Large-Scale Relationships between Sea Surface Temperature and Surface Air Temperature

Daniel R. Cayan
Scripps Institution of Oceanography, University of California, San Diego, La Jolla 92093

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ABSTRACT

Empirical relationships between the sea surface temperature (SST) and surface air temperatures (SAT) are examined on monthly, seasonal, and annual time scales for Marsden square areas in the North Pacific and the North Atlantic. On these time scales SST and SAT have roughly the same variance throughout the sample region. They are well correlated (contemporaneously) with warm seasons and months having slightly higher correlations than cold ones. For the most part, the spatial patterns and temporal changes in these statistics are similar between the North Atlantic and North Pacific.

1. Introduction

An immediate link between the upper ocean and the lower atmosphere can be seen in relating the sea surface temperature (SST) and the surface air temperature (SAT). The SST and SAT observations are commonly measured at points a few meters below and above the sea surface, and their difference (SST−SAT) can be taken as an indication of the vertical stability in the near-surface region. Over much of the oceans this difference is positive, indicating a sensible heat transport from the ocean to the atmosphere, although it varies tremendously in time and space (see, e.g., Roll, 1965). Spatially, the monthly and seasonal average SST field seems to exhibit less covariability on a large synoptic scale than the overlying atmosphere. This was indicated by correlations of SST and SAT between North Atlantic weather stations in a study by Kraus and Morrison (1966). In the time domain, it appears that the SST has its variability more confined to longer periods than does the SAT. Autospectra from weather station November show that SST has less energy than SAT for periods \( \leq 100 \) days and about the same energy as SAT in periods > 100 days (Dorman, 1974). At North Atlantic weather stations the variance of SST is generally a few times less than the variance of SAT for daily samples (Kraus and Morrison, 1966).

The current study uses contemporaneous statistical relationships to better understand the correlation between the upper ocean and lower atmosphere on broad spatial scales over time averages representing the short-period climate variability. The fields presented indicate the strong coupling that generally prevails, as shown by the large correspondence between the SST and the SAT fields. Also taken up here is the validity of using SST as an indicator of oceanic surface air temperature variability (e.g., Barnett, 1978). Correlations and variance ratios of SST to SAT are presented for monthly, seasonal and annual averages, and generally provide good justification for using the SST as an indication of the SAT variability on these time scales.

2. Data and analysis

All SST and SAT information was derived from individual Marine Weather Observations compiled in the surface marine deck, TDF-11, obtained from the Environmental Data Service in Asheville, North Carolina. Almost all of the SST observations are merchant ship injection temperatures which, when compared with bucket sea surface temperatures, are generally too warm by a few tenths to one degree centigrade in the North Pacific (see Saur, 1963; Barnett and Ott, 1976; Tabata, 1978). The standard deviation of observation errors was estimated to be about the same range, a few tenths to one degree centigrade. The SAT’s are measured from ship’s decks, usually a few meters above the sea surface.

The actual set of data analyzed here are space and time averages of the individual observations; averaging is necessary to minimize small-scale noise and data inhomogeneity. The various statistics shown are based upon monthly averages of Marsden square areas (10° latitude by 10° longitude). Simple time averaging of the monthly averages yielded seasonal and annual averages. Winter is taken to be December, January and February, and so on for spring, summer and fall. January–December of the same calendar year are taken together to form a year.
Fig. 1. Examples of monthly SST (lower) and SAT (upper) time series for midlatitude Atlantic (above) and Pacific (below) Marsden squares. Values are monthly anomalies from long-term monthly means. Note separate ordinates for SST and SAT.

Example monthly time series of SST and SAT for midlatitude Pacific and Atlantic Marsden squares are shown in Fig. 1.

Monthly Marsden square averages of North Pacific SST and SAT were computed for the 23 years, December 1949–November 1972. (More data were available for the Pacific in the period prior to December 1949, but this was not used because of questionable data quality.) North Atlantic monthly average Marsden square data for the 25 years, January 1948–December 1972, were made available through the courtesy of Andrew Bunker of the Woods Hole Oceanographic Institution [see Bunker (1976) for a description of the data processing].

