3. DETERMINATION AND IMPACT OF SURFACE RADIATIVE PROCESSES FOR TOGA COARE

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3.1 Overview

Experiments using atmospheric general circulation models (e.g., Palmer and Mansfield, 1984; 1986) have shown that the atmospheric circulation is very sensitive to small changes in sea surface temperature in the tropical western Pacific Ocean warm pool region. At the same time, sea surface temperature and the ocean mixed layer structure in the western Pacific Ocean warm pool region are very sensitive to changes in the surface heat, momentum and freshwater fluxes that are driven by the atmospheric circulation. The mutual sensitivity of the ocean and the atmosphere in the warm pool region places stringent requirements on models of the coupled ocean-atmosphere system. At present, the situation is such that diagnostic studies using available datasets have been unable to balance the surface energy budget in the warm pool region to better than 50-80 W m^{-2} (TOGA COARE Science Plan, 1989).

The TOGA Coupled Ocean-Atmosphere Response Experiment (COARE) is an observation and modelling program that aims specifically at the elucidation of the physical process which determine the mean and transient state of the warm pool region and the manner in which the warm pool region interacts with the global ocean and atmosphere. This project focusses on one very important aspect of the ocean-atmosphere interface component of TOGA COARE as described by the TOGA COARE Science Plan (1989), namely the temporal and spatial variability of surface radiative fluxes in the warm pool region.

A key aspect of understanding the principal processes responsible for the coupling of the ocean and atmosphere in the western Pacific warm pool region is the assessment of surface radiation fluxes and their variations. Solar radiation reaching the sea surface is mainly modulated by variations of cloudiness and solar zenith angle, both of which have large amplitude on short time scales. The amount absorbed by the ocean is determined by the surface reflectance which can be influenced by variations in surface wind speed and the turbidity of the upper ocean layers. The precise effect of the absorbed energy on the ocean mixed layer depends on its vertical distribution, which, since it is a strong function of wavelength, varies with cloudiness. Cooling of the ocean mixed layer is dominated by evaporative cooling; however, this process is strongly constrained by the fact that the large thermal radiative fluxes between the ocean surface and the atmospheric boundary layer strongly couple their temperatures. Thus, understanding how the coupled system responds to rapid transients of energy input requires examination of the variations of the solar and thermal radiation fluxes on short time scales to determine how the combined atmospheric-oceanic boundary layers integrate over these rapid and large variations.

Clouds decrease the amount of incoming shortwave radiation and increase the amount of downwelling longwave radiation. The effect of clouds on the surface radiation flux depends primarily on the cloud optical properties, with cloud base height (temperature) being an important parameter for determining the surface longwave flux. The extent to which cloud base temperature becomes the effective radiating temperature to the surface depends on the water vapor content of the subcloud layer (Stephens and Webster, 1979; 1981). Because of the high water vapor amount characteristic of the western Pacific Ocean, water vapor continuum emission in the atmospheric window region renders the subcloud layer nearly opaque (Stephens and Webster 1981), with most of the radiation emitted from the cloud being absorbed in the subcloud layer before reaching the surface. Because of the relative insensitivity of the surface downwelling longwave flux to clouds, the impact of cloudiness in the tropics on the surface irradiance is mainly to reduce the intensity of the solar flux (Stephens and Webster, 1979), although the importance of accurately determining the downwelling longwave flux should not be underestimated.

Besides varying the magnitude of the total surface irradiance, clouds change the spectral distribution of radiation at the surface, since clouds absorb in the infrared and do not absorb in the visible. Additionally, the presence of clouds enhances the absorption due to water vapor and thus modifies the spectral distribution by increasing the photon path length via multiple scattering by the cloud. In the presence of clouds, the shortwave portion of the spectrum as received at the surface will be relatively enriched in visible radiation compared with near infrared radiation. Thermal infrared radiation will also be enhanced. The change in spectral distribution of the incoming radiation in the presence of clouds affects the attenuation of radiation in the ocean, which varies spectrally. In the upper ocean, the attenuation coefficient of the radiation is a strong function of the wavelength (Simpson and Dickey, 1981), and both downwelling long-wave radiation and incoming solar radiation are selectively absorbed in the upper ocean. The absorption of solar radiation shows a strong spectral dependence, with the red and near infrared radiation absorbed within a few centimeters and the shorter wavelength radiation absorbed at considerably greater depths (e-folding depth for visible radiation is 8 m). Thus changes in cloudiness could alter the vertical distribution of heating in the boundary layer of the oceans as well as its magnitude. For most ocean mixed layer regimes this may not be very important, but it may be crucial in the low mean wind speed and high fresh water input regime of the western Pacific warm pool.

