A Short-Wave Radiometer Array Across the Tropical Pacific Ocean as a Component of the TOGA-TAO Buoy Array

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Introduction

The purpose of this document is to bring together pertinent information concerning the NOAA TOGA-TAO buoy array so that a decision can be made for the following questions:

1. Are the scientific gains from an array of short-wave radiation sensors in the equatorial Pacific Ocean sufficiently impelling that DOE/ARM should provide financial and material support to NOAA/PMEL to install and operate this array?
2. What scientists and/or scientific studies would directly benefit from such a data set?
3. *What should that array look like? That is, what sub-set of buoys should be so implemented given the per-buoy cost of the implementation?*

The TAO Array

The TAO array (Figure 1) is an array of approximately 65 buoys, placed across the Tropical Pacific Ocean on a near-permanent basis (Hayes et al. 1991). The program is managed and supported by NOAA with collaborative support from a large international group. The array should be in operation for the next decade and is likely to be extended westward through the Indian Ocean. The program manager is Dr. Michael McPhaden, NOAA/PMEL, Seattle, Washington.

Buoys are visited approximately every six months; some buoys are visited annually. Instrumentation is built, tested, and calibrated at the PMEL, but several different Pacific Rim countries provide logistical support. The costs to keep such a vast array operational are substantial.

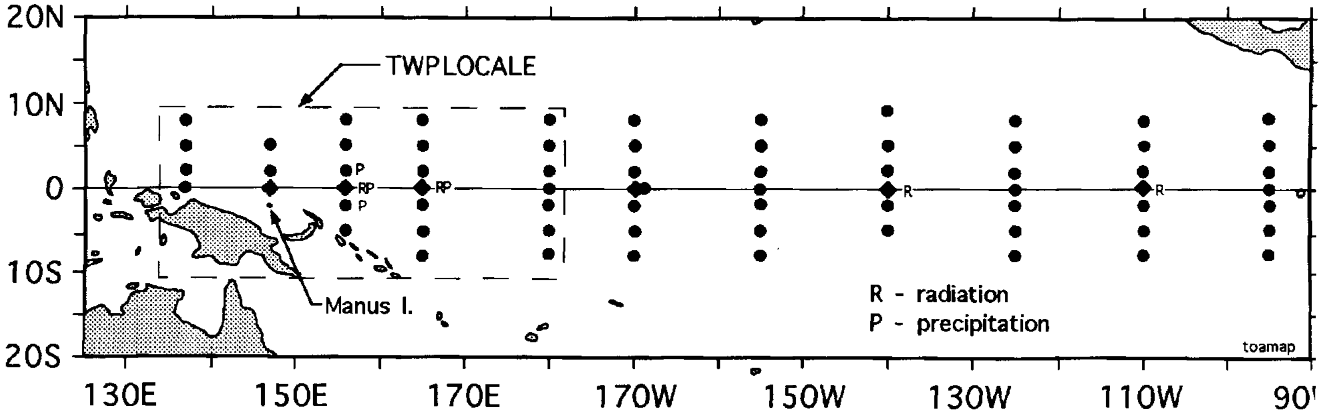

Figure 1. Chart of TAO buoy locations.

The Atlas and Proteus Moorings

Two different buoy designs are used in the TAO array: the Atlas and the Proteus. The buoys are similar in shape, but the Proteus buoy is larger, carries an acoustic-doppler current meter, and has some additional sensors.

Figure 2 is a sketch of one of the Atlas buoys which are the backbone of the NOAA TAO array. The hull of an Atlas buoy is a 2-m diameter, fiberglass-over-foam toroid, with a stainless-steel superstructure. Sensors are placed in the best possible locations for the required measurements. However, space is crowded and some compromises must be made. Every effort will be made to assure that radiometers are always in exposed locations, but that is an unresolved design issue.

The mooring is a single-point, taut-line design; hence, the buoy can rotate to any azimuth angle. Azimuth is measured as part of the wind measurement, and this could be used during processing of radiation data.