The locations of the Marsden squares used and the total number of observations are shown in Fig. 2. The Atlantic Marsden squares' locations are denoted by the centroid of the observations within that 10° square, while for the Pacific the geometric center of the Marsden square is indicated. The coverage in the Atlantic is generally better than the Pacific. In particular, the extreme western Pacific has several Marsden squares with very sparse data. In both oceans the data are scanty in the central lower latitudes. In the western Pacific, all data from Marsden squares 57–60 (centered at 15°N, 125–155°E) were discarded because of suspiciously high variability in the SST's. Also not covered in this analysis is Pacific Marsden square 91 (centered at 25°N, 175°E) which was not present in the original data set.

The Pacific spatial averaging procedure differed from that of the Atlantic. In the Pacific, the monthly Marsden square values were averages of monthly 1° square (subsquare) averages of the edited individual observations. In the Atlantic, all observations within the 10° square were averaged together for a month to form the monthly Marsden square average—no subsquare averages were formed first (Bunker, personal communication).

The type of averaging applied to the Atlantic temperature data results in biased averages when the field is not uniformly sampled (spatially) in the presence of horizontal gradients. (The averaging scheme used for the Pacific data also has this problem, but to a lesser extent since the subsquare averaging eases the data homogeneity problem.) However, for selected Atlantic Marsden squares, the Pacific type of averaging scheme was applied to the SST set and yielded monthly series that were quite similar to those obtained from Bunker, and the averaged data are thought to be adequate for purposes of estimating the large-scale interannual statistics shown in this report.

In the SST and SAT analysis, monthly, seasonal and annual fields of each of three variables were

Fig. 2. Location of Marsden squares and total number of observations in 1000's. Applies to both SST and SAT. Pacific locations are indicated by the geometric center of Marsden squares and Atlantic locations by the centroid of observation within Marsden squares.
Fig. 3a. SST – SAT difference in temperature (°C) computed from Marsden square averages. Upper, middle and lower panels are for January, winter and annual averaging periods, respectively.

computed: the sea-air temperature differences, SST – SAT; the variance ratio, \( \sigma_{SST}^2/\sigma_{SAT}^2 \); and the contemporaneous correlation of SST to SAT. The results are displayed in two panels of maps, one for January, winter and annual, and one showing summer for each of the above three variables (Figs. 3, 5, and 6).

These fields represent the most complete Northern Hemisphere SST and SAT data set heretofore assembled. Less complete geographical and time portions of them appear in various atlases and reports, but these deal mainly with just the air-sea temperature differences. The maps presented are designed to allow ready comparison of a number of features: North Pacific to North Atlantic, summer to winter, and monthly to seasonal to annual averaging periods.

3. Sea-air temperature difference (SST – SAT)

The sea-air temperature differences are shown (Figs. 3a and 3b) to illustrate the large spatial and temporal variations of this quantity, and to give insight into the variance ratios and correlations shown later. The instantaneous SST – SAT difference is directly related to the sensible heat flux
through the well-known bulk formula, but, of course, that flux is also strongly determined by the wind speed and to some extent by the stability of the atmospheric surface layer. Estimates of time averages of the sensible fluxes have a strong resemblance to the average SST – SAT field despite their dependence on the other variables [discussions of these heat fluxes can be found in Jacobs (1951), Clark (1967) and Bunker (1976)].

No attempt is made to account for any biases in the temperature difference due to observation errors, as discussed in Section 2. Since the biases are generally uniform the patterns are probably realistic but their absolute amplitudes are somewhat in doubt. However, the spatial and seasonal changes in the SST – SAT differences are often in excess of the 1°C probable error bias, and the larger scale features in the difference field are likely realistic, supporting past findings of strong regional and seasonal preferences in the sensible heating regime.

The striking feature of the average SST – SAT field is the tremendous change from strong winter patterns to weak summer patterns, indicating the predominance of the winter season for sensible heat exchange over the extratropical oceans (see Jacobs, 1951). The January and winter fields are positive throughout the sampling region with strong western maxima of ~4–5°C and rather weak eastern regions, generally less than 1.5°C, in both the Atlantic and the Pacific. Latitudinally, the wintertime maxima occur in midlatitudes at about 35°N, equatorward of the maxima in the variance fields. The July (not shown) and summer fields are quite weak (mostly <1°C, absolute) and have little western intensification. Also in summer, north of ~30–40°N, most of the difference values are negative, indicating the tendency of sensible heating of the ocean by the atmosphere. The annual pattern most closely resembles the winter patterns, since the winter amplitudes are mostly larger than those in summer.

