Sea Surface Temperature Observations:
From buckets to satellites

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Figure 2.18 | Global annual average sea surface temperature (SST) and Night Marine Air Temperature (NMAT) relative to a 1961–1990 climatology from state of the art data sets. Spatially interpolated products are shown by solid lines; non-interpolated products by dashed lines.
Global Mean SST/NMAT Time Series

Same Figure redrawn for readability. Note: lines w.r.t. their 1961-90 climas.
Global Mean SST/NMAT Time Series

Temperature Anomaly (°C)

Year

1900  1950  2000

HadISST1  COBE SST  ERSSTv3b  HadSST3  HadNMAT2

Common 1961-90 climatology from NCEP OI v.2
Transition to the modern Ocean Observing System

From Woodruff et al. [2008], In Climate Variability and Extremes during the Past 100 Years, Bronniman et al. (eds.)
ABSTRACT LOG

RECOMMENDED BY THE

MARITIME CONFERENCE OF BRUSSELS,

Kept on board the U. S. Commander, during the years 185

Indexed.

GENERAL ORDER.

Naval Department,
November 2, 1862.

The form of the "Abstract Log" recommended by the late Maritime Conference at Brussels is hereby approved and for use by the Navy of the United States.

In accordance with Section 6 of the Act of Congress approved August 5, 1862, a table is to be kept on board of all vessels in the Service, with the exception of the "Delaware," and the ships and the schooners of the late Navy that have not previously been so equipped, under the charge of the proper naval officer on board, and duly entered in the log book kept on board, by the Chief of the Bureau of Ordnance and Hydrography, at the end of each month of such other vessels as the Secretary of the Navy may direct.
The U.S. naval officer Matthew Fontaine Maury, b. Spotsylvania County, Va., Jan. 14, 1806, d. Feb. 1, 1873, was the first person to undertake a systematic and comprehensive study of the ocean. His work on oceanography and navigation led to an international conference (Brussels, 1853) that produced the International Hydrographic Bureau, established international standards of meteorological observations, and organized a uniform system of weather reporting at sea.

After a severe injury in a stagecoach accident in 1839 forced him from active service, Maury took charge (1842) of the Depot of Charts and Instruments in Washington, the predecessor of the U.S. Naval Observatory and the U.S. Naval Oceanographic Office. While in this office he undertook compilation of oceanographic data from old and current ship logs, and in 1847 he published the first (for the North Atlantic Ocean) of his Wind and Current Charts. During the Civil War he was a captain in the Confederate Navy and engaged in research in mine warfare and torpedoes. In 1868 he accepted a chair in physics at the Virginia Military Institute in Lexington.
Number of observations in ICOADS

http://icoads.noaa.gov/
In situ data: HadSST2
[Rayner et al., 2006]
Global Mean SST/NMAT Time Series

Temperature Anomaly (°C)

Year

hadisst1  COBE SST  ersstv3b  hadsst3  icoads

HadNMAT2 → ICOADS SST, R2.5
Modern measuring buckets on the desk of Dr. Elizabeth Kent, NOC, Southampton, U.K.
MODIS Scanning Swath
Satellite SST measurements from one sensor for one day (NOAA AVHRR)
Pathfinder SST: Monterey Bay, Oct 8, 1996 4km resolution
Satellite Observations

Donlon et al. [2010], OceanObs’09, Community White Paper

A. Kaplan, Small-Scale Variability in SST: Estimates From Drifting Buoys and Other Sources
Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA), from U.K. Met Office and GHRSSST, blend of many satellite data streams
Generic problem of the analysis of time-evolving fields

\[ T_{n+1} = A_n T_n + e_{\text{model}} \]

\[ H_n T_n + e^{obs} = T^{obs}_n \]

\[ H_2 T_2 + e^{obs} = T^{obs}_2 \]

\[ H_1 T_1 + e^{obs} = T^{obs}_1 \]
To combine various sorts of data together: \( T = (P^{-1} + R^{-1})^{-1}(P^{-1}M + R^{-1}D) \)