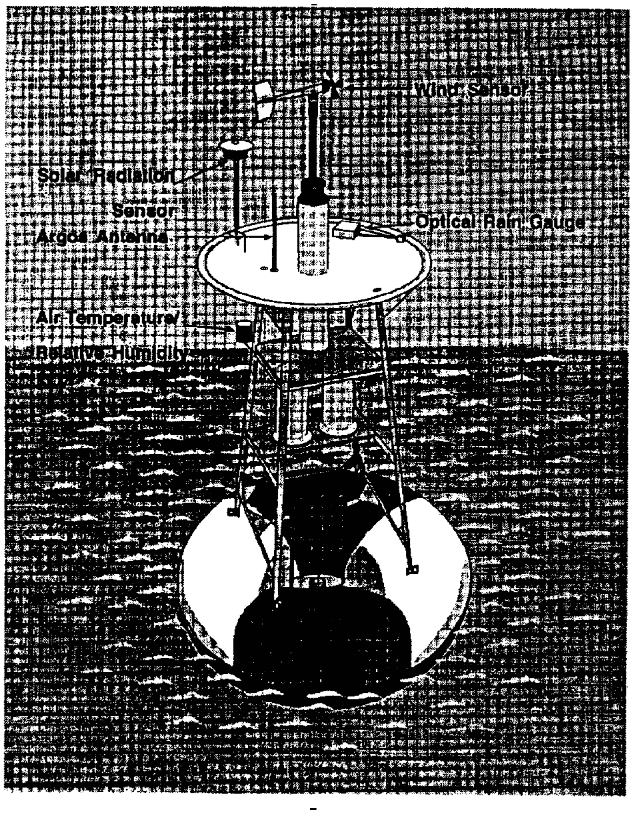

Figure 2. Sketch of ATLAS buoy.

Some of the Proteus buoys carry rainrate and shortwave radiation sensors already. Figure 1 shows locations of four radiation sensors across the Pacific at the equator and four rain sensors concentrated in the western side. Results from these measurements will be discussed later.

Data Collection and Archival

The "standard ATLAS sampling plan" (Hayes et al. 1992) is as follows: Winds are sampled at 2 Hz and vector-averaged for 6 minutes once each hour. Temperatures are averaged over 24 h and winds over 6 h. Air temperature and sea-surface temperature (-1 m) are sampled every 10 minutes and averaged hourly. Subsea temperatures and pressures are sampled every 10 minutes and averaged over each day.

Measurements are sent to PMEL via Service Argos using the NOAA series of polar orbiting satellites. Argos data capacity is limited; thus, the amount of data throughput is relatively small. We might expect to receive hourly statistics (mean, min, max, standard deviation) of radiation by this means. Argos data are available within a few hours of the time they are received at the satellite. Approximately 8 "hits" per day are common at the equator. An Argos message size can be set to 4-256 bits, but research applications generally demand the maximum size. As a convenience service, Argos disseminates data over the Internet daily.

Satellite availability coupled with occasional telemetry noise sometimes results in a break in the time series. On-board recording in the buoy data loggers provides a full backup data set which can be recovered whenever the buoy is visited, provided there are no failures, theft, or damage, as often happens to moorings.

A new data logger is required because the Atlas data system does not have sufficient capacity to accommodate radiation measurements. Radiation measurements today use the larger Proteus buoys. Part of the overall costs for a radiometer array would be to develop and manufacture a new data logger. Extra channels in this new logger would allow tilt, rainfall, surface salinity, and related measurements to be collected at the same time.

In Support of TWP

The ARM Tropical Western Pacific program will begin with an island installation on Manus Island, north of New Guinea. Additional island sites will be completed over the next few years.

A good strategy might be to begin a TAO radiometer implementation with the buoys in the approximate area of Manus. Figure 3 shows the TAO buoys in the far TWP.

