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Globality and optimality in SST field reconstructions from tree rings: ENSO and more

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1. Introduction Much work in the rapidly growing field of paleoclimatology has emphasized the need to put recently observed secular climatic trends and shifts within the context of natural low frequency variability [*Martinson et al.*, 1995]. For example, evidence for (1) global warming since the middle of the last century, (2) variations in the amplitude, duration and frequency of El Niño-Southern Oscillation (ENSO) events, (3) apparent state changes in Pacific Basin climate and the timing of the Indian Monsoon, and (4) severe mountain glacier retreat suggests changes in the base state of the global climate [*Hansen and Lebedeff*, 1988; *Cole et al.*, 1993; *Ebbesmeyer et al.*, 1991; *Parthasarathy et al.*, 1991; *Diaz and Graham*, 1996]. Many of these observations are likely tied to preferred, natural modes of spatial variability within the ocean-atmosphere system [*Wallace*, 1996], and on the Pacific Coast of the Americas, these patterns appear to tie the tropical surface ocean to mid-latitude and subpolar atmospheric heat and water vapor anomalies [*Horel and Wallace*, 1981; *Pan and Oort*, 1983; *Ropelewski and Halpert*, 1987; *Barnston and Livezey*, 1987; *Ropelewski and Halpert*, 1989; *Halpert and Ropelewski*, 1992]. Yet since most climatic observations extend back only until the middle of the last century, we lack sufficiently long and spatially complete time series to assess whether observed variability is natural or anthropogenically-forced.

Paleoclimatology provides additional data for the pre-historical period through the measurement of climatic proxies, or parameters which vary with climatic variables of interest. Proxy measurements made on tree rings, ice cores, reef corals and sponges, sediment cores and other archives provide qualitative to semi-quantitative estimates of climate for decades to millennia prior to the rise of direct observations [*Bradley and Jones*, 1992; *Jones*, 1996]. Ideally proxy observations may be used to produce what we term here a Climate Field Reconstruction (CFR): a near-globally complete, temporally continuous estimate of climate variability over some period of interest. Once we have the CFR it is straightforward to obtain temporal indices averaged over some sub-area of the global spatial domain.

The broader implications of CFR from paleoclimatic data are difficult to overestimate. Traditionally in paleoclimate research "reconstruction" indicates recovery of a single time-varying climate index, usually of a local nature (such as seasonal air temperature from the tree ring widths) or having an immediate physical connection (such as NINO3 reconstruction from any coral site affected by ENSO). The interpretation of proxy reconstructions, usually in terms of a linear or linearized function of instrumental quantities, is generally verified by means of comparison with local instrumental data over a short, recent common period, although verification is increasingly made via comparison with regional or synoptic scale observations over longer time periods. When the proxy data span both sparse and rich observational periods (e.g. in the equatorial Pacific, before and after World War II), an opportunity is provided to cross-validate proxy and instrumental data. For example, potential biases in a proxy-based record of SST variability (age uncertainties, sampling artifacts or other non-climatic information) are independent of those in the instrumental record (instrument calibration, precision, accuracy, measurement method, frequency and spacing of sampling, and analysis procedures). Thus, the proxy-based data can provide an independent assessment of the robustness of historical instrumental indices of tropical Pacific climate. Conversely we can use modern climate data to estimate the observational error expected when extracting estimates of climate variability from the proxy data. In either case, if the instrumental and proxy data describe climatic phenomena, then they should agree. Recent works developed along this line are *Kaplan et al.* [1997b] and *Villalba et al.* [1998]. Such intercomparison (or cross-validation) efforts are essential for the continuing study of pre-instrumental climate dynamics, and they provide an important link between research in climate dynamics and paleoclimatology.

The most effective use of paleoclimatic data for the study of climate dynamics is via CFR based on consideration of all available proxy information [*Kaplan et al.*, 1997b, 1998]. Our view of the role of CFR as a natural link between data (proxy or instrumental) studies and study of climate dynamics is illustrated in Figure 1. Only recently the possibility of reconstructing entire climatic fields has begun to be viewed as an accomplishable task. *Jones and Briffa* [1996] and *Kaplan et al.* [1997b] have discussed its prospects. *Bradley* [1996] and *Evans et al.* [1998] discussed the optimal set of sites from which to build such reconstructions. *Mann et al.* [1997] obtained very encouraging results by applying statistical techniques related to *Smith et al.* [1996] and *Kaplan et al.* [1998] for the reconstruction of surface temperature fields from the bank of available proxy climate data. Here we bring the problem of CFR from tree ring width indices into the context of optimal estimation [*Kaplan et al.*, 1998].

We describe the procedure below. As such this work focuses on the methodology of objective paleoclimatic reconstructions and complements the work of others such as *Villalba et al.* [1998], who seek to characterize and interpret the climate information content of North and South American Pacific coast tree ring data.

