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Measuring Sea Surface Temperature from Satellites: A Ground Truth Approach

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Determining the correction for atmospheric attenuation is a major problem in processing thermal infrared digital data from very high resolution radiometers aboard NOAA Polar Orbiting Satellites. An empirical equation for estimating this correction is developed. The coefficients of the equation are determined by using regression techniques and comparing satellite observations to sea surface temperature measurements. Although there is not sufficient data to fully evaluate this procedure, initial satellite measurements are within 0.5°C of independent sea surface temperature measurements.

Introduction

Over cloud-free oceanic areas, the very high resolution radiometer (VHRR) aboard NOAA-5 and the advanced very high resolution radiometer (AVHRR) aboard TIROS-N, both observing the thermal infrared (10.5–12.5 μm), can provide imagery in which the thermal structure of the sea surface is quite evident. Digital data related to such imagery can be quantitatively processed and thus provide a means for monitoring the ocean environment from space. However, the temperatures derived after applying standard calibration procedures are still only equivalent black-body temperatures which are uncorrected for atmospheric attenuation. The first factor, pertaining to the nonblackness of the radiator, is not critical because in the 10.5–12.5 μm bandpass, the ocean radiates as a black body to a very good approximation. The second factor, correction for atmospheric attenuation, is quite critical and must be accounted for.

Classically, calculations to correct for the effect of atmospheric attenuation on the source signal as it propagates from the ocean surface to the satellite are made by measuring the volume of water vapor in the atmospheric column. The data for such measurements is obtained from radiosondes, which, unfortunately, are not frequently launched over oceanic regions. Other methods to correct for atmospheric attenuation include several semiempirical models (Breaker et al., 1978). But, after applying corrections derived by such models, the satellite measurements can still differ from the true surface temperatures by two or three degrees Celsius.

Correcting for Atmospheric Attenuation

A model to correct for atmospheric attenuation can be developed for use whenever sea-truth (ground-truth) temperatures are available. The derivation starts with a simplified form of the radiative transfer in the atmosphere,

$$B_0 = B_s \exp(-\tau) + B_i[1 - \exp(-\tau)], \quad (1)$$

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where

B_0 = brightness observed by the satellite,
B_s = brightness of the sea surface,
B_i = brightness of the atmosphere,
τ = optical depth of the medium.

Equation (1) defines the atmospheric attenuation over a given path directly below the spacecraft (a path through one atmosphere). For observations to the side of the satellite subtrack, the surface radiation is attenuated over a longer path. The distance of this path is a function of the instrument or nadir angle at the satellite, and the height of the atmosphere. This distance can be computed geometrically following Fig. 1 and is given by

$$a=\left[(h+R)^2-(H+R)^2\sin^2 n\right]^{1/2}-\left[R^2-(H+R)^2\sin^2 n\right]^{1/2} \quad (2)$$

where

a = distance of attenuation path,
n = nadir angle,
H = height of satellite,
h = height of atmosphere,
R = radius of earth.

The height of atmosphere in this case can be assumed to be 100 km. The exact height is not critical, as what is needed is the distance ratio D given by

$$D=a/h \quad (3)$$

Applying the distance ratio to the optical depth, Eq. (1) becomes

$$B_0=B_s\exp(-\tau D)+B_i[1-\exp(-\tau D)]. \quad (4)$$

The atmospheric component (B_i) of eq. (4) is relatively small and is considered to be constant over a given area.

The Planck equation, which relates brightness to temperature, is nonlinear at thermal infrared frequencies. However, the error, as a result of linearizing the segment for local sea surface temperatures (10–20°C), is not significant. Thus replacing B by T, Eq. (4) becomes

$$T_0=T_s\exp(-\tau D)+C, \quad (5)$$

where

T_0 = temperature observed by the satellite,
T_s = temperature of the sea surface,
C = constant temperature value.

Solving equation (5) for T_s yields

$$T_s=(T_0-C)\exp(\tau D). \quad (6)$$

The coefficients required to correct for atmospheric attenuation (C and τ) can be computed by correlating the satellite measurements with sea truth using Eq. (6) as a regression equation.