Buoy Motion and the Expected Accuracy

Buoy tilting motion can be divided into three categories:

- wave-induced pitch and roll with periods of 1 to 10 sec
- mean tilts due to mooring tension, wind drag, or buoy imbalance
- erratic or impulsive motions from non-linear wave effects, mooring shock, or other such effects.

Radiometer errors from these effects are summarized in Figures 4, 5, and 6. By using a programmable platform, MacWhorter and Weller (1991) were able to compare shortwave radiation measurements from moving sensors with measurements from fixed ones. The study showed that a rocking at wave periods (5-10 sec) has a much smaller effect on errors than a mean tilt. Typical mean-square pitch angles for buoys are 5° to 15° (Figure 5) and the top-left graph in Figure 7 indicates errors of only a few percent from this.

A buoy can have a mean tilt of several degrees as a result of wind pressure, current drag, or payload/buoyancy imbalance. The top-right graph in Figure 4 shows that mean tilts of 5° can lead to errors in excess of ±10%, depending on sun position.

The bottom graph shows a comparison of a fixed, level radiometer to one on a rocking table. The lower trace comes from a level pyranometer. The upper trace comes from a pyranometer with a mean tilt of 10° toward the sun and also subject to rocking with an amplitude of 10°. Rocking periods of 5 and 20 sec were used. The basic results are 1) rocking period has little effect on the percent error, 2) the intrinsic time constant of the sensor damps short period motions, and 3) mean tilt can introduce significant error even at high sun angles. Jerks and sudden impulses, common on moorings, will be damped by the

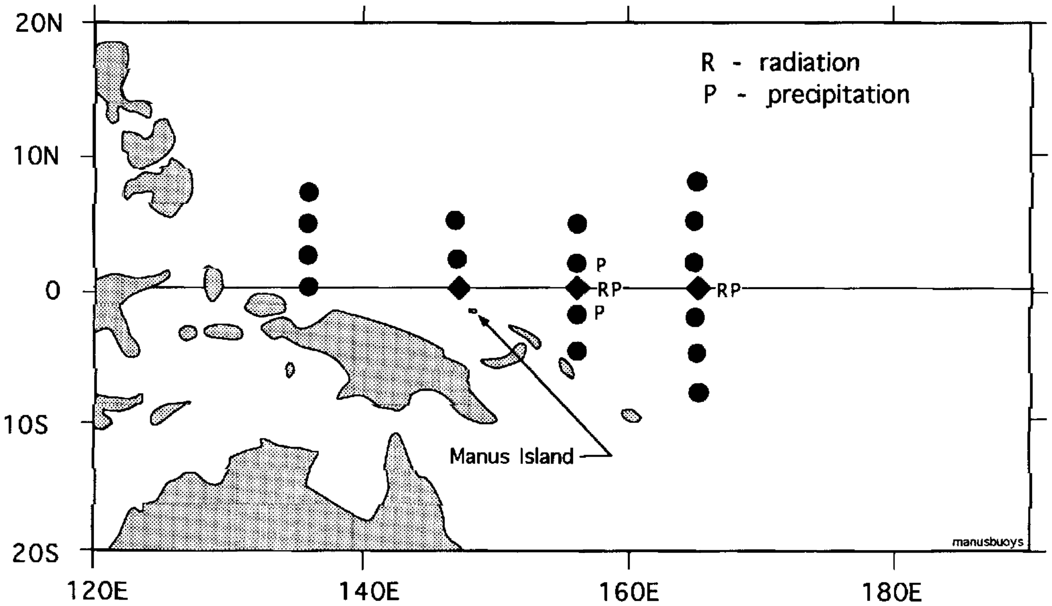

Figure 3. TAO buoys near Manus Island.