Discovery of least-squares estimation method: 1795

Gauss–Markov Theorem

If \( T^o = HT + \varepsilon, \)
\( \langle \varepsilon \rangle = 0, \quad \langle \varepsilon \varepsilon^T \rangle = R, \quad \langle \varepsilon^T \rangle = 0, \)
then the Least Squares Estimate (LSE)

\[
\hat{T} = (H^T R^{-1} H)^{-1} H^T R^{-1} T^o
\]

minimizes

\[
S[T] = (H T - T^o)^T R^{-1} (H T - T^o)
\]

and is the Best\(^1\) Linear Unbiased Estimate (BLUE) with error covariance

\[
P \overset{\text{def}}{=} \langle (T - \hat{T})(T - \hat{T})^T \rangle = (H^T R^{-1} H)^{-1}.
\]

\( \varepsilon \) is normal \( \implies T \) is a Maximum Likelihood Estimate (MLE)
\( \varepsilon \) and \( T \) are normal \( \implies T \) is the best among all (not necessarily linear) estimates.

\[^1\] \( ||T - \hat{T}||_S^2 = \langle (T - \hat{T})^T S (T - \hat{T}) \rangle \rightarrow \min \forall S \Rightarrow \text{minimal variance} \)
Thomas Bayes

Born

c. 1702
London, England

Died

7 April 1761
Tunbridge Wells,
Kent, England

One form of Bayes' theorem:

\[ P(A_i | B) = \frac{P(B | A_i) P(A_i)}{\sum_j P(B | A_j) P(A_j)} \]

Basis for estimating posterior probability distributions of geophysical parameters, simulating complicated distributions by
APPROXIMATING COVARIANCE

\[ C = \mathbf{E} \mathbf{\Lambda} \mathbf{E}^T + \mathbf{E}' \mathbf{\Lambda}' \mathbf{E}'^T \]

Reduced space optimal analysis

Successive corrections; Kriging
EOFs of SST (#1, 2, 3, 15, 80, 120)

EOF 1
14%

EOF 15
1%

EOF 80
0.1%

EOF 120
0.02%
Dynamics of El Niño – Southern Oscillation
Global Impacts of El Niño make it possible to compile historical chronologies of El Niño events (best known are original chronologies of W. Quinn, their revisions by L. Ortlieb)
Reconstructing SST via Reduced Space Optimal Smoother

Reconstruction from sparse 1877 data shows a huge El Nino, confirming climatologists’ beliefs.

The reconstruction of the moderate strength 1986 El Nino is quite believable.

The reconstruction comes out almost the same if the 1986 data are resampled as if they were measured in 1877!

These reconstructions lack many small-scale features which we try to bring in by using their statistical description from satellite data.
Trial reduced space OI analyses of basic ICOADS variables SST (with FP95 correction), SLP, winds, cloudiness, humidity; GHCN land station data: air temperature and precipitation, all on the same 4x4 degree monthly grid.

Intercomparison of different variables and with paleo and documentary data.
El Niño of 1877-1878 in analyzed anomalies

SST, °C: Dec 1877

SLP, mb: Sep 1877-Jan 1878

Zonal wind, m/s: Nov 1877

Meridional wind, m/s: Nov 1877

Precipitation, mm: Jul 1877

Sea surface height, cm: Dec 1877

I-COADS analyses

GHCN analysis

Ocean model response to the wind analysis
El Niño: Consistency of instrumental indices

- Data vanishes
- Reasonable consistency
- Reasonable consistency
- Good consistency

Legend:

NINO3 (SST from ships)

Central Eq Pacific zonal wind (ships)

Darwin vicinity pressure (ships)

Darwin pressure (land station)
Traditional index-making fields:

**SST**

Point mean: 0.0900511 ± 0.32603 range [-0.5217 to 0.71961]