The field of inverse modeling provides tools particularly suited for extraction of maximum information from a sparsely sampled, smoothly varying field. The term Objective Analysis (OA) encompasses a set of inverse methods employed in the estimation of the best fit field (here in a least squares sense) to both a sparse observational network of data and a description (a model) of how the field varies. Errors are admitted in both the observations and the model. A cost function, consisting of the appropriately weighted squared errors in the observations and the model, is then formulated. Minimization of the cost function with respect to the field variable produces the analyzed field which is consistent with both the data and the model, given prior estimates of how precisely the model and observations are known. The error in the OA analyzed field produced in this manner is a function of the observational error, the model error, and the extent to which the field is resolved by the observations, and can be compared to either a withheld set of data for validation or to the data used in the assimilation to check the assumed observational error magnitudes.

OA techniques have become a powerful tool used in the estimation of atmospheric and oceanographic fields of interest from spatially and temporally incomplete observations and imperfect models [*Bennett*, 1992; *Wunsch*, 1996]. Special "reduced space" analogues of this technique have been developed to reconstruct fields from sparse sampling in space and time when the fields are sufficiently smooth and have coherent, large spatial and long temporal patterns [*Cane et al.*, 1996; *Kaplan et al.*, 1997a]. Here we apply these same tools to the reconstruction of climate fields from the even sparser, but rapidly growing network of pre-instrumental paleoclimate records, in order to produce climate field reconstructions from proxy data. Bringing the CFR problem into the context of objective analysis provides three benefits: (1) the solution is optimal (provided the *a priori* assumptions hold), (2) error estimates are provided for the solution, and (3) the solution and assumptions can be tested for mutual consistency.

2. General approach to climate field reconstruction from proxy data using objective analysis Our approach to climate field reconstruction from proxy data will be quite similar to that applied previously to historical SST data [*Kaplan et al.*, 1997a, 1998], and involves 6 steps which are schematically outlined in Figure 1.

1. Characterization of the climatological mean and spatial covariance C of the target climate field. We use the modern instrumental data to provide estimates of these statistics. Such categorization of the signal can be further improved by first performing an optimal analysis of the historical instrumental data to provide reconstructions, which can later be used for verification of the modern period of the CFR based on paleoclimatic data.

2. Determination of the leading spatial modes of signal variability E (expressed as EOFs) and their energy distribution Λ (eigenvalues) through canonical decomposition of the covariance matrix C and truncation of statistically insignificant modes:
$$C \approx E\Lambda E^T$$
We then assume a reduced space form for the solution:
$$\mathcal{T}(t) = E\alpha(t)$$
where $\alpha(t)$ is the low-dimensional vector of amplitudes with which the modes E contribute to the climate field $\mathcal{T}$ at time t. For the modern period, vectors $\alpha(t)$ are known from the analysis of the instrumental data.

3. Calibration of the proxy data $d(t)$ in terms of the climate field. More precisely, their low-dimensional representation in terms of E and $\alpha(t)$ permits the estimation scheme:
$$d^o(t) = H\alpha(t) + \varepsilon^o$$
where H is a linear operator which maps from the climate field to the observed proxy values, and ε^o is the error in this map. The error covariance $R = \langle \varepsilon^o \varepsilon^{o\,T} \rangle$ is used to fit the analysis field to the observations within the context of their observational errors.

4. In some cases the instrumental data and an understanding of climate dynamics can be used to construct a model for climatic time transitions:

$$\alpha(t+1) = A\alpha(t) + \varepsilon^m$$

which can be used in CFR as an additional source of information.

5. Actual CFR analysis procedure: If the model of step 4 is available, then the solution is what is called the optimal smoother in *Kaplan et al.* [1997a]. Otherwise, the solution contains no temporal information, has a closed form, and is known as optimal interpolation:

$$\mathcal{T} = EPE^T H^T R^{-1} d^o \tag{1}$$

where

$$P = (E^T H^T R^{-1} HE + \Lambda^{-1})^{-1} \tag{2}$$

is the error covariance of the analyzed solution $\mathcal{T}$. *Kaplan et al.* [1997a] showed consistent means by which area-average indices and their error bars may be estimated from such an analysis.

6. Verification of the results: The initial verification is a comparison with the CFR based on instrumental data (see step 1). The more complicated issue is testing the consistency of the analysis. Technically, the solution obtained in the step 5 is optimal, assuming the proxy calibration scheme of step 3 holds for the entire period of reconstruction, and the proxy observational error ε^o is uncorrelated in time. We may approach the validity of these assumptions by ensuring the internal consistency of the analysis via cross-validation experiments with withheld data, comparison of the analysis results with independent data, and comparison of the residuals with the theoretical error in the analysis. All of these verification approaches become possible when the problem of paleoclimatic CFR is brought into the context of reduced space optimal estimation.

