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Tropical Ocean and Global Atmosphere (TOGA) Heat Exchange Project - A Summary Report

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ABSTRACT

A pilot data center to compute ocean-atmosphere heat exchange over the tropical ocean is proposed at the Jet Propulsion Laboratory (JPL) in response to the scientific needs of the Tropical Ocean and Global Atmosphere (TOGA) Program. Optimal methods will be used to estimate sea surface temperature (SST), surface wind speed, and humidity from space-borne observations. A monthly summary of these parameters will be used to compute ocean-atmosphere latent heat exchanges. Monthly fields of net surface heat flux over tropical oceans will be constructed using estimations of latent heat exchanges and short-wave radiation from satellite data. Verification of all satellite data sets with in situ measurements at a few locations will be provided.

The data center will be an experimental active archive where the quality and quantity of data required for TOGA flux computation are managed. The center is essential to facilitate the construction of composite data sets from global measurements taken from different sensors on various satellites. It will provide efficient utilization and easy access to the large volume of satellite data available for studies of ocean-atmosphere energy exchanges.

GLOSSARY

ABBREVIATIONS AND ACRONYMS

AVHRR	Advanced Very High Resolution Radiometer
CAC	Climate Analysis Center
CSIRO	Commonwealth Science and Industry Research Organization
CalSpace	California Space Institute
DMSP	Defense Meteorological Satellite Program
DoD	Department of Defense
ERS	European Space Agency Remote Sensing Satellite
GAC	global area coverage
GARP	Global Atmospheric Research Program
GATE	GARP Atlantic Tropical Experiment
GSFC	Goddard Space Flight Center
HIRS	High Resolution Infrared Sounder
ISCCP	International Satellite Cloud Climatology Project
JPL	Jet Propulsion Laboratory
MILDEX	Mixed Layer Dynamics Experiment
MSU	Microwave Sounding Unit
NASA	National Aeronautics and Space Administration
NCDC	National Climatic Data Center
NESDIS	National Environmental Satellite Data and Information Service
NOAA	National Oceanic and Atmospheric Administration
PI	principal investigator
PODS	Pilot Ocean Data System
RMS	root mean squared
RSS	Remote Sensing Systems
SIO	Scripps Institute of Oceanography
SMMR	Scanning Multichannel Microwave Radiometer
SOP	ship of opportunity
SSMI	Special Sensor Microwave Imager
SST	Sea Surface Temperature
STREX	Storm Transfer and Response Experiment
THEP	TOGA Heat Exchange Project
TOGA	Tropical Ocean and Global Atmosphere
WOCE	World Ocean Circulation Experiment
XBT	Expendable Bathythermograph

CONTENTS

SECTION I

INTRODUCTION

The atmosphere and the ocean are coupled together through the exchanges of heat and momentum. The net heat flux at the ocean surface is vital to understanding the variability of upper ocean heat budget and is an important factor in the evolution of sea surface temperature. The interannual variation of sea surface temperature in the eastern equatorial Pacific, known as El Nino, has far reaching climatic and economic effects (CRC, 1983). Understanding monthly time-scale variability of sea surface temperature in tropical oceans is the major objective of the decade-long TOGA program, sponsored by the World Climate Research Programme (WCRP). Within TOGA Scientific Plans (WCRP, 1985b), there are clear rationale and mandates for determining the heat and momentum fluxes between the ocean and atmosphere in the global tropical belt ($\pm 20^{o}$).

The net heat exchange at the ocean surface has four components; short-wave radiation, long-wave radiation, sensible heat, and latent heat. Over tropical oceans, short-wave radiation and latent heat have the largest monthly variance (e.g., Weare et al., 1980). Current knowledge regarding the variability of large-scale heat fluxes is based on estimates using bulk formulas and parameters reported by ship of opportunity (SOP) (e.g., Esbensen and Kunshnir, 1981). The parameters used are cloud cover, sea surface temperature, wind speed, air temperature, and humidity at surface level. Over tropical oceans, ship data are sparse except over a few heavily traveled shipping lanes. Over large areas, ship data are, at best, able to provide the general pattern of the climatological seasonal mean, but they are not adequate to resolve the monthly mean required to study annual and interannual variations. Space-borne sensors have the potential to provide the required coverage.

