Micropaleontology 74, 59–74 (2010).

241. Shevenell, A. E., Ingalls, A. E., Domack, E. W. & Kelly, C. Holocene Southern Ocean surface temperature variability west of the Antarctic Peninsula. Nature 470, 250–254 (2011).
251. DeLong, K. L. Geochemistry, Geophysics, Geosystems

252. Cole, J. E., Urban, F. E. & Overpeck, J. T. In Nature Geoscience 1, 362–375 (1996).

253. Cole, J. E. & Fairbanks, R. G. The Southern Oscillation recorded in the southwestern Gulf of Mexico from 1734 to 2008. Nature Geoscience 2, 492–495 (2009).

254. Bagnato, S., Linsley, B. K., Howe, S. S., Wellington, G. M. & Salinger, J. Tropical coral oxygen isotope records of interdecadal variability. Geophysical Research Letters 29, 403–422 (2014).

255. Hetzinger, S., Pfeiffer, M., Dullo, W.-C., Garbe-Schönberg, D. & Halfter, J. Tropical sea surface temperatures for the past four centuries reconstructed from coral archives. Paleoceanography 30, 226–252 (2010).

256. Nakamura, N. et al. Mode shift in the Indian Ocean climate under global warming stress. Geophysical Research Letters 36, 226–252 (2009).

257. Moustafa, Y. A., Pätzold, J., Loya, Y. & Wefer, G. Mid-Holocene stable isotope record of corals from the northern Red Sea. Science 315, 799 (2007).

258. Cole, J. E. Tropical Pacific forcing of decadal SST variability in the western Indian Ocean over the past two centuries. Science 287, 617–619 (2000).

259. Abdalati, S., Gajewski, H. & Millot, C. Improved ocean temperature data for the Indian Ocean. Nature Geoscience 3, 181–183 (2010).

260. Felis, T. et al. A reconstruction of sea surface temperature variability in the southeastern Gulf of Mexico from 1734 to 2008 C.E. using cross-dated Sr/Ca records from the coral Siderastrea siderea. Paleoceanography 29, 403–422 (2014).

261. Dunbar, R. B., Wellington, G. M., Colgan, M. W. & Glynn, P. W. Eastern Pacific sea surface temperature variability since AD 1649. Nature Climate Change 2, 799–804 (2012).

262. Moustafa, Y. A., Pätzold, J., Loya, Y. & Wefer, G. Mid-Holocene stable isotope record of corals from the northern Red Sea. Science 315, 799 (2007).

263. Charles, C. D., Cobb, K., Moore, M. D. & Fairbanks, R. G. Monsoon-tropical ocean interaction in a network of coral records spanning the 20th century. Marine Geology 201, 207–232 (2003).

264. Nakamura, N. et al. Mode shift in the Indian Ocean climate under global warming stress. Geophysical Research Letters 36, 226–252 (2009).

265. Dunbar, R. B., Wellington, G. M., Colgan, M. W. & Glynn, P. W. Eastern Pacific sea surface temperature variability since AD 1649. Nature Climate Change 2, 799–804 (2012).

266. Moustafa, Y. A., Pätzold, J., Loya, Y. & Wefer, G. Mid-Holocene stable isotope record of corals from the northern Red Sea. Science 315, 799 (2007).

267. Tudhope, A. et al. Variability in the El Niño-Southern Oscillation through a glacial-interglacial cycle. Science 291, 1511–1517 (2001).

268. Linsley, B. K. et al. Tracking the extent of the South Pacific Convergence Zone since the early 1600s. Geochemistry, Geophysics, Geosystems 7, Q5S003 (2006).

269. Cole, J. E., Urban, F. E. & Overpeck, J. T. Influence of mean climate change on climate variability from a 155-year tropical Pacific coral record. Nature 407, 989–993 (2000).

270. Moustafa, Y. A., Pätzold, J., Loya, Y. & Wefer, G. Mid-Holocene stable isotope record of corals from the northern Red Sea. Science 315, 799 (2007).

271. Charles, C. D. Interaction between the ENSO and the Asian monsoon in a coral record of tropical climate. Science 277, 925–928 (1997).

272. Alibert, C. & Kinsley, L. A 170-year Sr/Ca and Ba/Ca coral record from the western Pacific warm pool 2: A window into the variability of the New Ireland Coastal Undercurrent. Journal of Geophysical Research 113, 226–252 (2008).

