Estimation of Sea Surface Temperatures around Japan Using the Advanced Very High Resolution Radiometer (AVHRR)/NOAA-11

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(Received 29 July 1991; in revised form 21 October 1991; accepted 23 January 1992)

The accuracy of sea surface temperatures (SSTs) derived from the Advanced Very High Resolution Radiometer (AVHRR)/NOAA-11 is examined by comparison with sea-truth SSTs obtained from ocean data buoys during November 1988 through December 1989. We made a 122 point data set of buoy SSTs from the oceans around Japan and the corresponding brightness temperatures of channels 4 and 5 during cloud free periods. The satellite temperatures are corrected for atmospheric effects using the NOAA Multi-Channel SST (MC SST) and Cross Product SST (CPSST) algorithms. The two algorithms give similar results for our data set and result in biases of about $-0.1^\circ C$ with rms errors of about $0.6^\circ C$ relative to buoy SSTs. It is found that MCSSTs and CPSSTs tend to be higher than SSTs from the buoy in the Japan Sea in summer. New coefficients for the MCSST equations suitable for our data set are determined and the resultant rms error is $0.49^\circ C$. If we eliminate the cluster of anomalous summer data in the Japan Sea, the rms error becomes $0.43^\circ C$.

1. Introduction

The Sea Surface Temperature (SST) distribution in vast areas of the ocean can be measured by satellite infrared sensors. Polar-orbiting satellites and geostationary satellites have been monitoring the SST in the world oceans since the early 1970’s. However, these measurements were not accurate enough for various scientific requirements until the middle of 1980’s because correction methods for atmospheric effects, mainly for water vapor, and calibration systems for satellite-derived SSTs had not been established.

The Multi-Channel SST (MCSST) algorithm has been carefully examined as an operational method for monitoring the SST of the world oceans since the launch of NOAA-7, which carried the Advanced Very High Resolution Radiometer (AVHRR) with three infrared channels (McClain et al., 1985). Currently, National Oceanic and Atmospheric Administration (NOAA)/National Environmental Satellite, Data, and Information Services (NESDIS) publishes coefficients of the MCSST algorithm for the NOAA satellites in operation and occasionally updates them. Table 1 shows the published equations for AVHRR/NOAA-11. We will use data from this satellite and coefficients shown in Table 1 in the present study.

The MCSST algorithm uses a linear regression equation with two or more brightness temperatures. The equation for two brightness temperatures is written as,

$$\text{SST} = T_i + \gamma (T_i - T_j)$$

(1)
Table 1. Equations for SST estimation using AVHRR/NOAA-11 data. (a) The MCSST and (b) CPSST equations with coefficients given by NOAA/NESDIS (1991). (c) The MCSST equations with coefficients derived from our data set. (d) As in (c) after elimination of a cluster of points in the Japan Sea in summer. $T_4$ and $T_5$ denote the brightness temperatures of channel 4 and 5, respectively. Unit are °K. $\phi$ denotes satellite zenith angle.

