ENVIRONMENTAL ERRORS IN USE OF THE AIRBORNE INFRARED RADIATION THERMOMETER TO MEASURE SEA-SURFACE TEMPERATURE

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Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE

United States Naval Postgraduate School
Monterey, California

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ABSTRACT

An airborne infrared radiation thermometer (IRT) used to measure the sea-surface temperature is described, and the basic radiation principles on which the operation of the instrument depends are discussed. The environmental factors which may tend to introduce errors into the measurement of sea-surface temperature by the IRT are investigated: first by reviewing the works of some other authors; secondly by empirical means using field data supplied by the U.S. Naval Oceanographic Office and the Sandy Hook Marine Laboratory. The empirical results indicate that absorption and emission of infrared energy by atmospheric water vapor are the important physical phenomena which cause IRT error. The results suggest that with increasing values of the combination of sea level mixing ratio and air temperature, IRT error decreases. An attempt is made to explain these results on the basis of radiation principles previously described.

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1. Introduction.

One of the major problems facing those involved in the United States Navy's Antisubmarine Warfare Environmental Prediction System (ASWEPS) is the prediction of the thermal structure of the ocean. For any method of prediction of ocean thermal structure, a knowledge of the temperature field of the ocean surface is a necessity. Sea-surface temperature observations obtained from naval and commercial ships are not dense enough to permit detailed synoptic analysis of the sea-surface temperature field; thus the investigation of relationships between sea-surface temperature and the underlying vertical temperature structures, even when data are available, is difficult. However, the United States Naval Oceanographic Office has developed a generalized relationship between the sea-surface temperature distribution and the mixed-layer depth, a feature of the ocean thermal structure. [1] .

Use of an infrared thermometer seems to offer a tremendous step forward in the technique of collecting sea-surface temperature data. There are many advantages over previous conventional methods in obtaining sea-surface temperature data with a passive noncontact instrument, installed in a fast and far-ranging aircraft. Among these advantages are speed of data collection; low cost in terms of dollars and man-hours expended; efficiency of data gathering, especially when the instrument is carried in conjunction with other data-collecting instruments; and standardization of sea-surface temperature measurement techniques.

The method of obtaining sea-surface temperature data with an airborne infrared thermometer (IRT) was pioneered by the Woods Hole Oceanographic Institution. [2] . The Canadian Pacific Oceanographic Group, at Nanaimo, British Columbia, later used the Woods Hole instrument for feasibility

studies. [3] . From this early work evolved the use of the more reliable and sophisticated instruments of today to obtain sea-surface temperature data. One such instrument is produced by the Instrument Division of the Barnes Engineering Company, of Stamford, Connecticut. A similar instrument has been developed by the Fisheries Research Board of Canada.

To understand the basic principles on which these instruments depend, it will be necessary to discuss some of the basic characteristics of infrared radiation. Afterwards, the environmental limitations will be considered which enter into the use of infrared radiometers for measuring ocean-surface temperature.

2. Infrared radiation.

Infrared radiation is an electromagnetic radiation generated by vibration and rotation of the atoms and molecules within any material whose temperature is above absolute zero (-273C). Generally, the infrared spectrum is considered to lie between the wave length of .72 and approximately 1000 microns. [4].

At certain wave lengths in the infrared spectrum the ocean surface tends to act like a black body, in that it almost completely absorbs all radiation incident upon it. The radiation emitted by a black body is the maximum possible for a given temperature. The radiating and absorbing efficiency of a black body, called its emissivity, is unity. The emissivity of the ocean surface is 0.98 in the region of the infrared spectrum from 4 to 13 microns. [5].

Infrared radiation traveling through the earth's atmosphere, from any source, is subject to various degrees of absorption and scattering by many constituents of the atmosphere; these depletions depend, among other things, upon the wave length of the radiation considered. [6]. In the region from 8 to 13 microns the atmosphere is essentially transparent to infrared radiation. [7]. Thus, between 8 and 13 microns the ocean surface is nonreflective, since it approximates a black body with its associated complete absorption; and there is relatively little atmospheric attenuation of infrared energy emitted from the ocean surface in this wave length.

The emission of infrared energy from the ocean surface follows the Stefan-Boltzmann law:

$$W = \varepsilon \sigma T^4 \qquad (1)$$

where

W = total radiant flux emitted per unit surface area

ε = emissivity factor

σ = Stefan-Boltzmann constant (5.6×10^{-12} watts cm^{-2} $degrees^{-4}$)

T = absolute temperature at the radiating surface.

The temperature of the ocean surface usually ranges from a minimum of -2C (271K) to a maximum of 35C (308K); assuming the emissivity factor to be a constant 0.98, the total radiant flux from the ocean surface varies from 0.0304 to 0.0500 watts/cm^2. [5] .

The wave length distribution of radiant flux follows Planck's equation:

$$W_\lambda = C_1 \lambda^{-5} \left(e^{C_2/\lambda T} - 1\right)^{-1} \qquad (2)$$

where

W_λ = radiation emitted by a black body, per unit surface area per wave length increment

λ = wave length of the radiation

T = absolute temperature

C_1 and C_2 = constants

Integration of Planck's equation from 8 to 13 microns shows that 29% of ocean surface emitted radiation falls within this region at -2C, and 33% at 35C. Therefore, the radiant flux available for measurement in this

wave length region between these temperatures ranges from .29 x (0.0304) = 8.8 x 10^{-3} to .33 x (0.0500) = 16.5 x 10^{-3} watts/cm^2. [5] .

Furthermore, the change in radiant flux corresponding to a change of 0.2C at a temperature of -2C (the least favorable temperature) can be found by differentiating the Stefan-Boltzmann law:

$$\Delta W = 4 \varepsilon \sigma T^3 \Delta T \qquad (3)$$

$$= 4 x (0.98) x (5.6 x 10^{-12}) x (271)^3 x (0.2)$$

$$= 8.5 \times 10^{-5} \text{ watts/cm}^2$$

The radiant flux available for measurement and the incremental change computed are well within the detecting range of available thermal detectors. [5] .