3. Application to global sea surface temperature reconstruction from Pacific-American tree ring width indices

3.1 Tree ring data For this study we used 8 available groups of Pacific American tree ring width records, for a total of 165 chronologies (Table 1). Note that groups 7 and 8 are those used in the analysis of *Villalba et al.* [1998]. All 8 groups together cover the period A.D. 1-1990, though only one record (MWK519 from group 1) covers the period A.D. 1-300 and fewer than ten records cover A.D. 1-810.

3.2. Target climate field We attempt to reconstruct near-global SST fields with annual resolution (April – May averages) on the basis of the tree ring chronologies described above. Our source of SST data for the purposes of tree ring data calibration and verification is the recently produced analysis [*Kaplan et al.*, 1998] of the MOHSST5[*Parker et al.*, 1994] product of the U.K. Meteorological Office. MOHSST5 is a $5^o \times 5^o$ monthly compilation of historical (1856-1991) ship-based observations of SST, and the analysis employs the newly developed technique (similar to the one presented here) of the reduced space optimal smoother to objectively extract large scale variations of SST from incomplete spatial and temporal observations. Variance on small spatial scales (amounting to $(0.3\text{-}0.4)^2(^o\mathrm{C})^2$) not constrained by the observed data are filtered out by the reduction of the EOF space. The analysis is quite reliably capable of reconstructing anomalies associated with ENSO and other large scale phenomena, consistent with the purpose of CFR from proxy data as described here. We use annual means for the period 1856-1990 from this SST analysis (hereafter termed KaSSTa) for calibration of the tree ring data for 1856-1990, and for verification of the theoretical analysis error in the reconstruction by calculation of the actual residuals. The covariance structures C and the basis of the reduced space E are inherited from KaSSTa.

3.3. Climate field to proxy mapping Finding the appropriate mapping H from the climate field to to the proxy is an informal task which we solve in the following manner. We estimate the covariance matrix between the dataset of tree ring records and the low-dimensional vector of amplitudes known from KaSSTa for the modern period 1856-1990:

$$B = \langle d^o(t)\alpha(t)^T \rangle,$$

where $\langle\cdot\rangle$ means averaging over time, and perform its singular value decomposition (SVD)

$$B = U\Sigma V^T.$$

Table 1. Tree ring records used in this work

#	Location	N	Comment	Reference
1	California	54		*ITRDB* [1998]
2	Oregon	22		*ITRDB* [1998]
3	Washington	60		*ITRDB* [1998]
4	Central Chile	2	Precipitation sensitive	*LaMarche et al.* [1979]
5	Patagonia	16	Precipitation sensitive	*Villalba and Veblen* [1997]
6	Patagonia	20	Temperature sensitive	*Villalba et al.* [1996]
7	Alaska	12	Temperature sensitive	*Wiles et al.* [1997]
8	Southern Andes	9	Temp sensitive; upper elevation	*Villalba et al.* [1997]

We then discard the modes with small singular values and retain the 7 leading modes of covariance between the proxy and climate data. Thus we use the corresponding 7 linear combinations of the components of α as the climatically meaningful factors on which to perform a robust linear regression of the proxy data:

$$\xi(t) = V^T \alpha(t); d^o(t) = G\xi(t) + \varepsilon^o; G = \langle d^o(t)\xi(t)^T\rangle\langle\xi(t)\xi(t)^T\rangle^{-1}.$$

This gives us $H = GV^T$, and the estimation of $R = \langle\varepsilon^o\varepsilon^{o\,T}\rangle$ is straightforward. As a first guess, we assume R to have a diagonal structure. Observational errors vary by chronology; however, their variances average 80% of the signal variance. Note that the construction of H in this manner permits non-local information to be recovered by the tree ring chronologies.

3.4. Reconstruction procedure Leading components of KaSSTa amplitudes α show significant (r=0.6-0.7) lag-one correlation, which makes it possible, in the spirit of *Kaplan et al.* [1998] to use persistence of annual SSTs as a model for time transitions, and employ the optimal smoother as the procedure of the analysis. However on this first attempt of the analysis, we choose to keep things simple and use the optimal interpolation approach (Eq. 1,2).

3.5. Reconstruction Results Comparison between the present tree ring based annual SST anomaly reconstruction (here abbreviated TrSSTa) and KaSSTa is shown in Figure 2 in terms of RMS difference and correlation maps for the common period 1856-1990. Agreement between the two analyses is not perfect but encouraging, with areas of positive correlation encompassing most of the tropical Pacific and Indian Oceans. While the correlation pattern looks similar to the Pacific Decadal Oscillation (PDO)-like patterns presented in Figure 3 of *Villalba et al.* [1998], in fact they are somewhat shifted in space from them. The PDO pattern recovered from tree rings can be specified as the correlation pattern of Alaskan air temperature with SST (Figure 3, top; *Wiles et al.* [1997], *D'Arrigo et al.* [1997]). If absolute values of this pattern are used for shading of the correlation pattern of Figure 2, we find that the areas of negative correlation correspond to zero (or low) loadings of the PDO pattern (Fig. 3, bottom). This corroborates the conclusion of *Villalba et al.* [1998], that tree ring chronologies from the Pacific American coast successfully recover the PDO pattern, a known decadal-scale pattern of SST variability [*Zhang et al.*, 1997]. The large contribution of this pattern guarantees positive correlation with the analysis of instrumental data in all areas where its loadings are significant. There are also areas of low PDO loadings where TrSSTa provides an accurate reconstruction; however, in these cases, contributions from other SST patterns resolved by the tree ring chronologies are likely important.