<table>
<thead>
<tr>
<th>Type</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daytime</td>
<td>$SST = 1.01345T_4 + 2.659762(T_4 - T_5) + 0.526548(T_4 - T_5)(\text{SEC}\phi - 1) - 4.592$</td>
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<tr>
<td>Nighttime</td>
<td>$SST = 1.0527T_4 + 2.397089(T_4 - T_5) + 0.959766(T_4 - T_5)(\text{SEC}\phi - 1) - 15.520474$</td>
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<td>Daytime</td>
<td>$SST = \frac{0.19410T_5 - 48.15}{0.20524T_5 - 0.17334T_4 - 6.25}(T_4 - T_5 + 1.32) + 0.94575T_5 + 0.60(T_4 - T_5)(\text{SEC}\phi - 1) + 12.16$</td>
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<tr>
<td>Nighttime</td>
<td>$SST = \frac{0.19817T_5 - 49.15}{0.20524T_5 - 0.17334T_4 - 6.10}(T_4 - T_5 + 1.47) + 0.96554T_5 + 0.96(T_4 - T_5)(\text{SEC}\phi - 1) + 6.02$</td>
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<td>Daytime</td>
<td>$SST = 1.05495T_4 + 1.972497(T_4 - T_5) + 0.9740444(T_4 - T_5)(\text{SEC}\phi - 1) + 15.6652$</td>
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<tr>
<td>Nighttime</td>
<td>$SST = 1.063204T_4 + 2.336555(T_4 - T_5) + 0.7802193(T_4 - T_5)(\text{SEC}\phi - 1) - 18.4575$</td>
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<tr>
<td>Daytime</td>
<td>$SST = 1.041273T_4 + 2.159008(T_4 - T_5) + 0.8864231(T_4 - T_5)(\text{SEC}\phi - 1) - 11.826$</td>
</tr>
<tr>
<td>Nighttime</td>
<td>$SST = 1.0679137T_4 + 2.246805(T_4 - T_5) + 1.012306(T_4 - T_5)(\text{SEC}\phi - 1) - 19.7742$</td>
</tr>
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or

\[ \text{SST} = \alpha + \beta T_i + \gamma (T_i - T_j), \]

where \( T_i \) and \( T_j \) are brightness temperatures and \( \alpha, \beta \) and \( \gamma \) are constants if scan angle effect is ignored. Eq. (1) is theoretical form and Eq. (1') is used in practice. Coefficients are usually determined empirically. The basic idea of the MCSST algorithm originated from Anding and Kauth (1970). The theoretical basis and the history of the MCSST algorithm are given elsewhere (e.g., Prabakahara et al., 1974; McMillin and Crosby, 1984; McClain et al., 1985). Since the AVHRR on board the NOAA polar-orbiting satellites observes two or three infrared channels, AVHRR data are suitable for applying the MCSST algorithm. Previous studies examining SSTs derived from the MCSST algorithm with AVHRR data have documented that the rms error was about 0.6°C (e.g., Llewellyn-Jones et al., 1984; Strong and McClain, 1984; McClain et al., 1985; Tanba et al., 1988).

The empirically determined coefficients of the MCSST equations depend on the sampled data set. A set of MCSST coefficients suitable for estimating SSTs in a specified ocean is not always applicable to other oceans. Pearce et al. (1989) compared satellite SSTs derived from the AVHRR on NOAA-7 and NOAA-9 with in-situ observations off western Australia. They checked seven published algorithms. For their data set, two algorithms showed reasonable agreement, but the others showed large rms errors or large biases. Tanba et al. (1988) examined the MCSST equations for the AVHRR on NOAA-7 and NOAA-9 using a data set in Mutsu Bay, which has an area of about 60 km² and is located in northern Honshu, Japan. The coefficients of the MCSST equations derived by Tanba et al. were different from those of Strong and McClain (1984).

Walton (1988) has suggested that the parameter \( \gamma \) in Eq. (1) could be a function of temperature rather than a constant to cope with the various atmospheric conditions. Walton's algorithm is called the Cross Product SST (CPSST) algorithm and the equation takes on a nonlinear form because of the temperature dependence on the \( \gamma \) parameter. For CPSST, \( \gamma \) in Eq. (1) is written as

\[ \gamma = \frac{T_i \text{SST}_j - T_j \text{SST}_i}{T_i - T_j + \text{SST}_j - \text{SST}_i}, \]

where \( \text{SST}_i \) and \( \text{SST}_j \) are derived by the linear regression equation

\[ \begin{align*}
\text{SST}_i &= A_i T_i + B_i \\
\text{SST}_j &= A_j T_j + B_j
\end{align*} \]

and \( A_i, A_j, B_i \) and \( B_j \) are constants. Coefficients of the CPSST algorithm are shown in Table 1. According to Walton, the CPSST algorithm and the MCSST algorithm provide nearly equal accuracy under noise-free conditions. However, when the satellite data contain a significant amount of noise due to instrumental and atmospheric effects, the CPSST algorithm reduces its influence.