It has been demonstrated that space-borne observations can be used to determine the variability of short-wave radiation (Gautier et al., 1980) and latent heat flux (Liu and Niiler, 1984) to a useful accuracy. Methods to estimate surface net, long-wave radiation are currently being developed (Gautier and Frouin, 1985). Estimations of sea surface temperature and short-wave radiation are obtained from observations of the National Oceanic and Atmospheric Administration (NOAA) operational satellites. The estimation of latent heat flux will require using observations from different sensors on Department of Defense (DoD) spacecraft (Niiler, 1985). The NOAA and DoD produce operational data from these satellite sensors but they are not optimally designed for scientific investigations; continuous calibrations and algorithm improvements are required to meet TOGA requirements. In the TOGA implementation plan, the Science Steering Group recommended the establishment of a TOGA Heat Exchange Project (THEP) whose objective is to demonstrate the utility, accuracy, and techniques of remote sensing the ocean surface heat flux so that a future heat flux data center can prepare this flux on a routine basis. Here we propose the establishment of an "active archive" or "data conduit" at the Jet Propulsion Laboratory (JPL), where the increases in quality and quantity of data required for TOGA fluxes computation will be managed. This center is essential to facilitate the construction of composite data sets from global measurements taken from different sensors on various satellites. It will provide efficient utilization and easy access to the large volume of satellite data available for studies of ocean- atmosphere energy exchanges.

SECTION II

TECHNIQUES

As outlined in a number of TOGA documents (e.g., WCRP, 1985b), the goal of THEP would be estimation of monthly, 2^{o} x 2^{o} mean heat flux in the global tropical belt ($\pm 20^{o}$) to an accuracy of ± 20 w m^{-2}. The useful level of accuracy is ± 40 w m^{-2}.

A. SHORT-WAVE RADIATION

The model for computing solar radiation at the surface of the ocean was developed by Gautier et al. (1980), Diak and Gautier (1983), and Gautier and Frouin (1985), in order of increasing refinement in the parameterization of clouds and atmospheric profiles. High resolution (1 to 8 km, hourly) geostationary satellite data are used in the model. Each version has been tested with oceanic data. The results are summarized in Table 1.

Table 1. Evaluations of Short-Wave Radiation Model

Publication	Experiment	Root Mean Squared Difference (w m^{-2})	Bias
Gautier (1981)	GATE	17	5
Gautier and Katsaros (1984)	STREX	13	7
Gautier and Frouin (1985)	MILDEX	12	-

These results correspond to comparisons of daily, 10-20 km averages between satellite and in situ measurements. For larger spatial and temporal averages, as required by TOGA, the accuracy of the estimates will depend upon the nature of the real "error" [estimated here in terms of the root mean squared (RMS) difference] and the scales of correlation of the satellite computations. Estimates of 24-hour solar radiation, east-west spatial decorrelation scale is about 300 km over various tropical oceans, thus, 250 km (2^{o} x 2^{o}) resolution monthly-mean estimates would yield an expected uncertainty of 5 w/m^2 (provided that all of the initial daily high resolution RMS uncertainty of 15 w/m^2 is produced by a random process).

The International Satellite Cloud Climatology Project (ISCCP) will produce two data sets for irradiances from geostationary satellites: B-1 at 8 km and B-3 at 32 km resolution. Due to the smaller size, the B-3 data set will be used for estimating the net radiation budget until 1989. It is expected that B-3 production with ISCCP will terminate in 1989; at this time B-1 data will be used. A pyranometer will be installed at 15°S, 145°W on Rangiroa to provide in situ verification for the entire project.

It is expected that the basic geostationary radiation data set will be processed at California Space Institute (CalSpace)/Scripps Institute of Oceanography (SIO) at La Jolla, California and the results forwarded to JPL for the duration of the Project. In the first three years, only the tropical Pacific data will be verified. It is expected that data for all ocean basins will be processed at a later time.