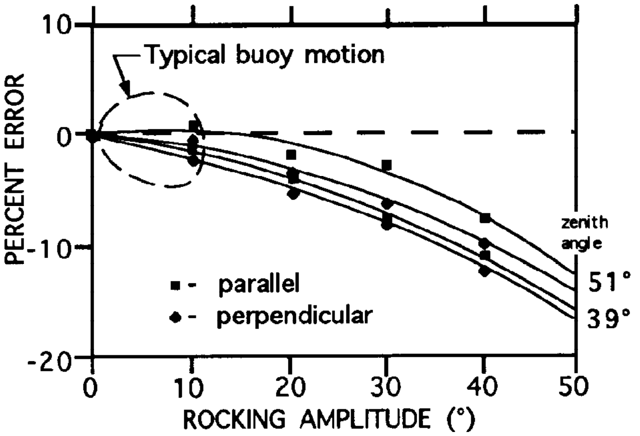

Figure 4. Errors in shortwave radiation measurements versus rocking amplitude.

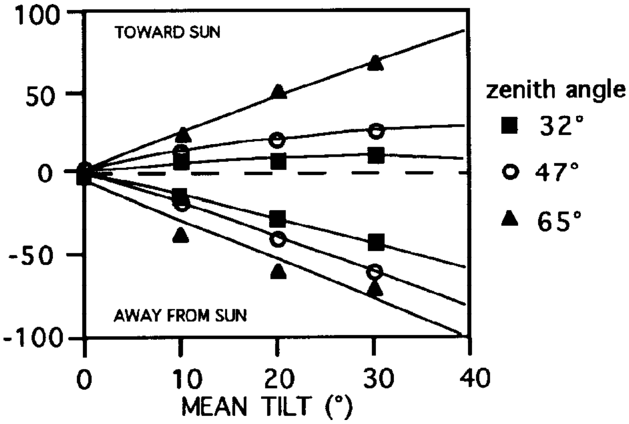

Figure 5. Errors in shortwave radiation versus mean tilt.

sensor and should have minimal effect on the measurement accuracy.

TAO Buoy Pitch and Roll

The TAO buoys are primarily surface following. This means that the buoys ride on the surface and the buoy tilt is almost identical with the surface slope. A study by Gilhousen (1987) shows how comparable buoys have similar motion in wave fields from 0- to 16-m high. The TWP generally has light mean winds (1 to 2 m s^{-1}) and waves are small. We expect rocking amplitudes to be less than 10°, and thus, errors introduced from rocking to be small.

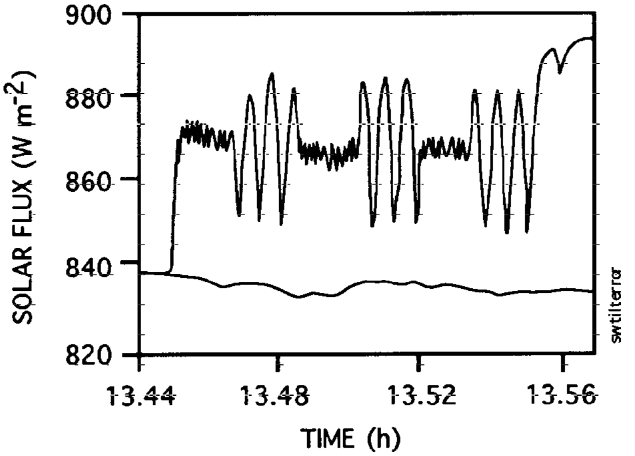

Figure 6. Time series of solar flux from level (bottom trace) and rocking (top trace) radiometer.

Buoy Heading

Buoy heading is measured as part of the wind measurement. Thus, the Atlas data set provides buoy headings every 6 h. The buoy is free to rotate on its mooring, and no special fins are used to encourage the buoy to head into the wind. Nevertheless, it is felt that the heading changes slowly with typical periods of days and, therefore, the azimuth measurement from the wind data will be sufficient for post-processing correction.