In this paper, the accuracies of the MCSST and CPSST algorithms in the oceans near Japan
are examined. First, we describe the data set produced using the AVHRR/NOAA-11 and ocean data buoys (Section 2). The algorithm published by NOAA is tested for our data set (Section 3) and then the new MCSST equations derived from our data set are presented and discussed (Section 4).

2. Data

The Earth Observing Satellite Center (EOSC) of Tohoku University has been receiving High Resolution Picture Transmission (HRPT) data from NOAA satellites since April 1988. The HRPT of NOAA-11, including data from the AVHRR and other sensors, are received in the daytime of 12–14 Japan Standard Time (JST) and in the nighttime of 1–3 JST. The AVHRR data of NOAA-11 during November 1988 through December 1989 were used in the present study.

The AVHRR on board NOAA-11 has three infrared channels which provide brightness temperatures of the earth surface and clouds. Their band widths are: channel 3 (ch. 3), 3.55–3.93 μm; ch. 4, 10.30–11.30 μm; and ch. 5, 11.50–12.50 μm.

In order to compare the satellite-derived SSTs with SSTs from in-situ measurements, it is necessary to make a data set which consists of pairs of SST values obtained by both methods at the same time and location. For satellite infrared SST observations, the area measured must be cloud free. As the sea-truth data, we have used water temperatures measured at 1 m depth by ocean data buoys. Four ocean data buoys were operated by the Japan Meteorological Agency (JMA) during November 1988 through December 1989, though there were some data gaps due to buoy maintenance. The locations of the ocean data buoys are shown in Fig. 1. The operation periods for each buoy are listed in Table 2. The JMA buoys measure eleven physical parameters related to air-sea interaction, including SST, every three hours.

![Fig. 1. The locations of the ocean data buoys and JMA observatories (Akita, Wajima and Yonago). The latitudes and longitudes of the ocean data buoys are: No. 21001, 36°40'N, 145°40'E; No. 21002, 37°55'N, 134°32'E; No. 21004, 29°00'N, 135°00'E; and No. 22001, 28°10'N, 126°20'E.](image)
Table 2. The distribution of the data for each buoy in Fig. 1 and the buoy's operation period. The number of nighttime data is shown in parentheses. Asterisk denotes the period of absence of buoy data.

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<td>(51)</td>
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The data set used here is produced as follows:

1. Images with cloud-free area near the buoy locations are selected by surveying quick look images from the AVHRR/NOAA-11.

2. Lines and pixels of the location of each buoy in the selected original AVHRR images are calculated.

3. 5 channels form $127 \times 127$ pixels near the calculated locations are sampled from the original AVHRR data.

Fig. 2. An example of a $127 \times 127$ pixel image. Images from 5 channels are shown for the four buoys and three Ground Control Points (GCPs). Upper four steps show the regions around No. 21001, No. 21002, No. 21004 and No. 22001 ocean data buoys. Lower three show those around GCPs. The GCPs are at Cape Tappi-Misaki, Cape Shiono-Misaki and Cape Bouno-Misaki.
(4) The $127 \times 127$ pixel images are produced for cloud detection and further investigation. Images with any indication of clouds such as anomalous patterns for oceanic structures, faint bright patterns seen in an enhanced visible image, etc. are eliminated as a result of careful examination by eyes.

(5) From the data screened by the cloud detection, the infrared channel data from $7 \times 7$ pixels around the buoy locations are sampled. These channel data from the $7 \times 7$ pixels are averaged and the result is substituted for $T_i$ in Eqs. (1)–(3).

(6) Two sea-truth SSTs, before and after the satellite observation, are sampled from the time series of buoy SSTs and are interpolated in time to obtain the sea-truth for each satellite observation.

The average of $7 \times 7$ pixels is taken in step (5) since the geometric correction used here is accurate to within 3 pixels. Figure 2 shows an example of images of the sampled data created in step (4). When step (3) is carried out, $127 \times 127$ pixels of data around three Ground Control Points (GCPs) are also sampled to check the accuracy of the geometric correction. Images around GCPs are also shown in Fig. 2.