B. LATENT HEAT FLUX

The method for estimating latent heat flux from space was outlined by Liu (1984a). The bulk aerodynamic formula

$$E = \rho C_E U(Q_s - Q)$$

is used to compute the moisture flux E when the transfer coefficient C_E and the surface air-density ρ are known and if the sea surface temperature T_s, the wind speed U, and the humidity Q at the surface level can be measured. In the equation, Q_s is the saturation humidity at sea surface temperature. The latent heat flux can be determined by multiplying E by the latent heat of vaporization. To study the annual and interannual variations in tropical oceans, monthly means over $2^o \times 2^o$ areas are required. A typical wind speed over tropical oceans is about 7 m/s, and a typical value for Q_s-Q is about 5×10^{-3}. Assuming a constant C_E, a 20% accuracy requirement for E corresponds to 20% accuracy requirements in U, Q, and Q_s; (i.e., 1.4 m/s in U, 0.7°C in T_s and 1×10^{-3} in Q). These accuracies correspond to a ± 20 w m^{-2} error in a typical 100 w m^{-2} signal of timespace latent heat flux variability.

The transfer coefficient has been determined by regression on spot measurements (10 minutes to 1 hour temporal mean at a fixed location) up to wind speeds of about 15 ms^{-1} (Anderson and Smith, 1981; Large and Pond, 1982). The variation of the coefficient with reference height, atmospheric stability, and different mechanism of transport at the interface can be accounted for by using atmospheric surface layer models (Deardorff, 1968; Liu et al., 1979). Esbensen and Reynolds (1981) have shown that monthly mean parameters can be used in the formula to get monthly mean flux at least for mid-latitude and subtropical oceans. Liu and Katsaros (1984) have shown that areal-mean can be used under typical summer mid-ocean conditions. Atmospheric stability depends on wind, temperature, and humidity gradients near the surface. At present, we do not have a good technique to measure surface level air temperature from space. However, stability has only a secondary affect on the estimation of moisture flux, therefore, it can be sufficiently approximated using space observations. We will input wind speed, sea surface temperature, and surface level humidity derived from space observations into the bulk parameterization model of Liu et al., (1979) to determine monthly mean latent heat flux. Below are the techniques of estimating T_s, U and Q from space observations.

1. Sea Surface Temperature

The sea surface temperature will be determined by microwave and infrared radiometers: an accuracy of better than 1°C has been demonstrated in comparison with drifting buoy and Expendable Bathythermograph (XBT) data over limited geographical areas (McClain et al., 1983). Technique improvements are possible by combining SOP and remotely sensed data. The National Environmental Satellite Data and Information Service (NESDIS)/Climate Analysis Center (CAC) produces a global 5^{o} x 5^{o}, monthly map of the combined Advanced Very High Resolution Radiometer (AVHRR)-SOP on an operational basis. A number of AVHRR regression coefficients, relative weights of ship data, and objective interpolation parameters are used in an optimized fashion for global analysis. These parameters can be changed to optimize the system for various special climate and geographical regions (e.g., WCRP, 1985a). They will change as more is learned on how to "fold in" buoy, XBT and SOP data. TOGA has selected the NESDIS/CAC product as the best global SST analysis now available for atmospheric global circulation modeling, but also recognizes that its resolution in space or its accuracy near the equator is not good enough to resolve the ocean processes (such as upwelling) nor to provide realistic air-sea interaction parameterizations (as computation of heat fluxes and delineating boundaries of strong atmospheric convective activity). It is our objective to produce a high resolution (2^{o} x 2^{o}, monthly), research data set of the tropical ocean SST from combined AVHRR-SOP-XBT records. Special emphasis will be given to:

- Easy and inexpensive access to the satellite irradiance data so new SST maps can be constructed as more insight is gained into modeling the SST retrievals from combined data or multisensor data sets

- Acquisition of documented satellite SST retrieval schemes as th. become available and optimizing these to the tropical conditions

- Acquisition and storage of 18 month delayed SOP, XBT, and buoy data.

The volume of data reported within 18 months is nearly four times what was available in the first month for the existing NESDIS/CAC product, and TOGA is making a special effort to accommodate these delayed data.