273. Colman, R. B., Wellington, G. M., Colgan, M. W. & Glynn, P. W. Eastern Pacific sea surface temperature variability since AD 1649. Nature Climate Change 2, 799–804 (2012).

274. Moustafa, Y. A., Pätzold, J., Loya, Y. & Wefer, G. Mid-Holocene stable isotope record of corals from the northern Red Sea. Science 315, 799 (2007).

275. Dunbar, R. B., Wellington, G. M., Colgan, M. W. & Glynn, P. W. Eastern Pacific sea surface temperature variability since AD 1649. Nature Climate Change 2, 799–804 (2012).

276. Moustafa, Y. A., Pätzold, J., Loya, Y. & Wefer, G. Mid-Holocene stable isotope record of corals from the northern Red Sea. Science 315, 799 (2007).

277. Linsley, B. K. et al. Tracking the extent of the South Pacific Convergence Zone since the early 1600s. Geochemistry, Geophysics, Geosystems 7, Q5S003 (2006).

278. Cole, J. E., Urban, F. E. & Overpeck, J. T. Influence of mean climate change on climate variability from a 155-year tropical Pacific coral record. Nature 407, 989–993 (2000).

279. Moustafa, Y. A., Pätzold, J., Loya, Y. & Wefer, G. Mid-Holocene stable isotope record of corals from the northern Red Sea. Science 315, 799 (2007).

280. Moustafa, Y. A., Pätzold, J., Loya, Y. & Wefer, G. Mid-Holocene stable isotope record of corals from the northern Red Sea. Science 315, 799 (2007).
281. Kuhnert, H., Pätzold, J., Wyrwoll, K. & Wefer, G. Monitoring climate variability over the past 116 years in coral oxygen isotopes from Ningaloo Reef, Western Australia. *International Journal of Earth Sciences* 88, 725–732 (2000).

282. Linsley, B. K., Ren, L., Dunbar, R. B. & Howe, S. S. El Niño Southern Oscillation (ENSO) and decadal-scale climate variability at 10°N in the eastern Pacific from 1893 to 1994: A coral-based reconstruction from Clipperton Atoll. *Palaeogeography, Palaeoclimatology, Palaeoecology* 15, 322–335 (2000).

283. Felis, T. et al. Subtropical coral reveals abrupt early-twentieth-century freshening in the western North Pacific Ocean. *Geology* 37, 527–530 (2009).

284. Drauf, B. R. M. & Griff, S. Variability of surface ocean radiocarbon and stable isotopes in the southwestern Pacific. *Journal of Geophysical Research* 104, 23607–23613 (1999).

285. Gorman, M. K. et al. A coral-based reconstruction of sea surface salinity at Sabine Bank, Vanuatu from 1842 to 2007 CE. *Palaeogeography, Palaeoclimatology, Palaeoecology* 27, PA3226 (2012).

286. Gullderson, T. P. & Schrag, D. P. Reliability of coral isotope records from the Western Pacific Warm Pool: A comparison using age-optimized records. *Palaeogeography, Palaeoclimatology, Palaeoecology* 145, 457–464 (1999).

287. Quinn, T. M., Taylor, F. W. & Crowley, T. J. Coral-based climate variability in the Western Pacific Warm Pool since 1867. *Journal of Geophysical Research* 111, C11006 (2006).

288. Munz, P. M. et al. Decadal-resolution record of winter monsoon intensity over the last two millennia from planktic foraminiferal assemblages in the northeastern Arabian Sea. *The Holocene* 25, 1756–1771 (2015).

289. Baran, B., Hall, I. R., Thorneley, D. J. R. & Barker, S. Solar forcing of North Atlantic surface temperature and salinity over the past millennium. *Nature Geoscience* 7, 275–278 (2014).

290. Tierney, J. E., Ummenhofer, C. C. & deMenocal, P. B. Past and future rainfall in the Horn of Africa. *Science Advances* 1, e1500682 (2015).

291. Kuhnert, H., Pätzold, J., Schnetger, B. & Wefer, G. Sea-surface temperature variability in the 16th century at Bermuda inferred from coral records. *Palaeogeography, Palaeoclimatology, Palaeoecology* 179, 159–171 (2002).