3. A brief description of the infrared radiation thermometer (IRT).

The infrared radiation thermometer consists of three basic parts: a radiometer optical head, an electronic processing system, and an indicating-recording system. With the use of appropriate optical filtering materials, the radiometer optical head collects and focuses radiation energy between 8 and 13 microns from the ocean surface onto a thermistor bolometer, a thermal-type detector with a very fast response time. A chopper blade and mask, each consisting of two opposed 90-degree sectors are placed at the front end of the optical head. As the chopper blade rotates, it either completely blocks incoming radiation by closing the 90-degree sector openings in the mask, or allows incoming radiation to fall on the detector when the chopper blade sectors are aligned with the mask sectors. A black body reference source is contained internally within the optical head. The temperature of the source is precisely controlled. The inside of the chopper assembly is highly reflective in the infrared. Therefore, as the chopper rotates, the thermistor bolometer alternately "sees" ocean-surface radiation and the reference source energy emitted from the stabilized black body. An electrical signal that is proportional to the difference between these two radiation energies is generated and then processed by electronic circuits to produce, either by meter or recorder, an indication of the ocean-surface temperature. [8].

4. The problem of infrared radiation thermometer error.

The degree of accuracy of sea-surface temperature measurements necessary to enable ASWEPS analysts to produce meaningful ocean thermal structures forecasts, to the best of this author's knowledge, has not been determined. As with the measurement of other environmental parameters, however, the most accurate values possible are always desired, within the limitations of equipment cost and ease of operation. In field use at the present time the IRT is subject to variable errors.[1] IRT error is the difference between the sea-surface temperature determined by conventional methods, say by a ship, and the sea-surface temperature as measured by an airborne IRT. From limited data available to the author, this error may be as large as 6F.

IRT error may be a function of distance from instrument to the sea-surface, air-sea temperature difference, air moisture content, or a relationship between distance, temperature, and moisture content of the air, which may be either simple or complex. Errors associated with *in situ* measurement of sea-surface temperature, such as described by the micro-surface theory in the next section, also contribute indirectly to the IRT error as discussed here.

[1]Laboratory accuracy of the instrument is about ±0.2C. [8]. The Barnes Engineering Company advertises an absolute accuracy of ±1.0C. [9] .

5. Theories relating to factors causing IRT error.

Most users of the airborne IRT for sea-surface temperature measurements acknowledge that no single factor will account for all of the IRT error for a given set of conditions. However, most do tend to support one of two theories concerning the mechanisms by which the errors may be introduced.

a. Micro-surface theory.

The first of these theories will be called the micro-surface theory. L. A. Walford, Director of the Sandy Hook Marine Laboratory, writes,

> ...heating or cooling of the sea takes place initially at the micro-surface and subsequently affects the sub-surface by downward mixing caused by waves, currents, or tides. The amount of difference (between IRT and bucket temperatures) will depend upon the amount of heating or cooling and the amount of mixing at the micro-surface. The difference will be high if the air is much colder or warmer than the sea and if the sea is calm. Conversely, the difference will be slight if air and sea are nearly the same temperature or, (sic) if there is much mixing from wave action. The amount of solar radiation on the sea surface and the amount of evaporation also are important. [8].

b. Observations relating to the micro-surface theory.

Clark and Frank also support this theory as a contributing factor to IRT error, but they suggest as well other possible effects mentioned later in this paper. [5].

McAlister and Ewing have found that for wind-swept bodies of water, surface temperatures determined by conventional methods are higher than the surface radiation temperatures, due to a cool micro-surface layer of water. For their tests the maximum magnitude of this difference was 0.6C. [11]. From the very limited amount of field data available to this author, it is interesting to note that by far the greatest number of observations showed IRT readings less than bucket temperature readings, which thus may tend to support this theory.

c. Atmospheric interference theory.

The second theory to explain IRT errors will be called the atmospheric interference theory. Atmospheric interference will include the effects of selective absorption of infrared energy by constituents of the earth's atmosphere and the effects of radiation of infrared energy by these same constituents.

The region 8 to 13 microns is contained in one of the infrared atmospheric windows, a term used to describe regions of the energy spectrum in which there is relatively good transmission of radiation energy through the atmosphere. Through an atmospheric window the appropriate infrared energy is subject to, on the average, considerably less atmospheric attenuation than are the wave lengths of energy outside a window. However, even within a window absorption of infrared energy by the atmosphere does take place. [7].

In the region between 8 and 13 microns the amount of absorption of infrared energy by the lower troposphere is a function primarily of the water vapor content of that atmospheric region; the amount of emission of infrared energy is primarily a function of the temperature of the source, which in this case is the water vapor. Haltiner and Martin cite evidence that in the infrared spectrum, at elevations below about 50 km, absorption and emission of infrared energy by atmospheric constituents are processes essentially independent of each other. [12].

Most persons involved with the use of the airborne IRT to measure sea-surface temperatures consider that the atmospheric interference theory explains the largest portion of the IRT error.

d. Observations relating to the atmospheric interference theory.

Richardson and Wilkins found IRT error to be almost directly proportional to height of the instrument during one set of tests. [13] . However, the instrument they used had a wider band pass of infrared energy than instruments in use today, and hence it was more subject to atmospheric interference. Since the moisture distribution with height was not given, no general conclusions can be inferred from this height-error relationship.

Tully, et al., using the same instrument as used by Richardson and Wilkins, noted an IRT error proportional to height. [3].

Malkus, while using an airborne IRT to measure sea-surface temperatures during a study of the mechanisms of origin of trade cumulus cloud groups, noted a small source of error in the IRT readings which she attributed to water vapor in the air column between the instrument and the sea-surface. Without resorting to calculations, she proposed that large humidity gradients in the air column between instrument and sea surface (greater than five times the maximum gradient observed) would be required to make the error larger than a few hundreths of a degree (C). [14].

Clark and Frank consider the effects of atmospheric interference. With actual airborne IRT recorder traces they show the effects of increasing the angle of view of the IRT so that the instrument "looks" through a longer column of air to the sea surface. The traces clearly indicate the increased atmospheric attenuation. No attempt is made to give quantitative results. [5].

Weiss, from the Barnes Engineering Company stated,

> It is possible to account for this effect (atmospheric attenuation) and correct the temperature measurement by introducing a quantity known as "optical thickness" which is dependent on specific humidity, pressure, and layer structure of the atmosphere. [8].