It is found that the standard deviation of $7 \times 7$ pixel areas without clouds is smaller than $0.25^\circ C$ in most cases. However, a few cloud-free data have standard deviations larger than $0.25^\circ C$ because they are located in strong temperature gradient regions. Such data are eliminated.

For each buoy, the distribution of combined data for each month is shown in Table 2. The total number of data is 122. More data are found in the summer season since some buoys were not operated in winter (see Table 2) and cloud-free situations occur more frequently during summer.

3. Results and Discussions

Figure 3 shows the result of comparison between the brightness temperatures of ch. 4 and sea-truth SSTs. The sea-truth SSTs are always higher than the brightness temperatures due to atmospheric attenuation of the infrared radiation from the ocean surface. The higher the sea-truth SSTs are, the greater the difference between the temperatures is. The maximum difference is

![Fig. 3. The relationship between brightness temperature (AVHRR ch. 4) and sea-truth SST observed by ocean data buoys. The circles are daytime observations, and the squares are nighttime observations.](image-url)
about 10°C at around 27°C buoy SST. SSTs estimated by the MCSST algorithm of NOAA shown in Table 1(a) are compared with the sea-truth SST (Fig. 4). In contrast to Fig. 3, Fig. 4 shows that the satellite-derived SSTs agree well with the sea-truth SSTs. Relative to the sea-truth SSTs, the MCSST-derived temperatures have a bias (MCSST minus sea-truth) of −0.13°C, an rms error of 0.58°C and a cross-correlation of 0.995.

Table 3 indicates the rms errors and biases for each of the ocean data buoys. The rms errors range from 0.41 to 0.71°C and the biases from −0.40 to 0.13°C. The largest bias and rms error appear for buoy No. 21001 east of Honshu and the best agreement for the buoy No. 21004 south of Honshu. Only the bias of buoy No. 21002 in the Japan Sea is positive. Figure 5 shows the time series of the difference between the satellite-derived SST and sea-truth SST for each buoy. It is evident for buoy No. 21002 that anomalies in July and August deviate toward positive and some exceed 1°C. These points cause the positive bias.

In order to investigate the deviating points further, differences between the brightness temperatures of ch. 4 and ch. 5 (\(T_4-T_5\)) are plotted against the sea-truth SSTs in Fig. 6(a). The relationship between \(T_4-T_5\) and the differences between the MCSSTs and buoy SSTs is shown in Fig. 6(b). In Fig. 6(a), a cluster of points appears at around \(T_4-T_5 = 2°C\) and buoy SST = 25°C. A cluster of points is also seen in Fig. 6(b) at around \(T_4-T_5 = 2°C\). The clusters seen in both figures

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**Fig. 4.** The relationship between satellite SST from the MCSST algorithm published by NOAA and buoy SST. The circles are daytime observations, and the squares are nighttime observations.

**Table 3.** The rms errors and biases of the satellite SSTs derived from the NOAA/NESDIS MCSST equation (Table 1(a)) relative to the sea-truth SSTs for each buoy.