Mean tilt is the biggest concern. A last sample of this error is a shipboard case taken by Dr. Peter Minnett from the *R/V Alliance* in the Mediterranean Sea in summer at solar noon. Just before noon, the ship reversed direction by 180° and a sudden decrease in measured irradiance was observed. The radiometer was fixed in a "level" position relative to the ship, but the ship listed by 4°. A 180° direction change was equivalent to a mean tilt change of 8°. The estimated error was 10 W m^{-2}.

Gimbles

An active stable platform is too bulky, too expensive, too unreliable, and requires too much power to be considered

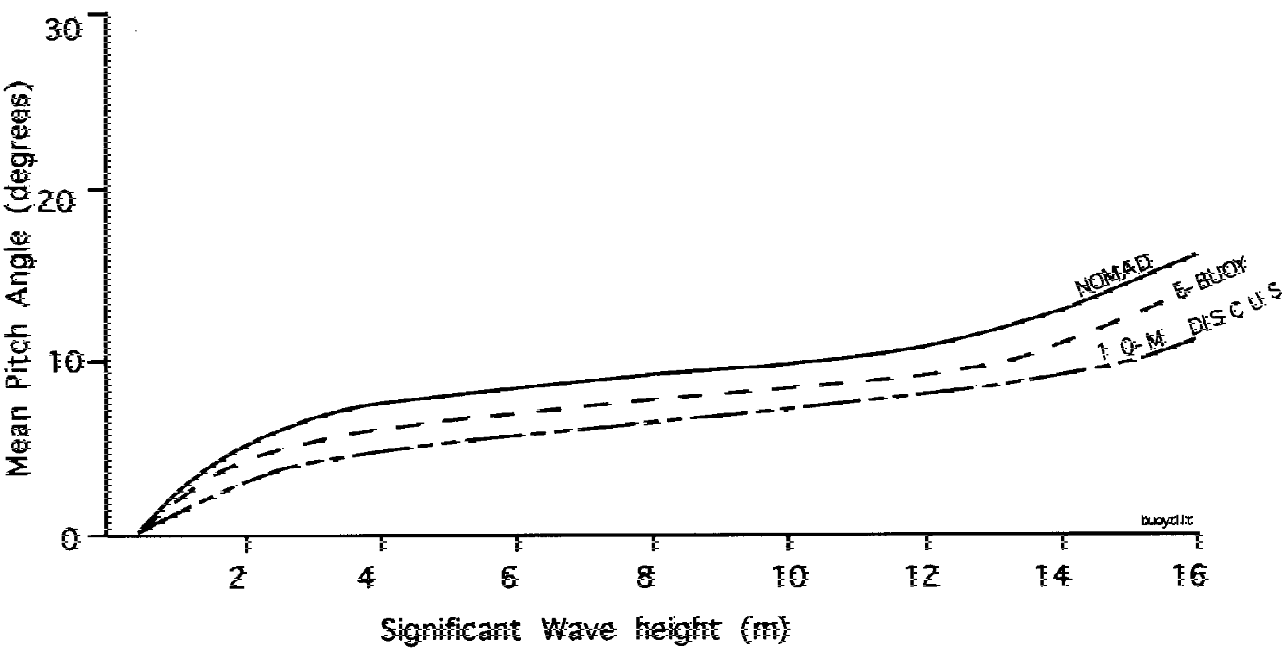

Figure 7. Mean pitch angles as a function of wave height for three oceanographic buoys.

for a buoy array. A passive gimble is one possible means for reducing mean tilt errors, but it has drawbacks. Wind drag on the counterweight can introduce mean tilt. If the weight is covered, the resulting structure is large enough to create problems in mounting; and it may conflict with other measurements on the small buoy tower. Software solutions may provide a better method. MacWhorter and Weller (1991) expand on the methods of Katsaros and De Vault (1986) and derive a method of reducing tilt errors significantly.