Reconstruction of individual years is illustrated by Figure 4. Compared to KaSSTa, TrSSTa weakens and somewhat distorts the SST structure of the 1877 El Niño and significantly enhances the strength of the 1942 La Niña. Theoretical error estimates presented on the same figure look somewhat over-optimistic, especially compared to the RMS plate of Figure 2. More robust estimates of the observational error in further stages of this work will deal with this problem.

The TrSSTa NINO3 index for the period A.D. 1-1990 is shown in Figure 5. In the earliest centuries of the reconstruction, very few tree ring chronologies are available and resolution of H is poor. Hence, the observational error variance R is large, and the analysis recovers anomalies very close to zero (climatology) with index error almost the magnitude of its true variance. As additional chronologies become available in the 16th century, the observational error variance decreases, the map from SST to tree ring chronology is more reliably resolved by the observations, and the solution finds index-average anomalies which approach the true variance of the signal.

Additional tree ring chronologies, especially prior to 1700, will further reduce the error in TrSSTa-estimated NINO3 by decreasing the observational error and improving resolution of the proxy-SST map.

4. Conclusions The climate field reconstruction described here has been derived using a reduced space optimal estimation technique, whose procedure is outlined in this paper. Multiple benefits arise from placement of paleoclimatological data within this context: (1) the solution is optimal (provided the *a priori* assumptions hold), (2) error estimates are provided for the solution, and (3) the solution and assumptions can be tested for mutual consistency, and adjusted if necessary.

As an application of this technique, we have presented estimates of the sea surface temperature (SST) anomaly field reconstructed from the available Pacific American coastal tree ring width database for the period A.D. 1 – 1990. The analysis produces SST field estimates whose theoretical errors are comparable to those of the historical SST analysis of *Kaplan et al.* [1998] for the mid 19th century. The results are encouraging enough to suggest that the tree ring data from the western tropical Americas may be used to reconstruct and study decadal-to-century scale variability in important climatic indices such as NINO3. Further, the results demonstrate the non-local nature of the climatic information that may be extracted from this set of tree ring data. Nevertheless, these reconstructions would benefit greatly from more spatially and temporally extensive proxy datasets.

The results presented here are only a first application of the objective analysis reconstruction method to this proxy data set, and should be tuned and elaborated in a number of ways: improvement of the algorithm for construction of the map from SST to tree ring chronology and more careful treatment of the tree ring data (for example, incorporation of hemispherically-dependent observed temporal lags between seasonal climate anomalies and tree growth); improved observational error estimates; incorporation of the model for time transitions; verification using independent climate indices of interest, such as the Quinn El Niño event ratings [*Quinn et al.*, 1987]; study of the primary modes of variability inferred from the reconstructed fields; and application of the method to more directly connected climatic fields such as air temperature and precipitation