The present author believes that this is an oversimplification of the total problem, for while optical thickness is directly related to atmospheric attenuation of infrared energy, the effects of atmospheric emission have been neglected. Frank, from the same Company, in recent personal communication has informed this author that he has no information on the effect of such a factor as relative humidity on the accuracy of IRT readings.

6. An empirical approach to relating IRT error to environmental factors.

In an effort to study the actual effects of environmental factors on the IRT error (the difference between sea-surface temperature as measured by a surface ship and the same sea-surface temperature measured by an IRT), two sets of data were used.

The Sandy Hook Marine Laboratory, of Highlands, New Jersey, provided the author with copies of monthly charts, "Middle Atlantic Area Surface Isotherms-°F from Infra-Red (sic) Radiation Thermometer Flight Plan..." for the months of April through December, 1963, and January and February, 1964. These data charts cover an area off of the coasts of Long Island and New Jersey between approximately 38N - 41N and 71W - 74W. Sea-surface isotherms are drawn on the charts in whole degrees Fahrenheit, as determined by an IRT installed in an aircraft flying at altitudes varying from 200 to 500 feet and flying legs 20 to 30 miles apart across the area. Usually two days were required to cover the area. A conversion factor (IRT error) is printed at the bottom of each chart. The conversion factor has been determined by comparing sea-surface temperature data obtained simultaneously by the IRT and at a number of check points (principally U. S. Light Ships). The conversion factor is a general approximation and is an average for a large area. The charts were annotated with some general weather information for each day an IRT survey was made. Although there were no surface ship weather reports annotated on the Sandy Hook charts, these data were obtained from the U.S. Naval Oceanographic Office.

The second set of data was supplied to the author by the U.S. Naval Oceanographic Office. It consisted of seven charts obtained in September and October of 1962 in the Gulf Stream area from approximately 33.5N to

35N and 74.5W to 76W. The charts were annotated with lines of sea-surface temperature (one value approximately every three miles), as determined by an IRT installed in an aircraft flying at 1500 feet and crossing the area on legs about 18 miles apart. The charts contained some surface ship weather reports. Other ship weather reports for this area at the appropriate times were obtained from the Meteorology Library at the U.S. Naval Postgraduate School.

The Gulf Stream area data were investigated first, since they were the most complete. They contained unsmoothed IRT and nearly simultaneous sea-surface temperature reports along with values of other environmental parameters from surface-ship weather reports.

The foregoing discussion on theories relating to factors causing IRT error served as a background to select the sea-level parameters for study, which are: mixing ratio, expressed as grams of water vapor per kilogram of dry air; air temperature, in degrees Fahrenheit; and air-sea temperature difference, in degrees Fahrenheit. A possible serious limitation to the investigation was complete lack of information regarding the vertical gradients of the parameter values from the sea surface to IRT altitude.

The first assumption made was that a single air mass overlay the area in question during the period of the IRT survey (a matter of hours). Secondly, it was assumed that such an air mass could be characterized by single values of mixing ratio and air temperature.

Values of mixing ratio and air temperature, as determined from surface ship weather reports for a given chart, were screened first to eliminate data that were obviously erroneous. Then the remaining values were averaged and in all cases the mean value closely approximated the median value of all the averaged reports. Therefore, both assumptions seemed valid.

IRT error was determined from values along the IRT track which were in close geographical proximity to reported ship positions. The IRT error values for any one chart were averaged and again the mean value closely approximated the median value of all the averaged reports.

A plot of mixing ratio versus IRT error was made for the values obtained from each of the seven charts. A least-square regression line and corresponding correlation coefficient was determined for this scatter diagram, as for all scatter diagrams presented in this paper, by use of the Control Data Corporation 1604 Computer located at the U.S. Naval Postgraduate School. The results are shown as Figure 1. The slope of the regression line, showing decreasing IRT error corresponding to increasing mixing ratio, was totally unexpected.

The author had assumed that increasing atmospheric moisture would be associated with increasing IRT error, due to increased absorption of the infrared energy from the sea surface. The relationship shown in figure 2, however, gives a clue to the physical processes which seem to be dominant. A scatter diagram of mixing ratio versus air temperature makes up the figure; and as might be expected under "normal" conditions over water, an increased air temperature is associated with an increased value of mixing ratio. Thus, it would appear that the increase of infrared energy radiated from the water vapor in the air itself tends to more than compensate for increased absorption of infrared radiation from the ocean surface by the water vapor. Figure 3 is a scatter diagram of air temperature versus IRT error.

In an attempt to consider the effects produced by the micro-surface, if in fact it does contribute to the IRT error, the author plotted air-sea

temperature difference versus IRT error. Again the apparent effect of a relatively warm air temperature on IRT error can be seen in figure 4. The author reached no conclusions regarding the effect of the micro-surface. Whatever the results of the magnitude of its contribution to IRT error, it would appear to be completely overshadowed by the interference of the atmosphere.

An effort was made to include possible results for cases of large air-sea temperature difference with corresponding low air moisture content and conversely, although such cases were not encountered. This was accomplished by combining the previously-determined values of mixing ratio and corresponding air-sea temperature difference for each chart and plotting these values versus IRT error, shown in figure 5.

The combination of sea level air-mass parameters which gives the best clue as to the relative magnitude of IRT error is the sum of air-sea temperature difference and mixing ratio. For a given value of mixing ratio, air-sea temperature difference is inversely related to IRT error; a low (high) value of air-sea temperature difference will give a relatively high (low) value of IRT error. These qualitative results seem to fit the atmospheric interference theory quite well: absorption of infrared energy by atmospheric water vapor and radiation of infrared energy by the water vapor appear to be the important physical processes. However, the author hesitates to assign quantitative values to them, since his work has been based on such a small amount of data.