The Need for On-Board Tilt Measurement

A tilt measurement should be incorporated with any radiometer measurements from moving platforms. Small electrolytic tilt sensors are available from several manufacturers. Pitch and roll measurements can be combined with compass measurements to correct the measured radiation and greatly improve measurement accuracy. The tilt sensor will be affected by wave-induced horizontal accelerations, which will produce false tilt signals. However, all wave-period motion will be removed by averaging over many wave cycles. Tilt sensors with time constants of up to 3 sec can be purchased. This should be quite effective in removing shorter period wave motions and, more important, the sudden jerks and impulses from the mooring.

Post-Processing Radiometer Data

Mean buoy heading changes very slowly, and measured heading as currently done on the Atlas buoys can be combined with measured pitch and roll to correct the radiometer measurement. This correction is expected to yield a much-improved estimate of solar flux without need of a gimble.

NOAA Experience with Radiometer Measurements

During one preliminary study for the Coupled Ocean Atmosphere Response Experiment (COARE), Chris Fairall operated his gimbled, ship instrumentation near a TAO buoy with a radiometer. Over about 30 days, the overall mean difference between the two measurements was 7 W m^{-2} and the rms error was 4 W m^{-2}.

According to Fairall (personal communication) the uncertainty in the mean surface energy budget is on the order of 10 W m^{-2} and is dominated by errors in atmospheric radiation.

McPhaden currently places the measurement uncertainty at ±50 W m^{-2} for TAO radiometers. This accuracy is sufficient to pick up ENSO events (Figure 8).

Costs and Schedules

Costs are not a consideration for the purposes of establishing scientific worth. Some notion of the kind of costs, however, are in order.

- **Radiometers and associated hardware.** Hardware costs should amount to approximately $10K per buoy. Annual calibration costs are about the same as for any radiometer installation.
- **Telemetry costs.** Service Argos charges will amount to about $2500 per year per platform under the "Joint Tariff Agreement" between the United States and France.
- **Maintenance and service provided by NOAA.** A significant aspect of this proposal is that NOAA or its collaborators will pick up all costs associated with ship support, technical support, data collection, data processing, and data archival. Viewed from this light, if there is real scientific value to ARM, the opportunity should not be missed. The value of this component of the ARM/TAO collaboration is estimated at over $4 million.

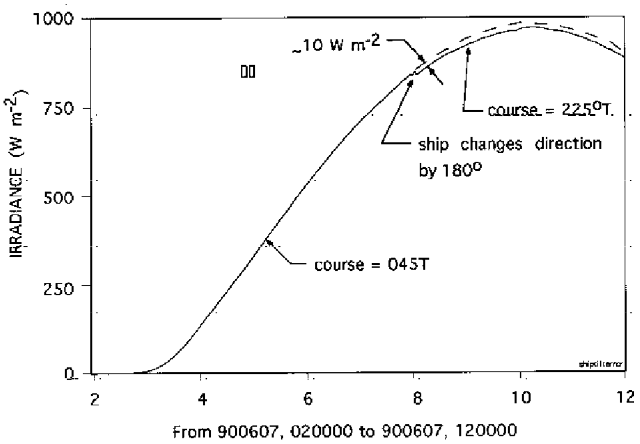

Figure 8. Error in irradiance measurement caused by an 8° change in radiometer tilt.

Risks, Risk Mitigation, and Risk Resolution

We should consider these and other ricks that might occur over the decade time scale of this project.

- **Extraordinary Error.** Some of the buoys will be in the mean currents of large magnitude. Some errors will be larger than expected. There is no means to clean the domes outside of the annual or semiannual maintenance visits. The belief is that rain will keep the domes clean, and indeed, field studies thus far substantiate this hope. However, data interpretation will always be a problem.
- **Unexpected Levies.** As the budget tightens, can an important radiation climate record cost ARM more and more to keep it going? The moorings will be attended by a variety of scientists from various countries. Additional costs and charges may be levied to keep the measurements or the logistics going.

References

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