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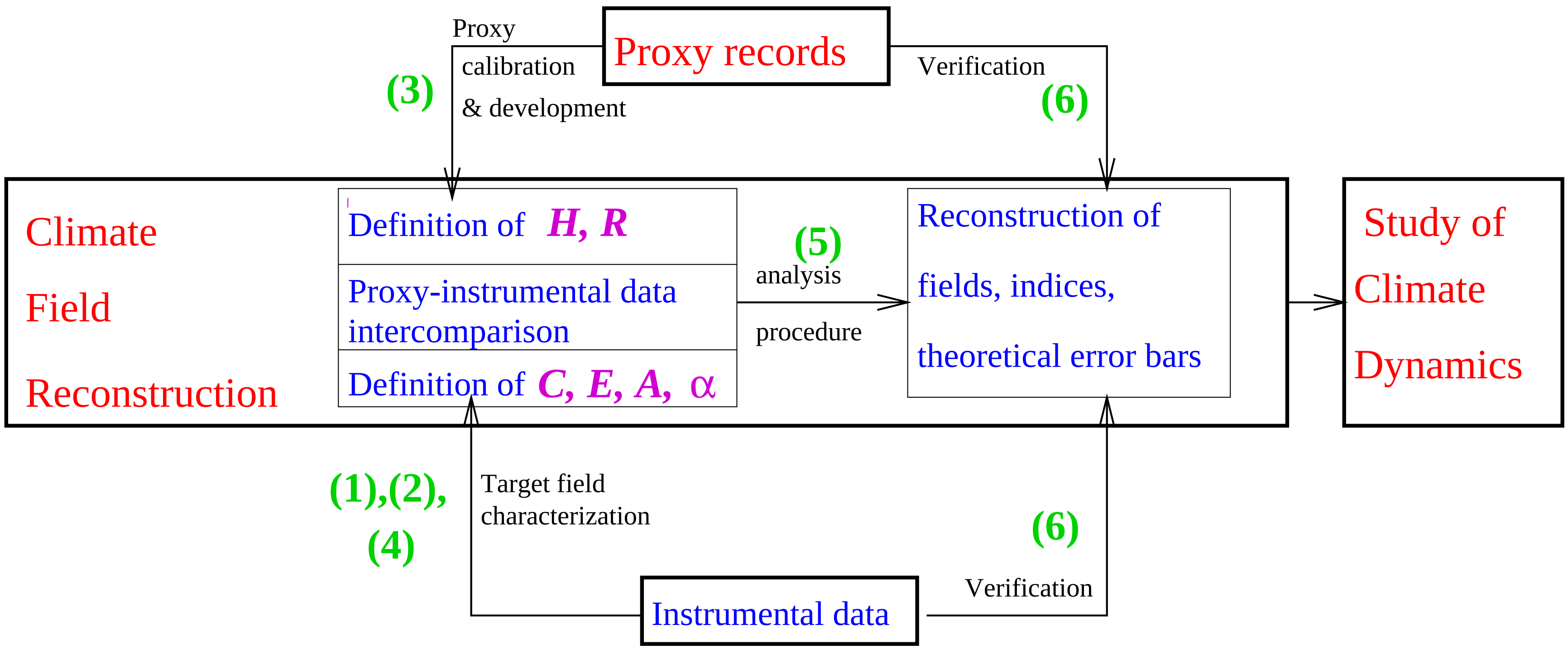
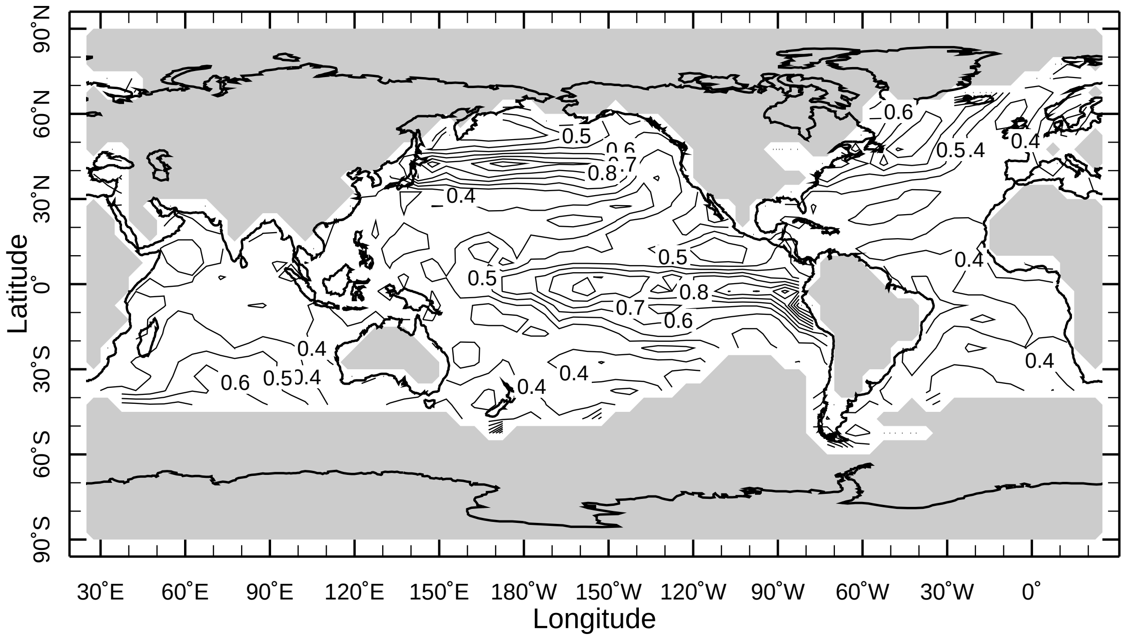
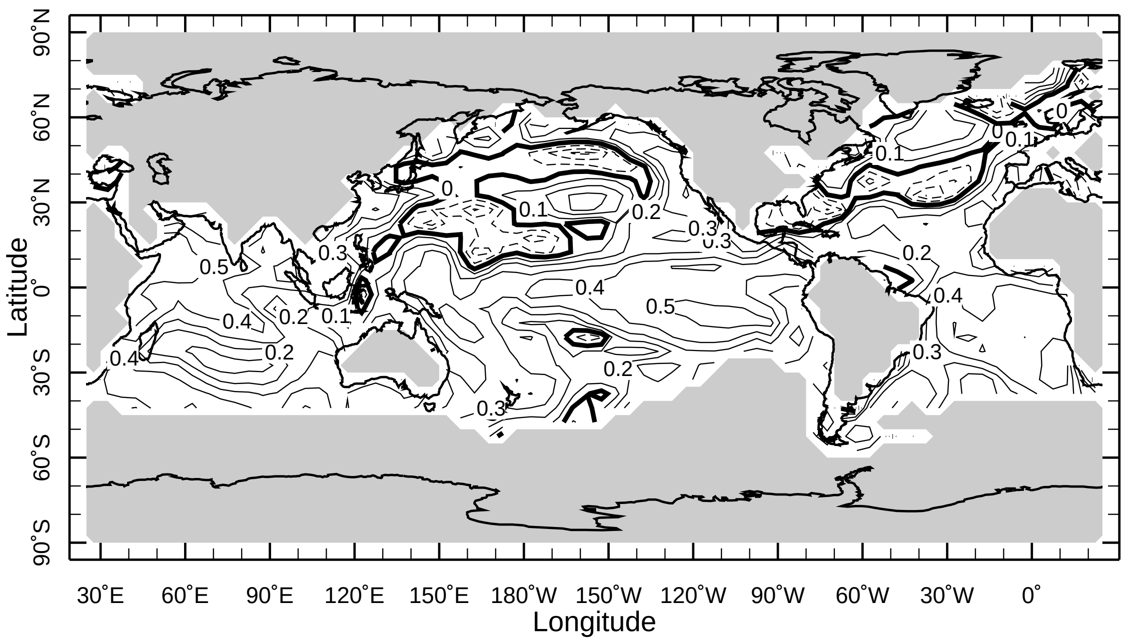