The primary satellite data for SST determination in the first three years of THEP will be produced, stored, and analysed at SeaSpace in San Diego. The SOP, XBT, and buoy data will be gridded and analysed at JPL, both on a delayed mode basis as well as routine mode, which is required to check the AVHRR derived SST fields. The focus area for the verified fields in the first three years will be the tropical Pacific. The NOAA-AVHRR global area coverage (GAC), which is available in 4 km resolution with 5 spectral bands, will be provided by NESDIS in NESDIS level Ib format. The level Ib GAC data will be processed using algorithms described in Bernstein (1982), McClain et al., (1983) and McClain et al., (1985) with modifications for aerosol effects as developed by Griggs (1984). The validation data for checking these algorithms come from specially equipped ships in the western Pacific, with continuous recording and calibrated SST sensors (maintained by G. Meyers at the Commonwealth Science and Industry Research Organization (CSIRO), Hobart, Australia). Multi-instrument algorithm improvements will be pursued through collaboration with Goddard Space Flight Center (GSFC) and the University of Wisconsin using the High Resolution Infrared Sounder (HIRS)/Microwave Sounding Unit (MSU). HIRS/MSU data for the global tropical band will be processed for THEP at GSFC to provide SST as well as other atmospheric parameters (Susskind et al., 1984).

2. Surface Level Wind Speed

Wind speed can be measured by a microwave scatterometer, radiometer, and altimeter. Spot comparisons between wind speed measurements by sensors on the NASA ocean-observing satellite, Seasat and coincident in situ measurements agree to within 2 m/s [Seasat Special Issues 1 and 2, J. Geophys. Res., 87 and 88 (C3)]. The random part of these errors can be removed in forming the averages, and the systematic errors can be reduced by empirical means (e.g., Liu, 1984b).

The Special Sensor Microwave Imager (SSMI) on board the Defense Meteorological Satellite Program (DMSP) operational aircraft, to be launched in early 1986, will measure surface wind speed and precipitable water (Hollinger and Lo, 1983). However, the combination of frequencies available to determine surface wind speed has not been used in past satellite sensors. The proposed operational D-matrix algorithm designed for SSMI wind retrieval is a simple regression that expresses the wind speed as a linear combination of brightness temperatures at various frequencies measured by the SSMI. To compensate for the nonlinearities of the brightness temperature model functions, nine different sets of coefficients were derived, with each set corresponding to a different climate zone. In a simulated study, using Seasat data, Wentz (1984) demonstrated some deficiency of this algorithm and possible improvement by inversion of the nonlinear model functions in a deterministic way. He also suggested to make use of the special SSMI engineering design to relate the antenna temperatures directly to the geophysical parameters. Antenna temperatures from SSMI will be obtained from NESDIS as soon as they are available and processed to geophysical parameters at Remote Sensing Systems (RSS) in Sausalito, California. They will be transferred to JPL on a monthly basis.

After the SSMI launch, the wind speed retrieved by Wentz's algorithm will be compared with those retrieved by others and evaluation of the satellite wind speed with quality in situ measurements, obtained during the Tropic Heat Experiment (in equatorial Pacific) and Ocean Storm Experiment (in north Pacific), will be performed. Routine comparisons will be made between the SSMI and the SOP winds in areas with more than 20 observations per month. There are other methods of estimating the surface wind speed under limited conditions (WCRP, 1983). We will check our results against those obtained by other methods when they are available at TOGA data centers.

3. Surface Level Humidity

A direct method of measuring Q from space-borne sensors has not been developed, but it has been demonstrated that the columnar water vapor (precipitable water) W can be measured very accurately by microwave radiometer (Alihouse, 1983). Liu and Niiler (1984) have shown that the monthly W is a very good predictor for monthly mean Q. A simple regression can account for both temporal and spatial variation. If a global regression between the two quantities is used, Q can be determined to an accuracy of 0.8×10^{-3} and if local regressions in the tropics are used, better accuracy can be achieved.

The algorithms for retrieving W are straightforward. Precipitable water will be retrieved from SSMI observations and made available to THEP in a similar fashion as wind speed. The values will be compared against radiosonde soundings at representative mid-ocean stations. The derived value's average Q will be compared with corresponding values obtained from SOP.