In an attempt to substantiate the results mentioned above, the author next investigated the Sandy Hook data. The major problem encountered during this work was the fact that the sea-surface temperatures determined

by the IRT were available only as smoothed isotherms drawn on the charts. Individual readings of IRT sea-surface temperature were not available to the author. Therefore, the value of correction factor (IRT error) printed on the charts was used as an overall value for the period of the chart (usually two days). A value of mixing ratio and air-sea temperature difference for each chart was determined from surface-ship weather reports using the averaging techniques previously described. A plot of this IRT error versus the corresponding sum of mixing ratio and air-sea temperature difference showed a relatively large scatter. This scatter diagram is shown as figure 6. Although the data fit a straight line poorly, the Sandy Hook data points were combined with those from the Gulf Stream area (figure 5) in order to extend the range of the mixing ratio plus air-sea temperature difference ordinate (figure 7).

7. Conclusions.

The airborne infrared radiation thermometer is a unique instrument that offers the oceanographer an opportunity to obtain a wealth of sea-surface temperature data quickly and easily. At least two marine laboratories of the U. S. Fish and Wildlife Service, Sandy Hook in New Jersey and Tiburon in California, are now using the instrument on a regular basis to provide monthly charts of off-shore sea-surface temperature patterns.

The accuracy of the instrument is dependent upon two environmental parameters, air moisture content and air-sea temperature difference. The amount of water vapor present in the air will determine how much of the infrared energy emitted from the sea surface is absorbed by the atmosphere and consequently is not available to the sensing head of the instrument. The value of air-sea temperature difference (or air temperature) will give a measure of the spurious infrared energy detected by the instrument due to emission of infrared energy from the atmosphere.

Investigation of field data supplied to the author leads to the conclusion that for an IRT altitude of 1500 feet or less, the error of the IRT will be relatively small for large values of air moisture content plus air-sea temperature difference, and conversely.

A more meaningful study of the effects of environmental factors on the accuracy of an airborne IRT could be accomplished with sea-surface temperature data collected by an IRT installed on a surface ship simultaneously with airborne IRT surface temperature data covering the ship's track. The use of the surface ship IRT would eliminate the anomalies obtained in the sea-surface temperature measurement by the bucket or cooling-water-intake method. Comparison of the two IRT values would then

indicate a very exact value of the error. By measuring the values of vertical gradients of air moisture content and air temperature during the temperature survey, comprehensive study of the effects of environmental factors on the accuracy of an IRT could be made.

The airborne IRT promises to become a most valuable tool for oceanographers in general, and for the ASWEPS program in particular. But, as more dependence is placed upon the instrument for sea-surface temperature data, more attention should be directed toward determing IRT accuracy.

9. Acknowledgements.

The author is indebted to Mr. George L. Hanssen of the U.S. Naval Oceanographic Office for supplying most of the field data used during this investigation. Also, the assistance of Associate Professor G. H. Jung during this investigation is most gratefully acknowledged.