<table>
<thead>
<tr>
<th>Buoy No.</th>
<th>Number of data</th>
<th>Results (°C)</th>
<th>rms error</th>
<th>bias</th>
</tr>
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<tr>
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<td>33</td>
<td></td>
<td>0.71</td>
<td>−0.40</td>
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<td>21002</td>
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<td>0.60</td>
<td>0.13</td>
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<td>21004</td>
<td>34</td>
<td></td>
<td>0.41</td>
<td>−0.13</td>
</tr>
<tr>
<td>22001</td>
<td>11</td>
<td></td>
<td>0.50</td>
<td>−0.34</td>
</tr>
</tbody>
</table>
are composed of the same data points. The cluster corresponds to the deviated points of July and August from buoy No. 21002 in Fig. 5. According to Fig. 6, the cluster is characterized by a value of $T_4 - T_5$ larger than that of the rest of the data and a large in-situ temperature (~25°C). The value of $T_4 - T_5$ is related to the atmospheric attenuation of infrared radiation from the sea surface mainly due to water vapor. Figure 7 shows the relationship between precipitable water vapor and $T_4 - T_5$ for all the data from buoy No. 21002 in the Japan Sea. The precipitable water vapor is obtained as an average of three radio sonde observations by the JMA observatories at Akita, Wajima and Yonago on the Japan Sea coast (Fig. 1). The data from the clusters in Fig. 6 are shown by black circles and a black square. The solid line shows the results of a model calculation using LOWTRAN 5 computer code (Takashima and Takayama, 1986) and the symbols “T” and “M” are the observational results of Barton et al. (1989). The solid line was drawn on the basis of calculations for various model atmospheres. The observations of Barton et al. (1989) were obtained off the southeast coast of Australia and the Coral Sea. It is obvious on the whole that as precipitable water vapor increases, the value of $T_4 - T_5$ also increases, which is the principle of the atmospheric correction of the MCSST algorithm. The black points, having large values of precipitable water vapor, group together again in Fig. 7 since they have values of $T_4 - T_5$ higher than those of the white points with larger values of precipitable water vapor. Therefore, this

![Figure 5](image_url)

Fig. 5. The time series of the difference between the NOAA MCSST values and sea-truth SSTs for each of the buoys. The black circles are daytime observations, and the black squares are nighttime observations.
Fig. 6. (a) The difference between ch. 4 and ch. 5 temperatures ($T_4 - T_5$) versus buoy SSTs. (b) $T_4 - T_5$ versus the difference between MCSST and buoy SSTs. The circles are daytime observations, and the squares are nighttime observations. Black circles and a black square indicate the cluster.

Fig. 7. The relationship between precipitable water vapor and $T_4 - T_5$ for the data of buoy No. 21002. The circles are daytime observations, and the squares are nighttime observations. The black circles and squares are the data points from the clusters in Fig. 6. The solid line is the result of an atmospheric model calculation by Takashima and Takayama (1986). The “T” and “M” symbols are the observational results of Barton et al. (1989). The “M”s are mid-latitude data by collected off the southeast coast of Australia with NOAA-7 and the “T”s are tropical data collected in the Coral Sea by NOAA-9.
cluster might be related to a high value of water vapor in the Japan Sea in summer i.e., a regional effect. However, it is still not clear why there is such a large disagreement between the MCSST and the sea-truth SST in an area with high atmospheric water vapor. The CPSST algorithm, which is expected to reduce atmospheric water vapor effects more effectively, causes the same positive bias for the Japan Sea data as the MCSST algorithm. To understand the mechanism of estimated SST deviation from sea-truth SST, further investigation is needed.

The CPSST algorithm is compared with the MCSST algorithm. For the present data set, it is found that the CPSST values are approximately equal to the MCSST values. The CPSST anomalies relative to the sea-truth SSTs are: bias $-0.07\,^\circ C$, rms error $0.55\,^\circ C$ and cross-correlation 0.995. This is similar to the result of Walton (1988), which means the brightness temperatures used here are rather noise free. The $\gamma$ parameter of the CPSST algorithm depends on the temperature (see Eqs. (2) and (3)). Figure 8 shows the relationship between $\gamma$ and the difference, $T_4 - T_5$. $\gamma$ is approximately constant for differences ranging from 0.3 to $3.0\,^\circ C$. According to Eqs. (1)–(3), when $\gamma$ is constant, the CPSST algorithm is equivalent to the MCSST algorithm. In Fig. 8, it is seen that $\gamma$ parameter changes considerably in the region of $T_4 - T_5 < 1\,^\circ C$. This may suggest that the CPSST is different from the MCSST when the temperature is lower than that of the present data set.

4. New MCSST Algorithms

By using all of the sampled data, the MCSST equations are rederived by the method of least-squares, with the results shown in Table 1(c). The bias is zero and the rms error is $0.49\,^\circ C$ (Table 4). As described in the previous section, some data points deviate toward positive for buoy No. 21002 in July and August in the Japan Sea. After eliminating these points, the MCSST equations are derived and shown in Table 1(d). The bias is zero and the rms error is $0.43\,^\circ C$.