**SLP**

Point mean: 0.0368566 ± 0.44381 range [-0.69183 to 0.63233]
Zonal wind

Meridional wind

Land precipitation

Land air temperature
<table>
<thead>
<tr>
<th>Variable</th>
<th>Abbr</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pacific Sea Surface Temperature</td>
<td>PST</td>
<td>Aug-Feb (180º-South American Coast, 10ºN -10ºS)</td>
</tr>
<tr>
<td>Sea Level Pressure Difference</td>
<td>PD</td>
<td>Jul-Feb [(150ºE-80ºE, 30ºS-10ºN) - (70ºW-160ºW, 30ºS-18ºN)]</td>
</tr>
<tr>
<td>Zonal Wind</td>
<td>ZW</td>
<td>May-Sept (130ºE-180º,10ºN-4ºS)+Sept-Mar(160ºE-140ºW,4ºN-8ºS)</td>
</tr>
<tr>
<td>Meridional Wind</td>
<td>MW</td>
<td>Jul-Feb (170ºE-90ºW, 0º-15ºS) - Jul-Feb (170ºE-90ºW, 0-15ºN)</td>
</tr>
<tr>
<td>Indonesian Precipitation</td>
<td>IP</td>
<td>May-Dec (100ºE-150ºE, 10ºS-10ºN)</td>
</tr>
<tr>
<td>Pacific Island Precipitation</td>
<td>PIP</td>
<td>Jun-Dec (160ºE-150ºW, 8ºN-8ºS)</td>
</tr>
<tr>
<td>Coastal South American Air Temp</td>
<td>CSALT</td>
<td>Jun-Mar (83ºW-60ºW, 30ºS-20ºN)</td>
</tr>
<tr>
<td>Pacific Island Air Temperature</td>
<td>PILT</td>
<td>Apr-Oct (160ºE-140ºW, 0º-30ºS)</td>
</tr>
</tbody>
</table>

New instrumental indices of El Nino – Southern Oscillation (ENSO)
William Quinn’s criteria for El Niño events

1. Very high sea and air temperatures with SST anomalies reaching 6-12°C above normal in peak months;
2. Presence of aguaje (red tide);
3. Thunderstorms, torrential rainfall, floods and erosion of the normally arid coastal lowlands;
4. Significant rises in sea level along the coast;
5. Invasion of northern and central Peruvian coastal waters by tropical nekton;
6. Destruction of housing areas, large buildings and sometimes whole cities by river inundations and flood waters;
7. Interruption of transportation as a result of destruction of bridges, roadways and railroad facilities by hydrological forces;
8. Departure of guano birds from coastal islands;
9. Mass mortality of various marine organisms, including guano birds, often with subsequent decomposition and a great stench from the release of hydrogen sulfide;
10. Destruction of agricultural crops and livestock;
11. Conditions causing the spread of tropical diseases;
12. Drastic reduction in coastal anchoveta fishery catches and fishmeal production.
TABLE 2. El Niño Events of Moderate and Near-Moderate Intensities, Their Confidence Ratings, and Information Sources