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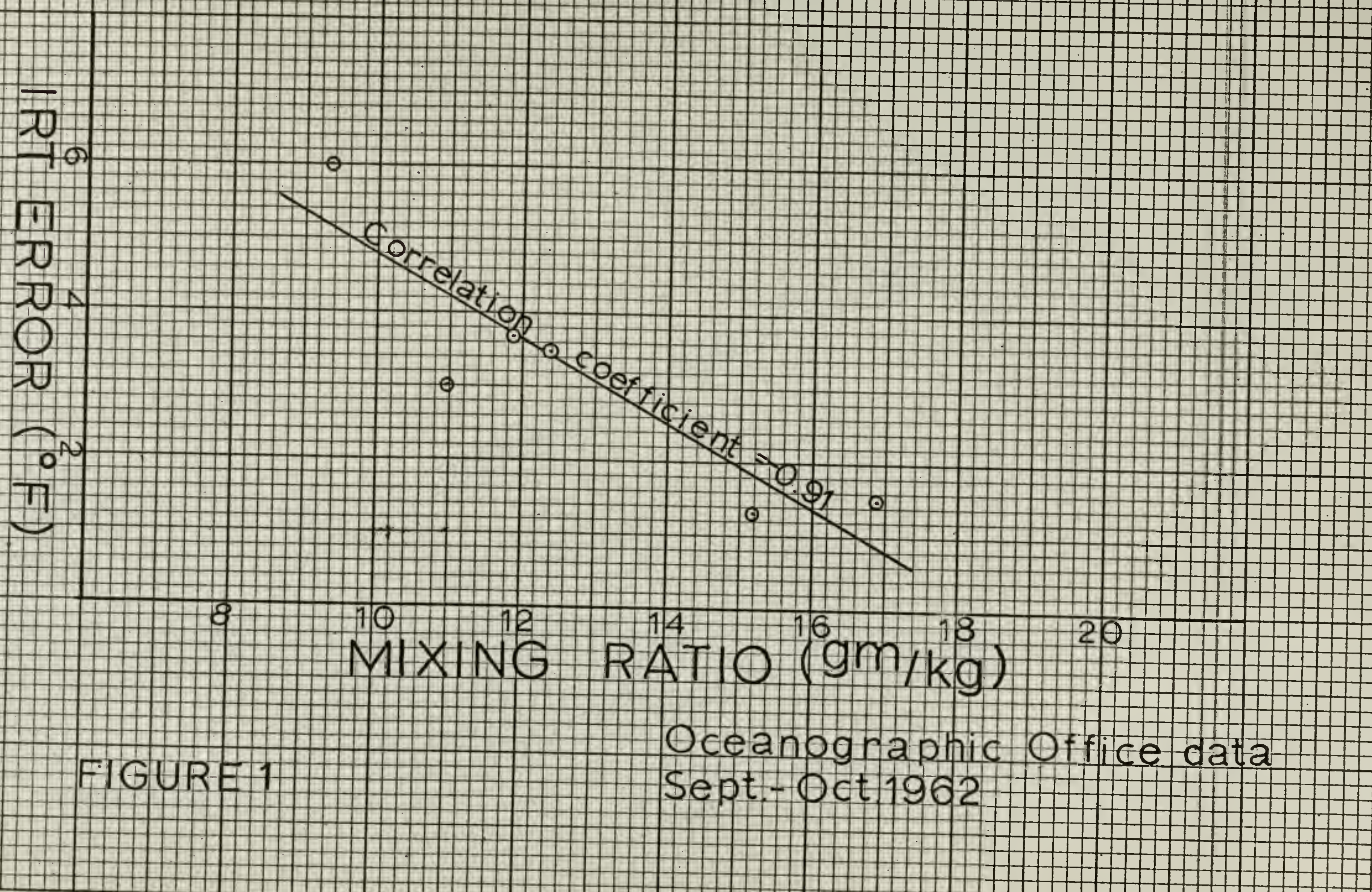
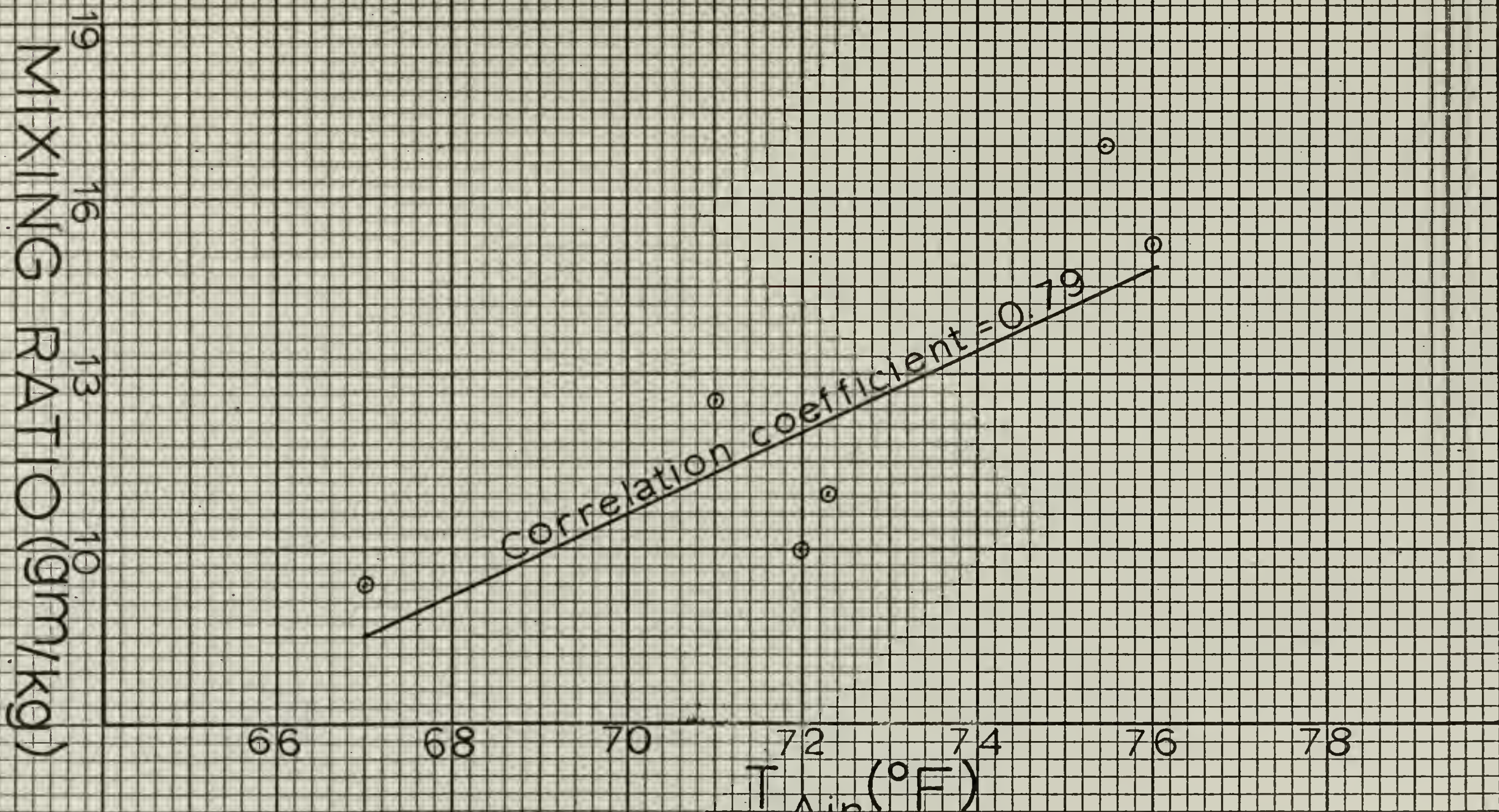


IRT ERROR (°F)
6
4
2
Correlation coefficient = -0.91
8
10
12
14
16
18
20
MIXING RATIO (gm/kg)
Oceanographic Office data
Sept.-Oct.1962