### a. Variance ratio $\sigma_{\text{SST}}^2/\sigma_{\text{SAT}}^2$

The SST variance for winter and summer are shown in Figs. 4a and 4b; for brevity’s sake the monthly and annual SST variances are not shown, nor are the SAT maps. The SAT variance closely resembles that of SST as will be seen. Variability of SST in the North Pacific and North Atlantic is discussed in detail by Davis (1976), Weare et al. (1976) and Weare (1977). Briefly, both the SST and SAT variances display western intensified patterns and much weaker, low-gradient interiors for all seasons and time scales in both oceans. Magnitude ranges of the variances are also quite comparable between the two ocean basins; monthly variances range from 0.25 to 3 or 4 ($^\circ$C)$^2$ in the Pacific and the Atlantic for the Marsden square averages.

The variances ratios ($\sigma_{\text{SST}}^2/\sigma_{\text{SAT}}^2$) are shown in Figs. 5a and 5b. Seasonally, there is a slight increase of the ratio in summer. This may result from a less energetic atmosphere in summer, causing lower SAT variances while the thermal signal of the ocean is concentrated in a shallow mixed layer, yielding slightly larger SST anomalies in summer than in winter, as discussed in Kraus and Morrison (1966). The ratio generally increases with increasing averaging period: the annual ratio of variance is slightly larger than the seasonal ratio which in turn is slightly larger than the monthly ratio. The indication is that the SST field over both the oceans has a “redder” spectrum than the SAT field, causing the shift in ratio with averaging period as suggested by Dorman’s (1974) results for a single ocean weather station. This may be affected by the strong thermal inertia of the oceanic mixed layer in contrast to a less persistent lower atmosphere.

Overall, the ratio maps indicate that the variance of SST and SAT are roughly equal. The smallest ratios are slightly less than 0.5 and the largest are slightly greater than 2 with a majority of them fall-
Fig. 4a. SST variance ($\sigma_{SST}^2$) in ($^\circ$C)$^2$ computed from Marsden square averages for winter.

ing between 0.5 and 1.5 (shown as the unshaded region in Figs. 5a and 5b). The similarity of the SST and SAT patterns of variance and the closeness of their amplitudes on the monthly to seasonal time scales is clearly indicated by these maps. This contrasts with local variance ratios for daily events in which the SST variability is considerably smaller than that of SAT (see Kraus and Morrison, 1966).

b. Contemporaneous correlation $\rho_{SST-SAT}$

Correlations between contemporaneous SST and SAT fields are presented in Figs. 6a and 6b. Correlations were computed for the time series with trend included (linear trends over the 23–25 year period were found to be ineffective in altering the correlation coefficients, so the trend-included correlations are representative of the phenomena on the shorter monthly to annual time scale).

The sample correlation fields shown can be interpreted with some statistical guidance provided by standard tests of significance (see Dixon and Massey, p. 200). Two pertinent guidelines are 1) for 23 and 25 independent samples (Pacific and Atlantic, respectively) a sample correlation coefficient must exceed 0.43 and 0.41 to be different from zero at the 95% level of confidence; and 2) for these sample sizes, a sample correlation coefficient of 0.75 is not significantly different from correlations in the range of about 0.45–0.87 at the 95% confidence level.

The correlations (Figs. 6a and 6b) are generally high (a majority of values exceed 0.75) for all averaging periods and seasons, indicating the high level of thermal communication at the interface on these rather large time and space scales. This high degree of correspondence is demonstrated visually in the monthly anomaly plots of SST and SAT shown in Fig. 2.

There seems to be a seasonal preference for the correlations to be greater in July (not shown) and summer than January and winter in midlatitudes. This conclusion is derived more from the large spatial scale of the seasonal change in correlation than from the magnitude of the change, which is fairly small (generally less than 0.25) relative to the significance limits mentioned above. This summer increase in correlation may be caused by weaker advective processes in the warm season (both in the atmosphere and in the ocean) coupled with weaker meridional temperature gradients, which together

Fig. 4b. As in Fig. 4a except for summer.
result in less noise and more complete thermal adjustment between the upper ocean and lower atmosphere than in the more energetic winter period. Another reason for this seasonal change may be that in summer months, the sampling density of the individual SST and SAT observations of several of the extratropical Marsden squares (not shown) increases considerably, which might result in less random sampling noise and thus better correlations.