292. Rosenheim, B. E. Salinity change in the subtropical Atlantic: Secular increase and teleconnections to the North Atlantic Oscillation. *Geophysical Research Letters* 32, L02603 (2005).

293. Draschba, S., Pätzold, J. & Wefer, G. North Atlantic climate variability since AD 1350 recorded in δ18O and skeletal density of Bermuda corals. *International Journal of Earth Sciences* 88, 733–741 (2001).

294. Moses, C. S., Swart, P. K. & Rosenheim, B. E. Evidence of multidecadal salinity variability in the eastern tropical North Atlantic. *Palaeogeography, Palaeoclimatology, Palaeoecology* 21, PA3010 (2006).

295. Hetzinger, S. et al. Caribbean coral tracks Atlantic Multidecadal Oscillation and past hurricane activity. *Geology* 36, 11–14 (2008).

296. Wanamaker, A. D. et al. Coupled North Atlantic slope water forcing on Gulf of Maine temperatures over the past millennium. *Climate Dynamics* 31, 183–194 (2007).

297. Haase-Schramm, A. et al. Sr/Ca ratios and oxygen isotopes from sclerosponges: Temperature history of the Caribbean mixed layer and thermocline during the Little Ice Age. *Palaeogeography, Palaeoclimatology, Palaeoecology* 18, PA1073 (2003).

298. Zinke, J. et al. Corals record long-term Leeuwin current variability including Ningaloo Niño/Niña since 1795. *Nature Communications* 5, 4607 (2014).

299. Zinke, J., Laveday, B. R., Reason, C. J. C., Dullo, W.-C. & Kroon, D. Madagascar corals track sea surface temperature variability in the Aguilhas Current core region over the past 334 years. *Scientific Reports* 4, 4393 (2014).

300. Cooper, T. F., O’Leary, R. A. & Lough, J. M. Growth of Western Australian Corals in the Anthropocene. *Science* 335, 593–596 (2012).

301. Wu, H. C., Moreau, M., Linsley, R. K., Schrag, D. P. & Corrège, T. Investigation of sea surface temperature changes from replicated coral Sr/Ca variations in the eastern equatorial Pacific (Clipperton Atoll) since 1874. *Palaeogeography, Palaeoclimatology, Palaeoecology* 412, 208–222 (2014).

302. Calvo, E. et al. Interdecadal climate variability in the Coral Sea since 1708 A.D. *Palaeogeography, Palaeoclimatology, Palaeoecology* 248, 190–201 (2007).

303. Tuohope, A. et al. Recent changes in climate in the far western equatorial Pacific and their relationship to the Southern Oscillation: oxygen isotope records from massive corals, Papua New Guinea. *Earth and Planetary Science Letters* 136, 575–590 (1995).

304. Sun, Y. et al. Strontium contents of a *Porites* coral from Xisha Island, South China Sea: A proxy for sea-surface temperature of the 20th century. *Palaeogeography, Palaeoclimatology, Palaeoecology* 19, PA2004 (2004).

305. Moses, C. & Swart, P. Stable isotope and growth records in corals from the island of Tobago: Not simply a record of the Orinoco. *Proceedings of the 10th International Coral Reef Symposium (Okinawa)* 580–587 (2006).

306. Wei, G., McCulloch, M. T., Deng, W. & Xie, L. Evidence for ocean acidiﬁcation and upwelling. *Science* 320, 136–139 (2008).

307. Evans, M. N., Fairbanks, R. G. & Rubinstei, J. L. A proxy index of ENSO teleconnections. *Nature* 394, 732–733 (1998).

308. Osborne, M. C., Dunbar, R. B., Mucciarone, D. A., Drauf, B. & Sanchez-Cabeza, J.-A. A 215-yr coral δ18O time series from Palau records dynamics of the West Paciﬁc Warm Pool following the end of the Little Ice Age. *Coral Reefs* 33, 719–731 (2014).

309. Kilbourne, K. H., Quinn, T. M., Taylor, F. W., Delcroix, T. & Gourion, Y. El Niño-Southern Oscillation-related salinity variations recorded in the skeletal geochemistry of a *Porites* coral from Espiritu Santo, Vanuatu. *Palaeogeography, Palaeoclimatology, Palaeoecology* 19, PA4002 (2004).

310. Hendy, E. J. Abrupt decrease in tropical Pacific sea surface salinity at end of Little Ice Age. *Science* 295, 1511–1514 (2002).