FIGURE 1



Oceanographic Office data
Sept.-Oct. 1962

FIGURE 2

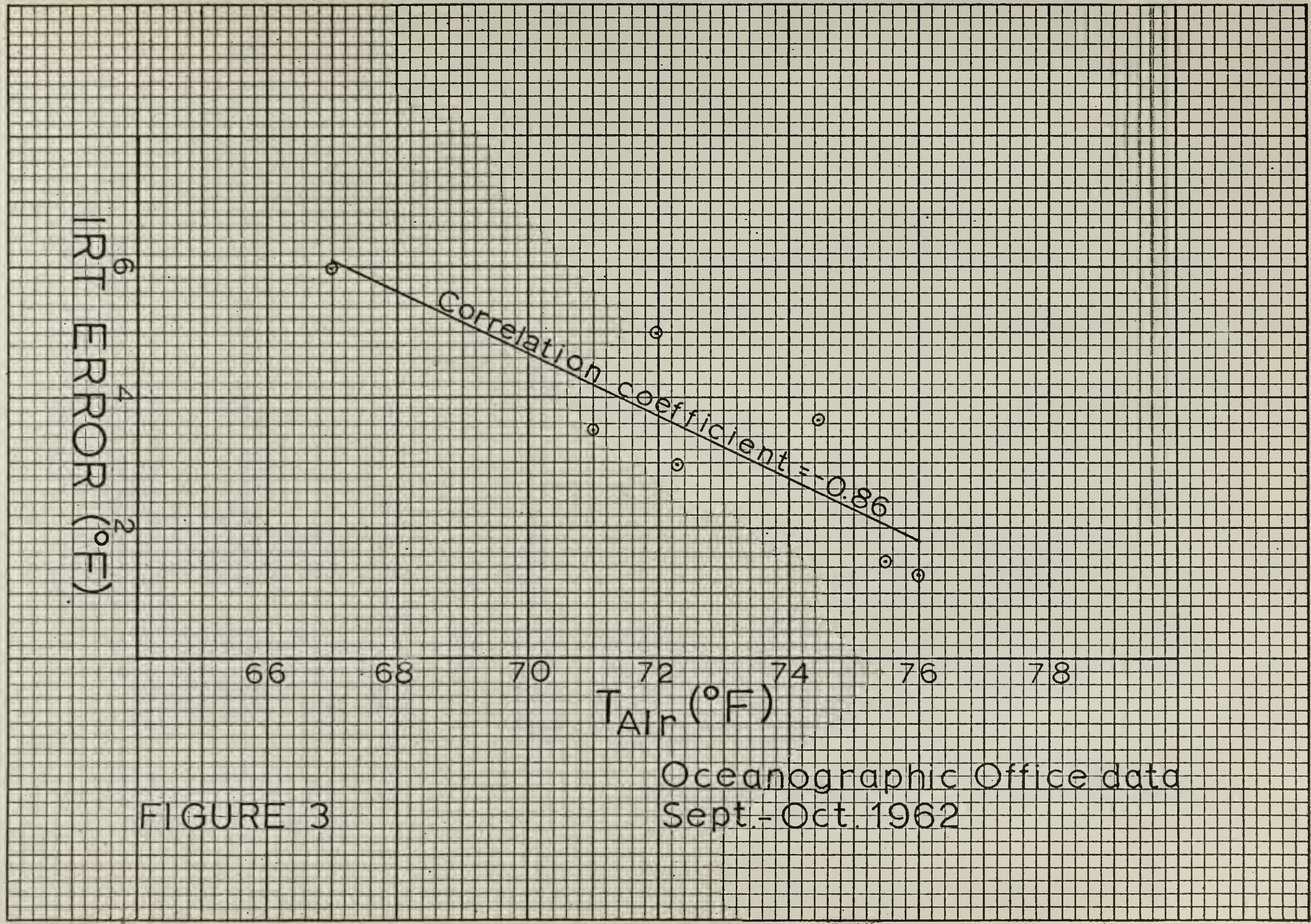

IRT ERROR (°F)
6
4
2
Correlation coefficient = -0.86
66
68
70
72
74
76
78
TAir (°F)
Oceanographic Office data
Sept.-Oct. 1962

FIGURE 3

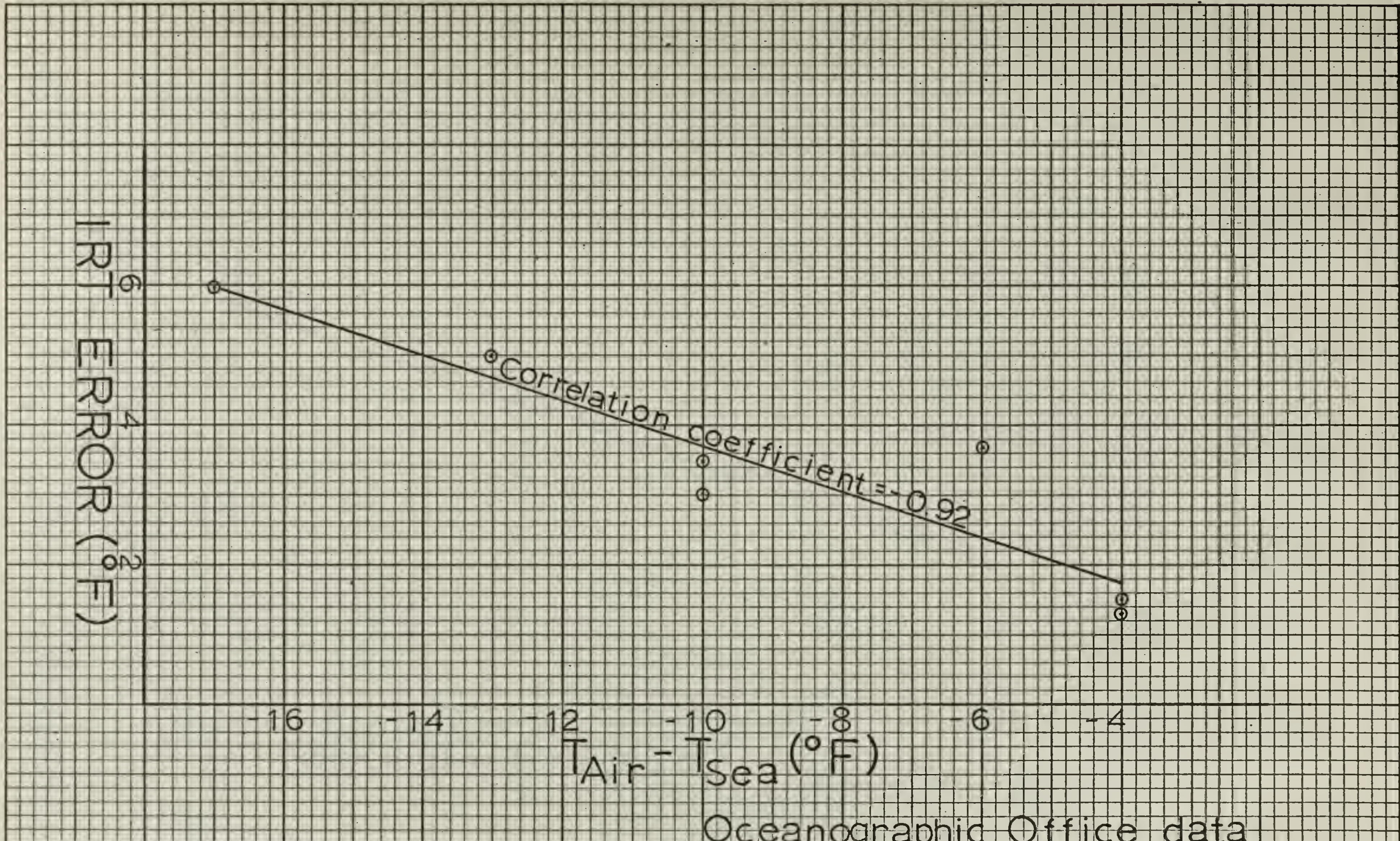

IRT ERROR (°F)
6
4
2
Correlation coefficient = -0.92
-16
-14
-12
-10
-8
-6
-4
$T_{Air} - T_{Sea}$ (°F)
Oceanographic Office data
Sept.-Oct. 1962