<table>
<thead>
<tr>
<th>El Niño Event</th>
<th>Event Strength</th>
<th>Confidence Rating</th>
<th>Information Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>1806-1807</td>
<td>M</td>
<td>3</td>
<td>Stevenson [1829], Remy [1931], and Unanue [1815]</td>
</tr>
<tr>
<td>1812</td>
<td>M</td>
<td>4</td>
<td>Palma [1894] and Gonzalez [1913]</td>
</tr>
<tr>
<td>1817</td>
<td>M</td>
<td>5</td>
<td>Eguiguren [1894], Labarthe [1914], Portocarrero [1926], and Taulis [1934]</td>
</tr>
<tr>
<td>1819</td>
<td>M</td>
<td>4</td>
<td>Eguiguren [1894] and Taulis [1934]</td>
</tr>
<tr>
<td>1821</td>
<td>M</td>
<td>5</td>
<td>Eguiguren [1894], Fuchs [1925], Remy [1931], and Taulis [1934]</td>
</tr>
<tr>
<td>1824</td>
<td>M</td>
<td>5</td>
<td>Spruce [1864], Basadre [1884], and Eguiguren [1894]</td>
</tr>
<tr>
<td>1832</td>
<td>M</td>
<td>5</td>
<td>Spruce [1864], and Eguiguren [1894]</td>
</tr>
<tr>
<td>1837</td>
<td>M</td>
<td>5</td>
<td>Eguiguren [1894], Labarthe [1914], Portocarrero [1926], and Taulis [1934]</td>
</tr>
<tr>
<td>1850</td>
<td>M</td>
<td>5</td>
<td>Eguiguren [1894], Fuchs [1925], and Taulis [1934]</td>
</tr>
<tr>
<td>1854</td>
<td>W/M</td>
<td>4</td>
<td>Spruce [1864], Eguiguren [1894], and Taulis [1934]</td>
</tr>
<tr>
<td>1857-1858</td>
<td>M</td>
<td>5</td>
<td>Eguiguren [1894], Labarthe [1914], Portocarrero [1926], and Taulis [1934]</td>
</tr>
<tr>
<td>1860</td>
<td>M</td>
<td>4</td>
<td>El Comercio (January 10, 1872), Raimondi [1897], Taulis [1934], and Eguiguren [1894]</td>
</tr>
<tr>
<td>1866</td>
<td>M</td>
<td>4</td>
<td>Bravo [1903], La Patria (February 9, 1874), and Bachmann [1921]</td>
</tr>
<tr>
<td>1867-1868</td>
<td>M</td>
<td>4</td>
<td>Eguiguren [1894], Puls [1895], and Taulis [1934]</td>
</tr>
<tr>
<td>1874</td>
<td>M</td>
<td>4</td>
<td>Eguiguren [1894], Labarthe [1914], Portocarrero [1926], and Taulis [1934]</td>
</tr>
<tr>
<td>1880</td>
<td>M</td>
<td>4</td>
<td>Bravo [1903], El Comercio (February 3, 1897, and February 22, 1897), and Bachmann [1921]</td>
</tr>
<tr>
<td>1887-1889</td>
<td>W/M</td>
<td>5</td>
<td>El Comercio (February 17, 1902), Bachmann [1921], and Taulis [1934]</td>
</tr>
<tr>
<td>1896-1897</td>
<td>M</td>
<td>4</td>
<td>Bachmann [1921], and Taulis [1934]</td>
</tr>
<tr>
<td>1902</td>
<td>M</td>
<td>4</td>
<td>Remy [1931], and Paz Soldan [1908]</td>
</tr>
<tr>
<td>1905</td>
<td>W/M</td>
<td>4</td>
<td>Labarthe [1914], Portocarrero [1926], Petersen [1935], Taulis [1934], and Schweiger [1961]</td>
</tr>
<tr>
<td>1907</td>
<td>M</td>
<td>3</td>
<td>Murphy [1923], Portocarrero [1926], Vogt [1940], Hutchinson [1950], and Taulis [1934]</td>
</tr>
</tbody>
</table>
| 1914          | M              | 5                 | |}

| 1918-1919     | W/M            | 5                 | Lepillo and Cesario [1924], and Belley [1925] |
SST El Nino indices vs Quinn’s historical rankings
Quinn’s El Nino event strength chronology vs meridional wind (equatorial convergence) index: 1950-1999
Independent ENSO indices vs Quinn: 1900-1949
Same Figure redrawn for readability. Note: lines w.r.t. their 1961-90 climatologies.
Figure 2.17 | Global monthly mean sea surface temperature (SST) anomalies relative to a 1961–1990 climatology from satellites (ATSRs) and \textit{in situ} records (HadSST3). Black lines: the 100-member HadSST3 ensemble. Red lines: ATSR-based nighttime subsurface temperature at 0.2 m depth (SST$_{0.2\text{m}}$) estimates from the ATSR Reprocessing for Climate (ARC) project. Retrievals based on three spectral channels (D3, solid line) are more accurate than retrievals based on only two (D2, dotted line). Contributions of the three different ATSR missions to the curve shown are indicated at the bottom. The \textit{in situ} and satellite records were co-located within 5° × 5° monthly grid boxes: only those where both data sets had data for the same month were used in the comparison. (Adapted from Merchant et al. 2012.)
For a sparse grid observational error covariance $R$ is usually assumed diagonal; its elements are estimated as uncertainties in the grid box averages.