Figure1: Methodology of climate field reconstruction from proxy data. Numbered arrows on the diagram correspond to the steps in our CFR procedure (see text).



RMS[TrSSTa-KaSSTa]
point mean: 0.46956 ± 0.16341 range [0.2287 to 1.508] Δ=0.1
RMS of 2 fields



corr[TrSSTa,KaSSTa]
point mean: 0.22179 ± 0.19119 range [-0.37121 to 0.61524] Δ=0.1
Correlation of 2 fields

Figure 2: Comparison between KaSSTa and TrSSTa for the period 1856-1990: rms difference, ^{o}C (top) and correlation (bottom)

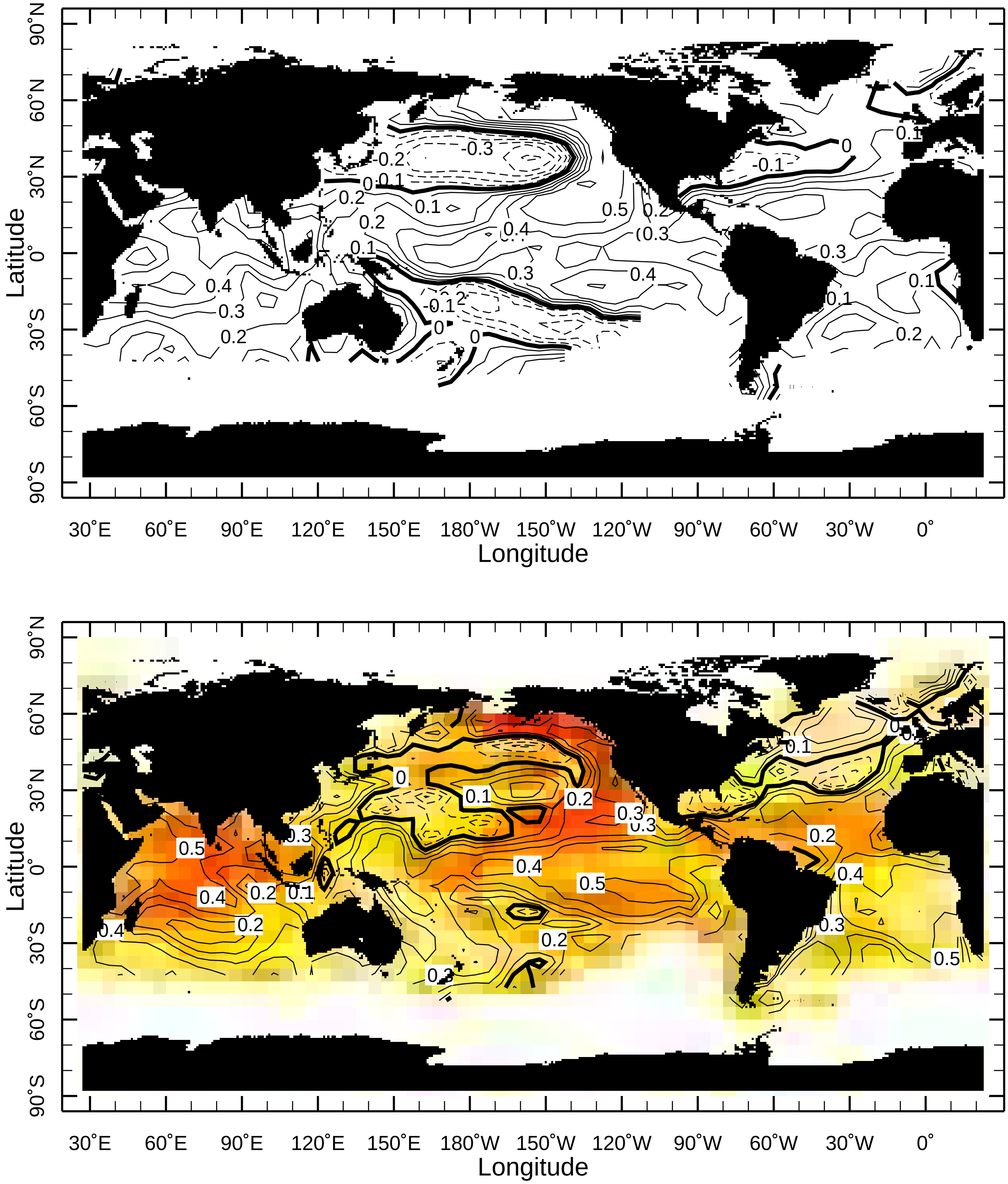


Figure 3: PDO pattern obtained as that of 1908-1990 correlation between Alaskan air temperatures and KaSSTa (top); the absolute values of the same used for shading of the correlation pattern from Figure 2 (bottom).