FIGURE 4

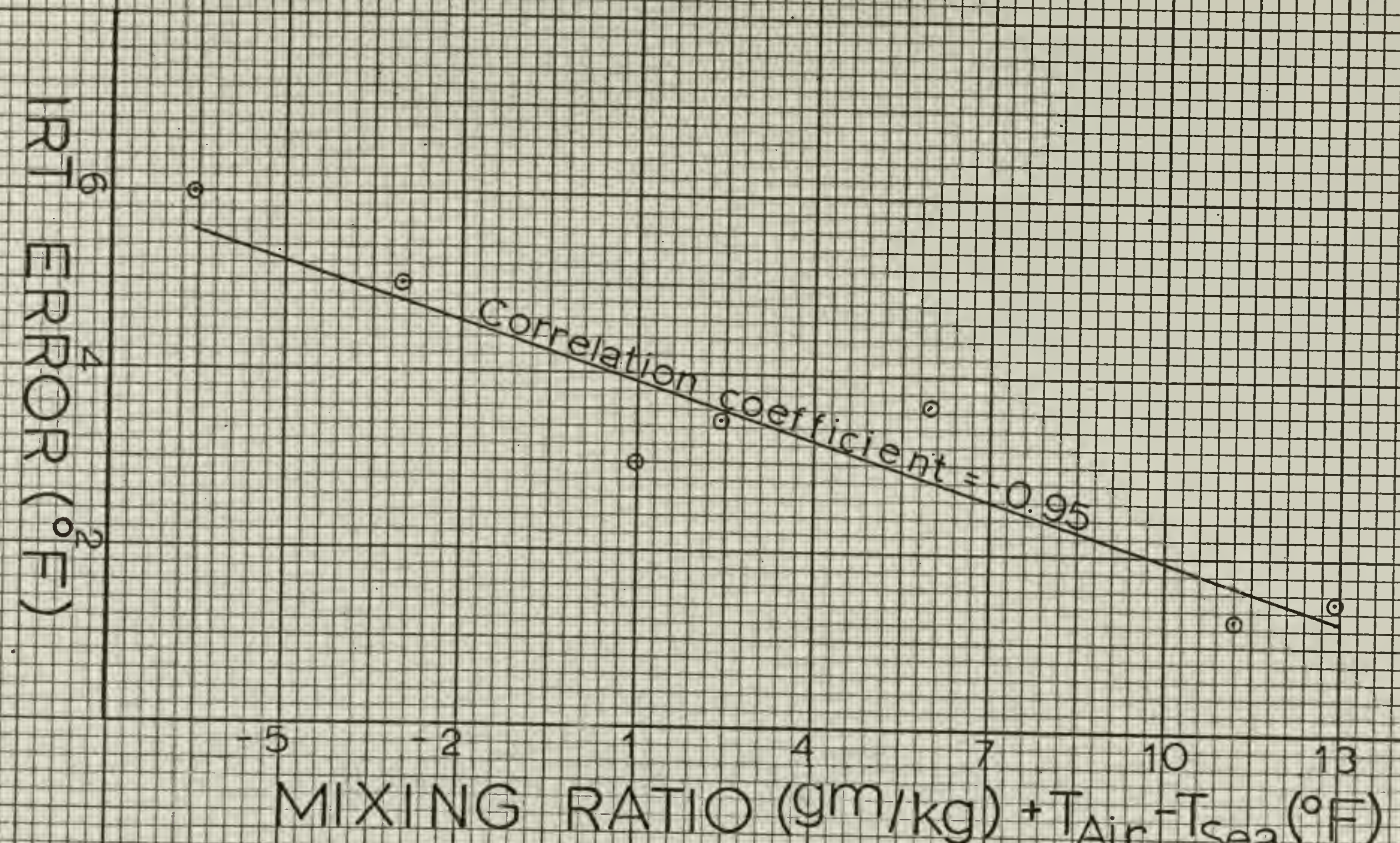


FIGURE 5

Oceanographic Office data
Sept.-Oct. 1962

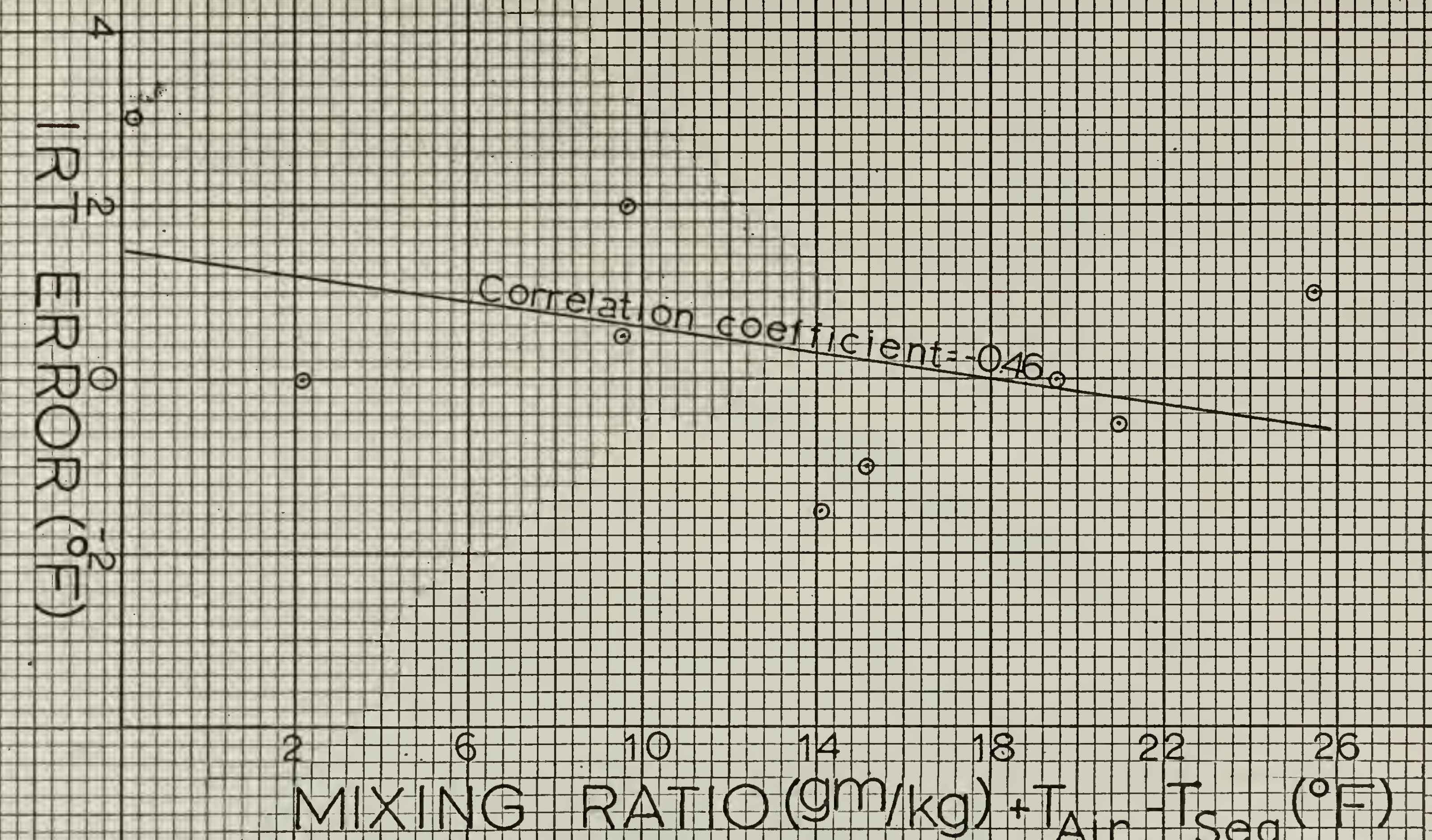


FIGURE 6