Although much information must come from in situ observations, obtaining an integrated perspective of the surface radiation fluxes over the entire warm pool region requires analysis of satellite measurements. The principal difficulty with the retrieval of longwave fluxes is determination of cloud base height and boundary layer water vapor amount. Surface longwave flux in the tropics is likely to be more sensitive to boundary layer water vapor amount, which is the easier problem to address via remote sensing, than to cloud base height.

3.2 Research Plan

This project has two principal goals: the establishment and validation of data analysis methods for the remote sensing of surface radiation fluxes that can be used routinely after the field phase of TOGA COARE; and an improved understanding of the atmospheric forcing of fluctuations in the surface radiation balance and the impacts of these fluctuations on the ocean mixed layer.

The key scientific problems to be addressed in this research are:

- *What are the microphysical and radiative properties of clouds in the warm pool region and how do they vary spatially and temporally?*
- *What are the temporal and spatial variability of surface radiation fluxes in the Pacific warm pool region and how are they influenced by clouds?*
- *How do the cloud properties and surface radiative fluxes vary with mesoscale and synoptic scale forcing?*
- *How sensitive is the sea surface temperature and the ocean mixed layer to high frequency (the order of several hours) fluctuations in the surface radiative flux associated with changes in cloudiness?*

Because of the complementary information obtained from different measurements and using different analysis techniques, the best results will come from a combined analysis of several datasets. Especially during the TOGA COARE IOP, the availability of many special surface and aircraft datasets will significantly augment the remote sensing analysis results. This research will therefore be accomplished in three stages:

- *remote sensing pilot study to develop and compare satellite algorithms;*
- *validation of remote sensing algorithms using TOGA COARE IOP surface and aircraft observations and preparation of high-resolution analyses for the IOP; and*
- *diagnostic and modelling studies utilizing the analyzed fields.*

The investigators are planning to provide the following high-resolution analyses for the entire TOGA COARE IOP initial primary domains of:

- *sea surface "skin" temperature*
- *surface reflectance*
- *surface wind speed*
- *atmospheric precipitable water*
- *cloud properties including cloud fractional coverage and optical depth*
- *surface radiation fluxes*
- *tropospheric radiative heating and cooling rates.*

The analyses will be accomplished principally by satellite remote sensing, largely based on the International Satellite and Cloud Climatology algorithms developed by Rossow and colleagues (Rossow et al, 1988; Rossow et al., 1989a,b; Rossow and Lacis, 1990; Rossow et al., 1990; Bishop and Rossow, 1990). The analyses will be produced on a spatial scale of 30 km and a temporal scale of 3 h for the entire TOGA COARE IOP domain and period. These analyses will be made available to other TOGA COARE investigators, and we expect them to have widespread utility in many aspects of TOGA COARE.

Available surface and aircraft data will be utilized to validate the remote sensing algorithms and will also be blended with the satellite retrievals for the final analysis products. An aircraft sub-program is proposed specifically to investigate cloud radiative properties and to validate the satellite-derived surface radiative fluxes.

3.3 Satellite Remote Sensing Data

The principal datasets utilized for the remote sensing studies are the ISCCP datasets (radiances from imaging instruments and analysis results), the High Resolution Infrared Radiometer Sounder and Microwave Sounding Unit (HIRS2/MSU) infrared/microwave radiances (as well as the operational analyses of these data, called TOVS products) and the DMSP Special Sensor Microwave Imager (SSM/I) brightness temperatures.