There is an interesting difference between these SST — SAT correlations and SST — (1000–700 mb) thickness correlations over the North Pacific as found by Namias (1973). Namias' results show that the large-scale structure and circulation of the atmosphere affect the communication between the sea surface and the lower troposphere; the correlation between SST and thickness decreased in the summer with increasing static stability in the lower subtropical atmosphere. The present study indicates that this isolation apparently does not penetrate into the lower atmosphere surface layer, as the correlations between SST and SAT are highest during the summer period.

As expected, the correlations increase with in-
creased averaging period; the annual period generally shows greater correlations than the seasonal periods which, in turn, exceed those of the monthly periods. This is a result of successive elimination of the higher frequency uncorrelated part of the signals by temporal smoothing.

The winter correlation fields display some interesting spatial variations (ranging from <0.5 to >0.75) while those in summer are quite uniformly high (>0.75). The winter western Pacific is marked by smaller correlations than the central and eastern Pacific regions. In contrast, the winter western Atlantic shows larger correlations than the eastern Atlantic regions. The large spatial coherence of these winter correlation patterns prompts speculation about phenomenological causes. The lower correlations in the western Pacific seem consistent with the western intensified SST and SAT variance and difference fields and active storm generation regions in the winter that would likely result in more small-scale uncorrelated geophysical noise than in the less active central and eastern regions.\(^1\) Surprisingly, although similar western intensified conditions exist in the western Atlantic, the correlations there are relatively high (>0.75). It is difficult to offer plausible physical explanations for this contrasting behavior, and perhaps sampling errors are responsible. However, the patterns seen are large in scale, and sampling errors, to be effective, must be organized spatially. No such organization is seen in the overall sampling density (see Fig. 2) or in a breakdown of samples into individual monthly costs (not shown). There could be another sampling error involved here, this one nonrandom, and operating most strongly in the Atlantic, whose Marsden square averaging of the initial observations was unweighted by position. Artificially correlated signals in SST and SAT would arise in Marsden squares having high horizontal gradients if the Marsden square was not uniformly spatially sampled. In that case (assuming normal conditions) the supposed monthly anomaly is a spatial difference resulting from inadequate sampling, and not from temporal variability. Since the spatial gradients in the SST and SAT are very similar and the sampling pattern for the two is the same, these artificial signals in the two fields would be highly correlated. The western Atlantic, having high gradients, would be especially prone to have this kind of error. This may help to explain the correlation difference between the western and eastern Atlantic; however, the magnitude of this effect is difficult to assess due to unequal sampling from month-to-month and between Marsden squares.

4. Summary

The large-scale features of sea surface temperature (SST) and surface air temperature (SAT) are well related on monthly, seasonal and annual time scales over the North Pacific and North Atlantic. The ratio of variance \(\frac{\sigma^2_{\text{SST}}}{\sigma^2_{\text{SAT}}}\) is close to 1 and the contemporaneous cross correlations are high over most of the basins. The actual values of the observed SST and SAT are not in perfect accord as the differences \(\text{SST} - \text{SAT}\) can be very large, as high as 5–6°C on monthly time scales for the long-term mean. However, the substitution of SST and SAT as made by Barnett (1978) seems to be admissible in capturing the variability of the large spatial scale fields on monthly to annual time scales.

The Pacific and Atlantic have variance ratios, sea-air temperature differences and correlations that are generally similar in their patterns, ampli-

\(^1\) Interaction between the strongly contrasting sea surface and the overlying atmosphere in the western Pacific is discussed at length in a series of papers that emerged from the AMTEX study, issued by the Japanese National Committee for GARP (1977).
tude ranges and seasonal changes. A striking difference is between the winter correlation fields; the Pacific has relatively small correlations in the west and large in the central and eastern region, seemingly consistent with the western intensified forcings, while the Atlantic shows the reverse pattern—high correlations in the west and lower in the east. It is not certain if this incongruity arises from sampling error or is geophysical in nature.

The SST field is better correlated with the SAT field over the Pacific and Atlantic than it was shown to be with the 1000–700 mb thickness filed in the northeastern Pacific by Namias (1973). The poor correlation between SST and thickness in this region was attributed to strong static stability resulting from atmospheric subsidence, which inhibits “thermal communication” between the ocean and lower atmosphere. This stability apparently does not inhibit exchange locally at the sea surface, however, as the SST and SAT are seen to be generally very well correlated. In fact, during the summer, when there is the least SST-thickness correlation, SST and SAT are best correlated. This points out that a strong SST-SAT relationship does not necessarily imply a strong coupling between the lower troposphere and the sea surface.
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