311. von Gunten, L., Grosejin, M., Reni, B., Urruita, R. & Appleby, P. A quantitative high-resolution summer temperature reconstruction based on sedimentary pigments from Laguna Aucelo, central Chile, back to AD 850. *The Holocene* 19, 873–881 (2009).

312. Neukom, R. et al. Multiproxy summer and winter surface air temperature field reconstructions for southern South America covering the past centuries. *Climate Dynamics* 37, 35–51 (2011).

313. Neukom, R. et al. Inter-hemispheric temperature variability over the past millennium. *Nature Climate Change* 4, 362–367 (2014).

314. Thompson, L. G. et al. Annually resolved ice core records of tropical climate variability over the past 1800 years. *Science* 340, 945–950 (2013).

315. de Jong, R., von Gunten, L., Maldonado, A. & Grosejin, M. Late Holocene summer temperatures in the central Andes reconstructed from the sediments of high-elevation Laguna Chepical, Chile (32° S). *Climate of the Past* 9, 1921–1932 (2013).

316. Elbert, J. et al. Late Holocene air temperature variability reconstructed from the sediments of Laguna Escondida, Patagonia, Chile (45°30'S). *Palaeogeography, Palaeoclimatology, Palaeoecology* 369, 482–492 (2013).
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Julien Emile-Geay and Nicholas P. McKay created the database structure. Nicholas P. McKay wrote code to collate and standardize input from data contributors. Darrell S. Kaufman located missing essential metadata, cross-referenced the database with previous products, and was responsible for the Author Contributions section. Jianghao Wang, Julien Emile-Geay, and Kevin J. Anchukaitis wrote code to analyze and visualize the database contents, with input from Kaustubh Thirumalai and Michael N. Evans. Darrell S. Kaufman, Lucien von Gunten and Nicholas P. McKay coordinated the development of the data product, with input from other PAGES2k coordinators (Nerilie J. Abram, Michael N. Evans, Hugues Goosse, Raphael Neukom, Chris Turney). Julien Emile-Geay made all of the figures and wrote the initial data descriptor, with substantial input from Nerilie J. Abram, Kathryn J. Allen, Kevin J. Anchukaitis, Dmitry V. Divine, Daniel A. Dixon, Michael N. Evans, Helena L. Filipsson, Konrad Gajewski, Hugues Goosse, Darrell S. Kaufman, Belen Martrat, Helen V. McGregor, Nicholas P. McKay, David J. Nash, Raphael Neukom, Thomas Opel, Steven J. Phipps, Cody C. Routson, Marit-Solveig Seidenkrantz, Marie-Alexandrine Sicre, Jeanne-Marie St. Jacques, Jessica E. Tierney, Chris Turney, Jonathan J. Tyler, Andre E. Vieu, Lucien von Gunten and Johannes P. Werner. All authors reviewed the manuscript and take responsibility for the integrity of the data. The list of author names is divided into four groups:

**Tier 1:** The first six co-authors are the principal data analyzers, manuscript writers and project coordinators. They include: Julien Emile-Geay, Nicholas P. McKay, Darrell S. Kaufman, Lucien von Gunten, Jianghao Wang, Kevin J. Anchukaitis.

**Tier 2:** The next group of 14 co-authors are the primary regional data managers who spent at least three weeks compiling and formatting a large number of proxy records for this data product. They include: Nerilie J. Abram, Jason A. Addison, Mark A.J. Curran, Michael N. Evans, Benjamin J. Henley, Zhixin Hao, Belen Martrat, Helen V. McGregor, Raphael Neukom, Gregory T. Pederson, Barbara Stenni, Kaustubh Thirumalai, Johannes P. Werner, Chenxi Xu.

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The time devoted, as specified above, includes only the activities related to the generation of this data product, not the time to generate the original data or anything that was included in a prior publication. Author names are ordered alphabetically for each group, except the first. Most (69) authors contributed data: they either generated the proxy data or they obtained them from existing archives or publications, or they formatted and entered the data into the database. In addition, most (61) authors certified the data: they verified that the records met the criteria as described in the data descriptor, including the temperature sensitivity of the proxy record, and in some cases, they provided comments to facilitate the informed reuse of individual records. The data certifier for each record is identified in Supplementary Table 1.
Additional Information

Table 1 is only available in the online version of this paper.

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