The basic satellite radiance data used in deriving the ISCCP high resolution results for the TOGA COARE region are obtained from the Japanese Geostationary Meteorological Satellite (GMS-4) every 3 hours at the synoptic reporting times. However, four-times-daily observations (at approximately 2:30, 8:30, 14:30 and 20:30 local time) are also available from the AVHRRs on two NOAA polar orbiters. The ISCCP datasets include the original radiances (Schiffer and Rossow 1985, Rossow et al. 1987) and analysis results containing information about clouds and the surface sampled every 30 km and 3 hr (Rossow et al. 1988, Rossow and Schiffer 1991).

The standard ISCCP retrievals can be extended by combining the additional spectral channels in the AVHRR data with the HIRS2/MSU data. The HIRS2 radiances are obtained four-times-daily from the two NOAA polar orbiters with a spatial resolution of about 15 km. Current analysis techniques reduce the spatial resolution to 60 km (Susskind et al 1984); but the operational analysis is only available at a resolution of about 250 km and only once per day. However, special analysis of these data for the TOGA COARE IOP will supplement the basic imaging datasets.

The Special Sensor Microwave/Imager (SSM/I) is on the polar-orbiting Defense Meteorological Satellite Program (DMSP) F8 satellite (Hollinger, 1988). This satellite makes twice-daily passes at roughly local noon and midnight. The SSM/I has four frequencies (19.35, 22.234, 37.0 and 85.5 GHz) and dual polarization capabilities on all except the 22.235-GHz frequency which records only the vertical polarization. The effective ground resolution of the 85.5 GHz data is 15 km, ranging to 69 km at 19.35 GHz.

Broadband total flux measurements may also be available from the French-Soviet SCARAB experiment during the TOGA COARE IOP. If these data are available, they can be used to provide a consistency check on the surface radiative flux calculations as well as more direct constraints on surface albedos.

3.3.1 Sea surface "skin" temperature

To properly diagnose energy exchanges between the atmospheric and oceanic boundary layers, the actual "skin" temperature of the ocean must be determined, rather than the bulk mixed layer temperature. Fortunately, satellite radiometers measure skin temperature directly, although all current analysis methods have been tuned to produce bulk temperatures for comparison with ship measurements. During TOGA COARE, we intend to compare and separate the quantities measured by ships and satellites in some detail as this may provide some insight into the mixed layer dynamics in this region.

We plan to compare different techniques for retrieval of sea surface temperatures from satellite data to develop a standard of accuracy independent of ship measurements. The ISCCP cloud analysis (Rossow et al. 1988) currently uses one IR channel (wavelength about 11 microns) to obtain SST from clear radiance values and the operational atmospheric profiles of temperature and humidity. A new technique is being developed, similar to the NOAA operational method, that uses all of the IR channels on the AVHRR (at 3.5, 10.5 and 11.5 mm) to remove residual cloud and water vapor effects. This new study is also examining ways to monitor the calibration of these channels. These results will be obtained at a spacing of 25 km. Other methods of determining SST include that of Susskind et al (1984) using HIRS2/MSU data. Although SSM/I does not have the lower frequency channels required for retrieval of SST (Wilheit et al. 1984, Petty 1990), the MSU instrument maybe useful for this purpose.

3.3.2 Ocean surface reflectance

Ocean surface reflectance is required to determine the net shortwave irradiance at the surface. The ocean surface albedo is small (about 6%), but it can vary by about a factor of two because of changes in the particulate amount in the upper 10 meters of the ocean and by even larger factors as a function of solar zenith angle and wind roughening of the surface. Although these variations only change the total absorbed solar flux by amounts less than 10-20 W m-2, this is still about 10% of the net radiative flux. Current techniques to remotely sense surface albedo only work under clear-sky conditions (e.g., Rossow et al., 1989a), so surface reflectance under overcast conditions can only be determined by modelling. Our model (Rossow et al. 1989a) determines the ocean reflectance as a function of angle wind speed. Turbidity effects can also be included. A comparison of modeled with retrieved surface reflectances by Rossow et al. (1989a) showed the model to be correct to within 2% for geometries away from glint conditions.

We plan to combine surface wind analyses with the satellite measurements to determine whether wind and turbidity effects play any significant role in determining the variability of the surface radiative fluxes.

3.3.3 Surface wind speed

Wind roughening of the sea surface alters the reflectance of the ocean surface by causing surface bubbles (Tanaka and Nakajima, 1977). Modelling of oceanic surface albedo therefore requires determination of surface wind speed.