Sandy Hook data
April - Dec. '63, Jan. - Feb. '64

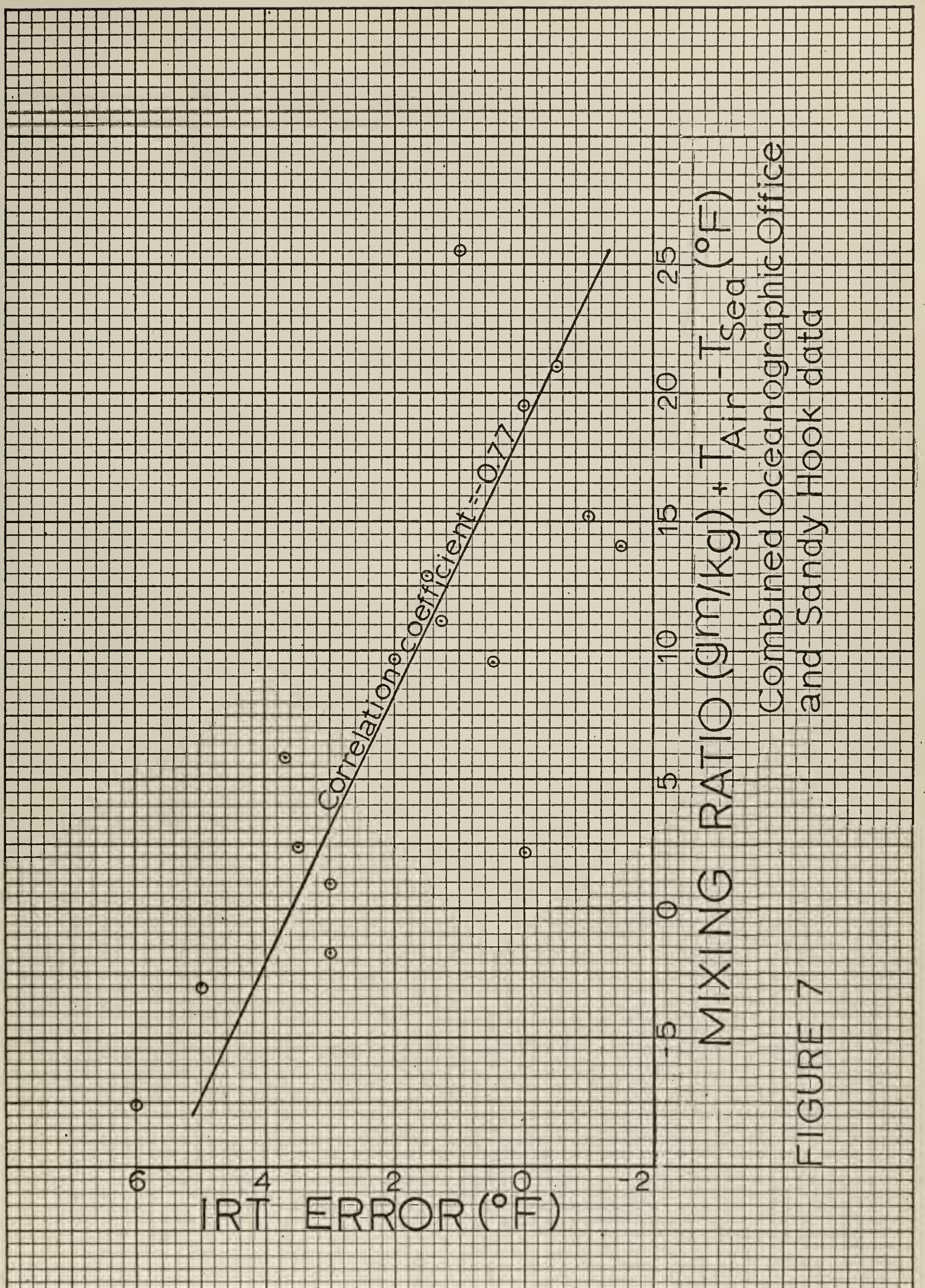


FIGURE 7
Combined Oceanographic Office
and Sandy Hook data