$$F(x,y) \text{ [or } F(x,y,t)]$$

Error variance for the mean of $N$ observations is

$$\sigma^2/N$$
ICOADS SST data for July 2011:

Ships

Drifting Buoys

A. Kaplan, Small-Scale Variability in SST: Estimates From Drifting Buoys and Other Sources
Dominance of drifting buoys in the 21st century over other in situ observations of SST

A. Kaplan, Small-Scale Variability in SST: Estimates From Drifting Buoys and Other Sources

**Annual totals of SST observations from drifters**

**Annual percentages of drifting buoys SST observations**
CCI OSTIA –

global daily 6km (0.05 degree)

in situ independent gapless

SST data set
Estimates for the error std of drifters’ average over monthly $1^\circ \times 1^\circ$ bins

(a) $\sigma^*_b(\sigma_D)$

(b) $\sigma^*_b(\sigma_O)$

std SST

$0^\circ C$ $0.1^\circ C$ $0.2^\circ C$ $0.3^\circ C$ $0.4^\circ C$ $0.5^\circ C$ $0.6^\circ C$ $0.7^\circ C$ $0.8^\circ C$ $0.9^\circ C$ $1^\circ C$
ICOADS drifters minus OSTIA SST differences

Temporal mean

Zonal mean

A. Kaplan, Small-Scale Variability in SST: Estimates From Drifting Buoys and Other Sources
Measurements from these platforms are characterized by biases $b^p$, $p = 1, \ldots, P$ and by the random error on top of them, so that $K$ observations from $p$-th platform will have errors as follows:

$$e^p_k = b^p + \varepsilon^p_k, \quad k = 1, \ldots, K,$$

where $\varepsilon^p_k$ for all $p$ and $k$ are independent random numbers with zero mean and standard deviation $\sigma$. Since $p$-th platform’s bias value $b^p$ does not depend on $k$, it is the same for all errors $e^p_k$, $k = 1, \ldots, K$ of this platform’s measurements. But biases of different platforms $b^p$, $p = 1, \ldots, P$ are independent random numbers from a probability distribution with zero mean (assumed this way for simplicity here) and standard deviation $\beta$. (With apologies, hereinafter $\beta$ is not the first derivative of the Coriolis parameter over latitude.) Obviously, the mean error of our $PK$ observations is

$$\bar{e} = \frac{1}{PK} \sum_{p=1}^{P} \sum_{k=1}^{K} (b^p + \varepsilon^p_k) = \frac{1}{P} \sum_{p=1}^{P} b^p + \frac{1}{PK} \sum_{p=1}^{P} \sum_{k=1}^{K} \varepsilon^p_k,$$

and the variance of the mean error (the expectation of its squared value) is

$$\mathbb{E} \bar{e}^2 = \frac{\beta^2}{P} + \frac{\sigma^2}{PK}.$$  \hfill (1)
Recall that $PK$ is the total number of observations averaged here, and $\mathbb{E}e^2$ represents the error variance in this average. Yet, according to Equation (1), when $PK$ becomes so large that

$$\frac{\sigma^2}{PK} \ll \frac{\beta^2}{P},$$

error variance $\mathbb{E}e^2$ only decreases to the value that is essentially independent of the total number of observations:

$$\mathbb{E}e^2 \geq \frac{\beta^2}{P}.$$

Instead, it requires an increase in the number of platforms $P$ in order to achieve further reduction.


However, platform biases of $\sim 0.3$ C for drifting buoys would be inconsistent with, e.g., studies by Reverdin et al. (2010, 2013).
P observational platforms, K observations from each
RMS[drifters-OSTIA] for monthly $1^\circ \times 1^\circ$ bin averages
(a) RMS SST difference
(b) RMS SST diff w/o seasonal means
(c) RMS, $1^\circ \times 1^\circ$ bins
(d) RMS, $0.05^\circ \times 0.05^\circ$ bins

A. Kaplan, Small-Scale Variability in SST: Estimates From Drifting Buoys and Other Sources