Histograms in Fig. 9 show the frequency distribution of SST estimation errors. The case of NOAA MCSST algorithm is shown in Fig. 9(a) and that of Eqs. (d) in Table 1 in Fig. 9(b). The number of data in Fig. 9 is 112 because of eliminating the cluster of the Japan Sea. For this data set, rms error of NOAA MCSST algorithm is $0.55\,^\circ C$ and bias $-0.23\,^\circ C$. According to Fig. 9(a),
Fig. 9. Histograms of SST estimation errors. (a) The case of NOAA MCSST algorithms. (b) The case of Eqs. (d) in Table 1. Classes ranging from −0.45 to 0.45°C are shading.

A class from −0.45 to −0.15°C has highest frequency. This causes the negative bias. The rate of data whose errors are within ±0.45°C is 66%. In the case of Fig. 9(b), the bias is improved and the rate of data whose errors are within ±0.45°C is 72%. Generally speaking, about 60% of data points are within ±σ where σ is the standard deviation, which is close to rms error. Therefore, the rms error can give a standard in a statistical sense to investigate SST variations seen in images.

By using the new MCSST equations derived here, SST variations of about 0.5°C can be detected at oceans around Japan during this study period. However, the present data set has few points where buoy SSTs are lower than 10°C. The usefulness of MCSST and CPSST in such a low temperature range in the ocean near Japan is not clear at present. In order to clarify this problem, we need to collect more pairs of SST data obtained by satellite, buoy and ship.
Table 4. The rms errors and biases of satellite-derived SSTs by the equations listed in Table 1.

<table>
<thead>
<tr>
<th>Equations (Table 1)</th>
<th>Number of data</th>
<th>Results (°C)</th>
<th>rms error</th>
<th>bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>122</td>
<td></td>
<td>0.58</td>
<td>-0.13</td>
</tr>
<tr>
<td>(b)</td>
<td>122</td>
<td></td>
<td>0.55</td>
<td>-0.07</td>
</tr>
<tr>
<td>(c)</td>
<td>122</td>
<td></td>
<td>0.49</td>
<td>-0.00</td>
</tr>
<tr>
<td>(d)</td>
<td>112</td>
<td></td>
<td>0.43</td>
<td>-0.00</td>
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</table>

measurements in various situations of sea, atmosphere and satellite sensors.

5. Summary

In order to examine the accuracy of satellite-derived SSTs, we made a data set from the AVHRR on NOAA-11 and ocean data buoys in the seas near Japan during November 1988 through December 1989. When we use the coefficients published by NOAA, the MCSST and CPSST algorithms result in biases of about -0.1°C and rms errors of about 0.6°C for our data set. The MCSST equations are newly derived using the data set, and the rms error is 0.49°C. Some MCSST and CPSST values are higher than sea-truth SSTs in the Japan Sea in summer. When we eliminate these points and determine the MCSST coefficients again, the rms error is 0.43°C.

Large scale oceanographic experiments such as TOGA require high accurate SST estimate, especially in the tropical oceans (~0.3°C). For further Earth Observing System, NASA (1984) reported the required accuracy of SST measurement for mass and energy fluxes as 0.5°C. The present study suggests that this requirement could be satisfied if the study area is limited and satellite data are treated carefully with in-situ measurements.

Acknowledgements

We wish to thank the Oceanographical Division of the Marine Department and the Meteorological Research Institute of the Japan Meteorological Agency for providing us with the data from the Ocean Data Buoys. This study is supported by a Grant-in-Aid for Scientific Research 01646010 from the Ministry of Education, Science and Culture, Japan, and is also supported as part of the cooperative research work between Tohoku University and the Tohoku Electric Company. We would like to extend our gratitude to Mr. S. Kizu and Miss M. Toyoshima for their assistance making Fig. 7.

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