Surface wind speed will be determined using the SSM/I data after Wentz et al. (1986). New coefficients have been determined for the SSM/I channels, which will be published shortly (Wentz, personal communication).

3.3.4 Precipitable water

Water vapor amount is needed for the retrievals of surface temperature from satellite radiances and for the calculation of radiative fluxes, particularly the transient variations of the net thermal fluxes. Moreover, water vapor and skin temperature are the key to determining the latent heat fluxes that are the first-order balance to the solar heating. Since a correlation has been found between precipitable water amount and surface-level humidity over oceans, satellite-based estimates of precipitable water amounts have been used to determine the surface latent heat flux (Liu 1986). By combining several estimates of water vapor amounts and short-term skin temperature variations, we plan to examine this relationship more closely.

The infrared radiances measured by HIRS2 and AVHRR are also sensitive to precipitable water vapor amounts. The CO2 band channels, used for temperature sounding, are affected by water vapor, so that retrieval of the temperature profile also implies a first-order calculation of water vapor absorption. However, this can be improved by taking advantage of the remaining channels that have stronger dependence on water amounts (Hayden et al., 1981). The very strong pressure dependence of the water vapor continuum absorption makes measurements at 10-12 mm much more sensitive to the water vapor nearest the surface. If we are able to improve SST retrievals to an accuracy of 1 degree or better, then we may be able to isolate the signal associated with near surface water vapor by combining microwave, IR sounder and AVHRR radiance measurements. The intense TOGA COARE IOP in situ measurements provide a unique opportunity to attempt this analysis.

3.3.5 Cloud properties

Our principal interest in cloud properties is to determine their effect on the surface radiative fluxes. The primary dataset is the ISCCP analysis (Rossow et al., 1988; Rossow and Schiffer, 1991), which describes the cloud optical thickness and cloud top temperature and pressure for each image pixel. Using an approach similar to that employed by Rossow et al. (1989a; 1989b) and Rossow and Lacis (1990), these quantities are retrieved from visible and "window" infrared radiance measurements by satellites (see also Rossow et al., 1985). At night, only the cloud top temperature/pressure is retrieved because there is no visible radiance data. The retrieval is done by comparison of radiative transfer model calculations of narrowband radiances to the satellite measurements as a function of viewing geometry, of atmospheric composition and temperature structure, and of surface reflectances and emittances. These same quantities are then employed in the flux calculation model.

Since only two wavelengths are analyzed, only the two most important cloud properties are retrieved (optical thickness and temperature). However, the retrieval model is based on a detailed cloud microphysical model that is assumed to be unvarying in the ISCCP analysis but can be varied if other information is available.

Comparison of the satellite-based values of LWP to in situ measurements of cloud water content and surface-based measurements of cloud base altitude also allows for study of the relations between the remotely sensed parameters and the cloud water content, which depends on the vertical extent of the clouds. This will be key to determining whether the cloud base location and temperature can be inferred from existing satellite datasets. Cloud base temperature is needed to determine cloud effects on downwelling thermal fluxes at the surface.

3.3.6 Surface radiation fluxes

The radiative transfer model to be employed in the retrievals is that used in the GISS climate GCM (Hansen et al., 1983). All radiatively significant atmospheric constituents are included and vertical inhomogeneities are explicitly represented. The modeled atmosphere is vertically divided into twelve layers, with eight in the troposphere and four in the stratosphere (model layers can be varied). The properties of the stratosphere above the 5 mb level are specified from the climatology used in the GCM.

Clouds are described by two "microphysics" models (cloud particle size distribution and phase), one representing water clouds and one representing ice clouds; these model parameters can also be varied. Cloud optical properties are determined using the ISCCP dataset from radiances at 0.6 mm wavelength. The spectral variation of cloud optical thickness is determined by referencing the optical parameters to those at 0.6 mm using the microphysical models. Thus, specification of the cloud optical thickness at this single wavelength sets values of optical thickness at all wavelengths for the flux calculations.

Ocean directional albedo is specified as a function of solar zenith angle and wind speed (after Minnis and Harrison 1984). Surface emissivities are set to unity, consistent with ISCCP radiative retrievals; however, spectrally dependent emissivities can be specified as a function of surface type.