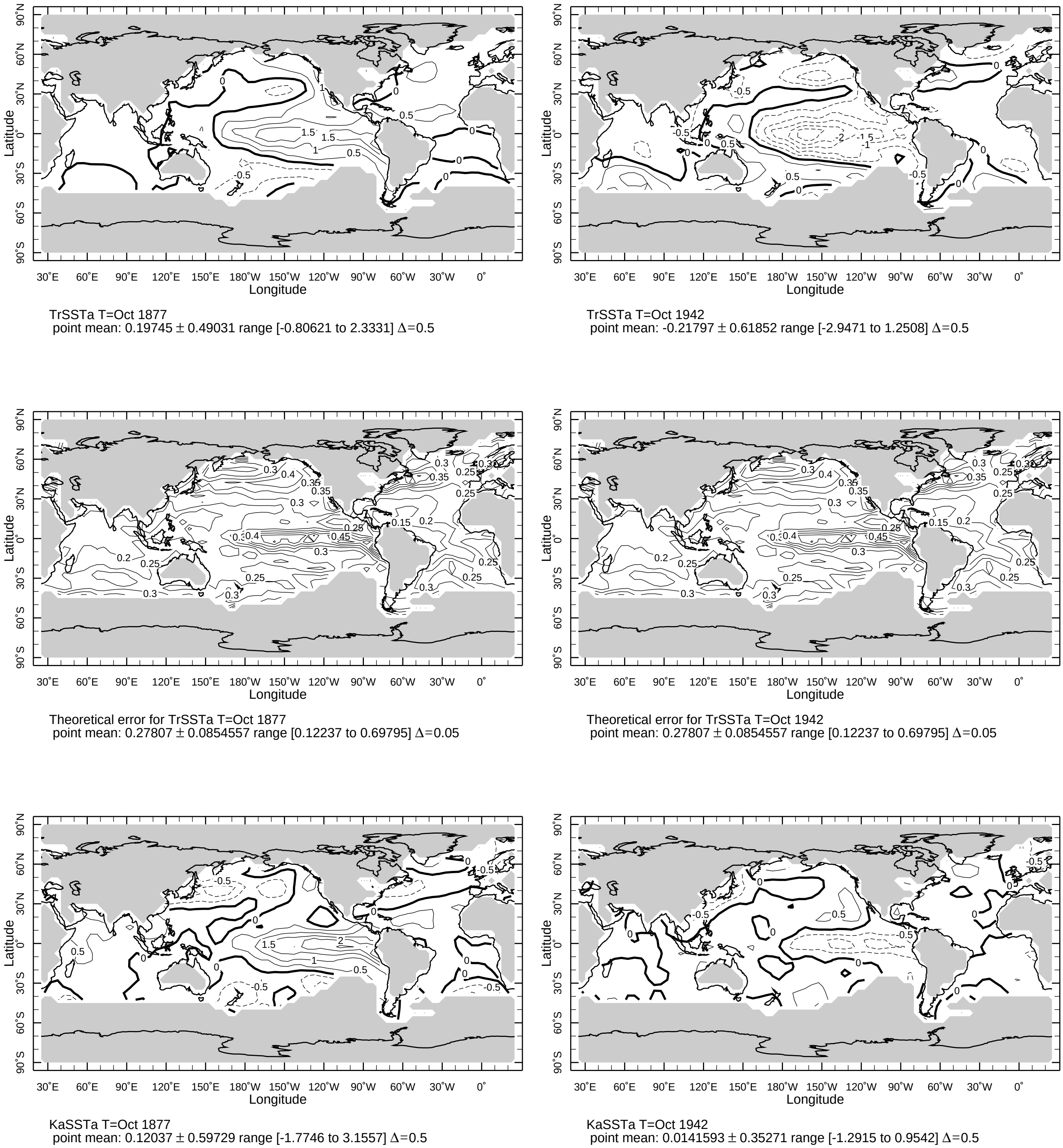


Figure 4: From top to bottom: TrSSTa fields, theoretical error in TrSSTa, and KaSSTa for 1887 (left) and 1942 (right). Contour values are in ^{o}C.

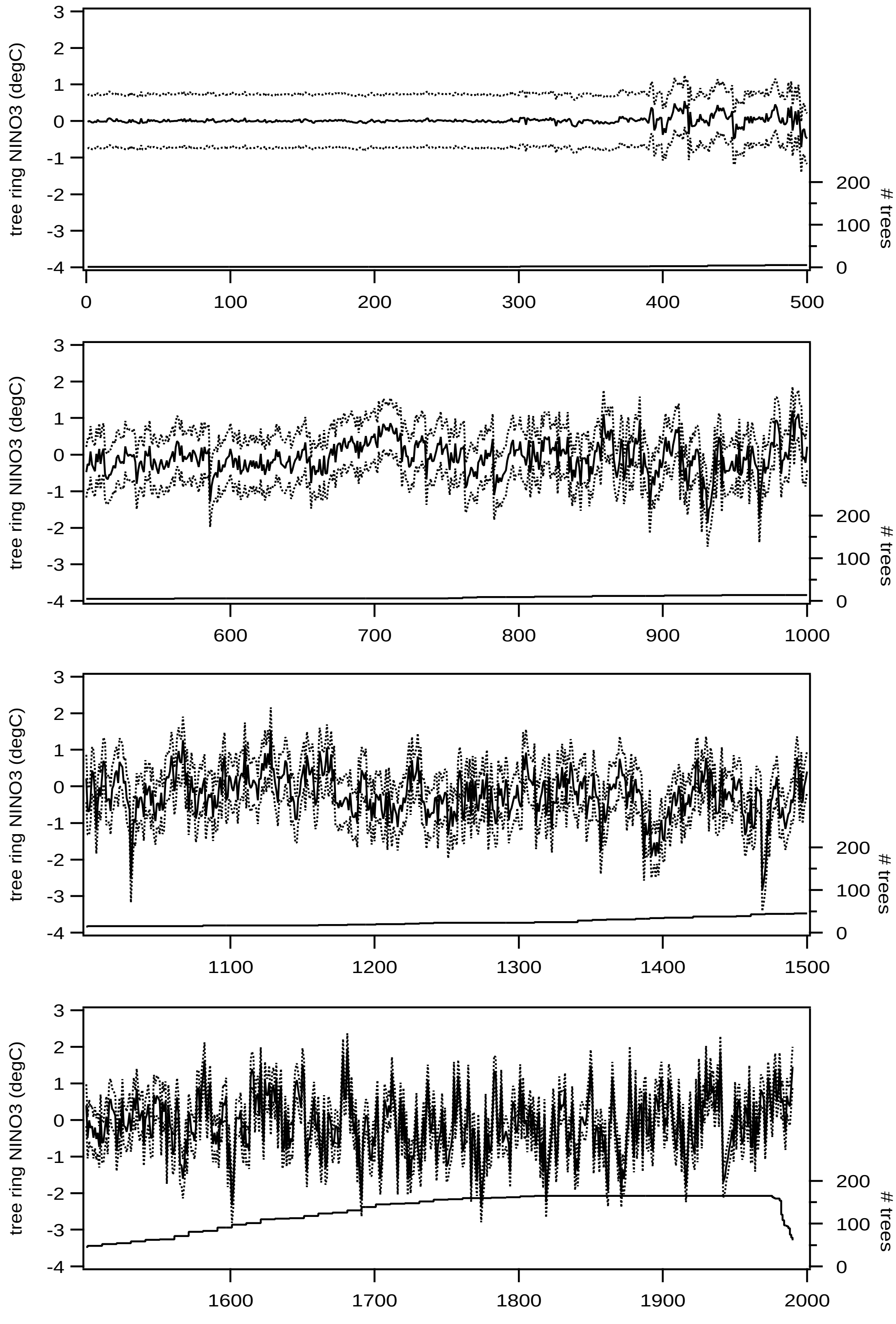


Figure 5: NINO3 (°C) estimated from TrSSTa (solid line) with 1-σ error intervals (dotted lines, left axis). Number of tree ring chronologies used in the reconstruction of different years are shown in the bottom part of the plots (solid line, right axis).