SECTION III

DATA FLOW

Although the wind speed, precipitable water from SSMI, and the sea surface temperature described earlier will be the core data for estimating surface latent heat flux, there are some alternate space-borne data sets. The Scanning Multichannel Microwave Radiometer (SMMR), on board a NASA earth-observing Satellite, Nimbus 7, is designed to measure surface wind speed, sea surface temperature and atmospheric precipitable water (Gloersen et al., 1984). Although it has outlived its life expectancy, it is still functioning, and the data are being processed at GSFC. The data from Nimbus/SMMR will provide coverage before the launching of DMSP/SSMI. We plan to acquire the operational geophysical products of this instrument for THEP and carefully check these against our in situ data files. Meteorological reports from mid- cean stations and SOP will be acquired routinely from National Climatic Data Center (NCDC) for evaluation of space measurements. Research quality measurements on freighters traveling certain routes are being planned. The CSIRO is planning to make meteorological measurements continuously on freighters traveling between Tasmania and Japan. The National Science Foundation and the U.S. TOGA office are funding experiments on ships of opportunity going from Panama to Honolulu beginning summer, 1985. We will also try to use some of these measurements and those from other field experiments in our verification studies. At the end of the decade there will be a new generation of sensors on board the Navy Remote Ocean Sensing System (NROSS) and the remote sensing satellites of the European Space Agency (ERS-1 and 2).

THEP will archive 2^{o} x 2^{o}, monthly mean data summary for each of the parameters in the area between 20^{o}N and 20^{o}S from the American coast to 120^{o}E beginning with January 1, 1985 data or those taken immediately after launch. Verification of all statellite data sets, at a number of locations, will be provided. The satellite products will be forwarded to JPL within six months and SOP data from NCDC should be acquired within 18 months. Complete references to retrieval algorithms will be cataloged. The following table lists the parameters expected from each principal investigator (PI) and the institution where the data will be processed.

A catalog of data archived at THEP will be available for on-line search through the Pilot Ocean Data System (PODS). One year after the heat flux data are cataloged, remote users will be able to browse through fields of heat flux or the intercomparison between satellite and in situ estimates through PODS. Orders, in hardcopy or magnetic tape, can then be made.

Since one of the largest anomalies in the tropical Pacific took place in 1982 and the required sensors (NIMBUS/SMMR, NOAA/AVHRR, NOAA/VISSR) were all in place, an attempt will be made to produce data files starting from January 1, 1982.

Table 2. THEP Data Flow Summary

PI	Institution	Parameter
Gautier	SIO/CalSpace	Surface net insolation
Bernstein	SeaSpace	Sea surface temperature
Wentz	RSS	SSMI wind speed and precipitable water
Liu	NCDC	Meteorological reports from SOP and mid-ocean stations
Liu	TOGA Data Centers	Supporting and verification data
Liu	GSFC	Nimbus/SMMR wind speed, sea surface temperature, and precipitable water.

SECTION IV

MANAGEMENT

THEP will be overseen by the following steering committee:

W. T. Liu, (resident project scientist), Jet Propulsion Laboratory

P. P. Niiler, (TOGA representative), Scripps Institute of Oceanography

C. Gautier, California Space Institute/Scripps Institute of Oceanography

R. L. Bernstein, SeaSpace

F. J. Wentz, Remote Sensing Systems.

THEP data flow should start in early 1986. We view this project as being responsive to research science needs and, in its initial stages, as experimental. We encourage researchers to continue the process of testing and improving retrieval schemes and analysis methods. By the end of TOGA and the World Ocean Circulation Experiment (WOCE), ten years from now, we anticipate that a global remote sensing capability of research quality data will have been installed on an operational basis. This proposal is the first step.

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15. Supplementary Notes

16. Abstract

A pilot data center to compute ocean-atmosphere heat exchange over the tropical ocean is proposed at the Jet Propulsion Laboratory (JPL) in response to the scientific needs of the Tropical Ocean and Global Atmosphere (TOGA) Program. Optimal methods will be used to estimate sea surface temperature (SST), surface wind speed, and humidity from space-borne observations. A monthly summary of these parameters will be used to compute ocean-atmosphere latent heat exchanges. Monthly fields of net surface heat flux over tropical oceans will be constructed using estimations of latent heat exchanges and short-wave radiation from satellite data. Verification of all satellite data sets with in situ measurements at a few locations will be provided.

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