Evaluating the Model

At the Southwest Fisheries Center, a computer program series is available for quantitatively processing satellite data. Each processing run covers a region that is approximately 140 km^2 on the earth's surface. The atmosphere is assumed to be homogeneous over the given region. Typically, only about 15 sea-truth measurements are available for regression analysis to determine the specific coefficients of the atmospheric correction equation. The statistics to this approach, as applied to a region off Monterey Bay

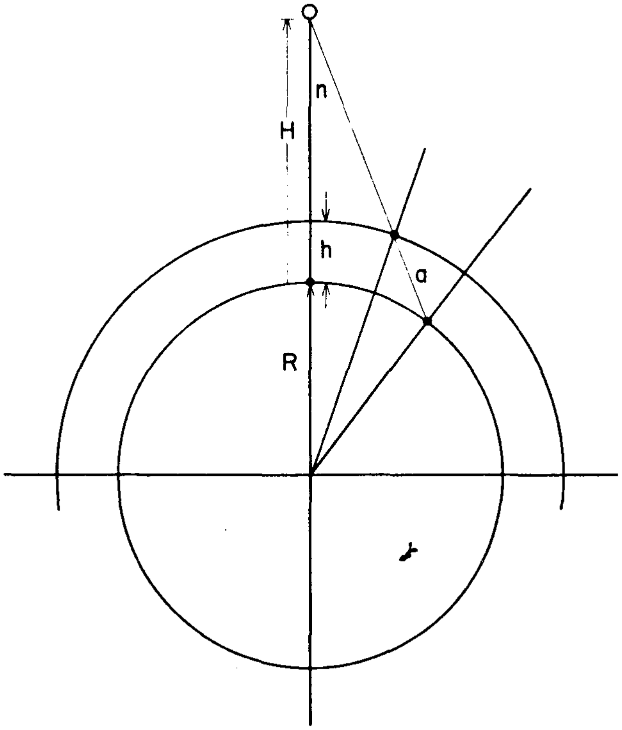

FIGURE 1. Atmospheric attenuation path.

taken from NOAA-5 orbit 8145, are listed in Table 1 where,

R = the coefficient of correlation between sea truth and satellite measurements,
$\bar{\Delta}$ = mean difference between sea truth and satellite measurements,
S_Δ = standard deviation of the difference,
N = number of surface measurements.

The statistics in the column labeled "uncorrected" describe the relationship between sea truth and satellite measurements which were not corrected for atmospheric attentuation. The statistics in the column labeled "Corrected" describe a similar relationship, but where the satellite measurements have been corrected for atmospheric attenuation using Eq. (6).

The statistics in Table 1 show the degree to which the data fits the equation used to correct for atmospheric attenuation. To fairly evaluate the use of such an equation, an independent source of data is needed. For the region involved, there were two independent sources of data available (see Table 2). During an unrelated survey conducted by NASA, two surface temperature measurements coinciding with the time of the satellite pass were taken. The measurements only differed from the corrected satellite values by 0.0 and 0.5°C, respectively. Another measurement, obtained from a drifter drogue deployed by the Scripps Institute of Oceanography, differed from the satellite measurement by only 0.4°C.

It is unfortunate that more data is not readily available to evaluate this approach. However, the results presented should indicate that suitable corrections

TABLE 1 Statistics Related to Satellite-Measured Sea Surface Temperature for NOAA-5 Orbit 8145

	Uncorrected	Corrected
R	0.84	0.93
$\bar{\Delta}$	0.06	0.01
S_{Δ}	0.80	0.46
N	14	14

TABLE 2 Independent Data Sources

Corrected Satellite	NASA	Δ
11.1	11.1	0.0
10.3	10.8	0.5

Corrected Satellite	SIO Drogue	Δ
13.7	14.1	0.4

for atmospheric attenuation over a given region can be determined by applying regression techniques. The procedure offers a means for using satellite measurements to extrapolate beyond a ship's single point observation of sea surface temperature.

References

Breaker, L., Klein, J., and Pitts, M. (1978), Quantitative measurements of sea surface temperature at several locations using the NOAA-3 Very High Resolution Radiometer. NOAA Tech. Memorandum NESS 98, U.S. Dept. Commerce, NOAA, NESS.

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