The relevant model output quantities are: upward and downward solar (two wavelength bands corresponding to visible and near-IR) and thermal (total and "window") fluxes at the surface for clear, totally cloudy and fractionally cloud conditions.

3.3.7 Tropospheric radiative heating and cooling rates

Although tropospheric heating and cooling rates are not required to determine surface radiative fluxes, they are easily obtained as a by-product of the ISCCP algorithm. We expect to provide these analyses for eight levels in the troposphere.

3.4 In Situ Validation Data

TOGA COARE provides a unique opportunity to validate satellite retrieval algorithms in the tropics due to the high density of surface and aircraft observations of relevant parameters. The following in situ measurements will have particular utility in validating the satellite retrieval methods:

- *ship-borne and land-based observations of surface radiation fluxes*
- *ship-borne and land based observations of near-surface air temperature and humidity*
- *ship-borne observations of ocean "skin" and "bulk" temperatures*
- *ship-borne and buoy observations of ocean mixed layer vertical structure*
- *radiosonde measurements of atmospheric water vapor and temperature profiles*

- *aircraft measurements of cloud microphysical properties and radiative fluxes*

- *aircraft microwave measurements of sea surface temperature*

In the TOGA COARE Intensive Flux Array it is planned that there will be six ships. On each ship will be an Integrated Sounding System (ISS) consisting of a RASS system which provides a high resolution vertical profile of the water vapor content up to about 600 mb, a 915 MHz profiler, an omega-sonde system, and a suite of surface radiometers which will measure incoming shortwave radiation and both upwelling and downwelling longwave radiation.

3.5 Results of Master Directory Search

As stated in Section 1.2 of this report, the project just described was chosen as one of the scenarios from among Penn State's interdisciplinary Eos-related projects because of its varied and complex earth science data needs.

The Master Directory search was performed from PSU utilizing a SUN SparcStation 1+ running SUN OS. NSSDC's on-line data and information services were accessed via Internet.

3.5.1 Usefulness of the database contents

A loosely constrained database search was performed in order to find what data sets might be available (unanticipated as well as anticipated) with appropriate characteristics. The best results given the intended goals of this project in particular will come from a combined analysis of a number of different data sets. The discovery of additional data sets for use in this project was therefore a hoped-for outcome in the MD database search. In this initial, broad-based search, 263 entries were returned using 'earth atmosphere' as the only topical search parameter. No additional parameters were used as search constraints for fear of unknowingly eliminating some potentially interesting but unanticipated data set. Nevertheless, no 'interesting' data sets were found before giving up in frustration when faced with searching a very long list that had no meaningful ordering.

In searching for data on a project basis, some major inconsistencies were found. The list of investigators associated with specific data sets that were familiar to Drs. Curry and Ackerman did not match the names of the people that they personally knew had a major association with a given data set. This problem was apparent with the entry for the 'Fire' data set. There was also a lack of cross-referencing between investigators and data set names (e.g., Rossow - Fire).

As a further exploration of the Master Directory aside from the TOGA COARE related work, aircraft data on Antarctic ozone was searched for but not found.

3.5.2 Functionality of the user interface

Browsing the large number of entries returned as a result of loosely constrained queries proved to be quite tedious, since the entries were not in any order that allowed the user to search the list in anything other than in an exhaustive, top-to-bottom fashion. Sorting or grouping the returned entries into some user-requested order (e.g., alphabetical by project, investigator or by geographical area) would have been a significant aid in manually searching the returned entries.

Again, similar to the experience in the preceeding scenario (c.f. Section 2), the strictly hierarchical, menu-driven interface was very quickly found to be more of a hindrance than a help. It proved to be particularly frustrating for a user who wanted to retrieve information on specific data sets or highly constrained groups of data sets that were known or assumed to be in the MD database. Single parameter values among multiple search parameters could not be individually changed without backtracking through the menu structure. The available value choices were also extremely limited for most search parameters, and some combinations simply didn't seem to be allowed (e.g., campaign/project description).

A method for inputting user-specified search keywords or values and a more flexible means of combining them without abandoning the non query language approach seemed to be needed.

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