Radiation budget components and their parametrization in JASIN

By RICHARD J. LIND and KRISTINA B. KATSAROS
Department of Atmospheric Sciences, University of Washington,
and
MARIANNE GUBE
European Space Agency, Darmstadt

(Received 18 October 1982; revised 16 February 1984. Communicated by Professor R. G. Fitridge)

SUMMARY

Components of the radiation balance over the sea surface were measured from RV Meteor and MV Endurer during July, August and September in the eastern North Atlantic (59°N 12°W) during the 1978 Joint Air Sea Interaction (JASIN) Experiment. Each component was modelled using routine hourly surface weather observations and compared to measurements. These models were used to estimate radiation components for RV John Murray and HMS Hecla. Daily net radiation at the surface ranged from 50 to 190 W m\(^{-2}\) during JASIN. Standard deviations of daily mean net radiation averaged 45 W m\(^{-2}\) for phase I of JASIN (23 July through 8 August), and 23 W m\(^{-2}\) for phase II (22 August through 3 September). Shortwave irradiance estimates made with an empirical formula due to P. E. Lumb, using solar zenith angle and cloud amount and type, gave results to within 10 W m\(^{-2}\) for most 5-day periods, confirming results of other investigators. Shortwave exittance calculations, based upon smoothed observations of albedo by R. E. Payne, were made using both measured and model-derived shortwave transmittances. Our results showed high correlation between model results and measurements. A recent model of longwave irradiance by two of the authors, RJL and KBK, gave results to within 10 W m\(^{-2}\) when compared to daily mean measurements. The accuracy of these models, over periods of a few days, was found to approach what is obtainable with direct measurements.

1. INTRODUCTION

The 1978 Joint Air–Sea Interaction (JASIN) experiment (Pollard 1978) provided opportunities to study the radiation budget at the sea surface. The net radiative heat balance at the air–sea interface is given by

\[ E_{\text{net}} = E_s + M_s + E_l + M_l \]  

where \( E_{\text{net}} \) is the radiative heat flux into the ocean, \( E_s \) solar irradiance, \( M_s \) upwelling solar irradiance (shortwave exittance), \( E_l \) longwave irradiance from the atmosphere and \( M_l \) the longwave exittance from the sea surface. Shortwave exittance can be expressed as \( M_s = -\alpha E_s \), where \( \alpha \) is the albedo of the sea surface. Definitions, terminology and symbols follow IAMAP Radiation Commission suggestions (Raschke 1978).

Shipboard measurements of radiation components were made from RV Meteor (59°N 12°30′W) and MV Gardline Endurer (60°15′N 14°30′W). Measurement periods were from 23 July through 8 August (phase I) and from 22 August through 3 September 1978 (phase II). The JASIN area and ship positions are shown in Fig. 1. Radiation measurements for the NE corner of the meteorological triangle were unavailable for analysis, but HMS Hecla and RV John Murray shared duties at that location and hourly surface weather observations were logged. Radiation components at the NE corner could therefore be calculated for each hour by models utilizing these observations. Shortwave irradiance was calculated using Lumb’s (1964) formulation and longwave irradiance was estimated using the model of Lind and Katsaros (1982). Shortwave exittance was modelled by using shortwave transmittance, calculated from Lumb’s formulae, and solar zenith angle as input parameters to smoothed albedo observations of Payne (1972). Comparisons were made between model results and measurements to determine the accuracy of each model before it was applied to the NE corner of the JASIN triangle.
2. INSTRUMENTATION

RV Meteor and MV Endurer were identically equipped to measure each component of the radiation budget. Uplooking shortwave sensors were Kipp and Zonen pyranometers (type CM5) having two concentric hemispheres of Schott glass transparent to wavelengths less than 2.8 μm. Neither pyranometer was temperature compensated, but errors induced were less than 2%. Each was deployed high upon its respective ship to minimize interference from ship superstructures. Gimbal mountings were used to keep the sensors horizontal.

Downlooking Kipp and Zonen pyranometers, to measure shortwave exitance, were gimbal mounted from booms over the bow on RV Meteor and at mid-beam on MV Endurer. Interference with the radiation field and shadowing by the ship were large for MV Endurer due to the position of the mounting. Periods when ship shadows contaminated pyranometer data were determined from reports of ship heading and solar azimuth angle calculations. These contaminated data were not used in the ensuing analyses for MV Endurer (Lind 1981).

Longwave irradiance was measured by Eppley Precision Infrared Radiometers, model PIR. These pyrgeometers have mirrored silicon hemispheres with nearly constant transmittance over wavelengths from 4 to 50 μm. Eppley-supplied compensation circuitry was used to correct for detector temperature (Albrecht and Cox 1977). RV Meteor used bead thermistor temperature measurements from within the thermopile and upon the inner surface of the dome to correct for temperature differences. Worst case corrections were less than 3 W m⁻².
Longwave exitances were calculated from the Stefan–Boltzmann Law

\[ M_l = \varepsilon_s \sigma T_s^4 + \rho_s E_l \]  

(2)

where \( \varepsilon_s \) is water emittance (0.96), \( \rho_s \) longwave reflectance (0.045), \( \sigma \) Stefan–Boltzmann constant and \( T_s \) water surface temperature. Values for \( \varepsilon_s \) and \( \rho_s \) are taken from Mikhaylov and Zolotarev (1970). If measurements of \( E_l \) are not available, it is adequate to use \( \varepsilon_s = 1.0 \) and \( \rho_s = 0.0 \). Over conditions experienced during JASIN, this gives results within 1 W m\(^{-2}\) of values calculated using Eq. (2). Water temperature measurements were obtained from ship engine cooling intakes for RV Meteor and from dipped buckets for the other ships. No corrections were made for temperature deviations between the interface and the depth at which \( T_s \) was measured. Such deviations are estimated to be less than \(-0.3^\circ C\) during JASIN, and resulting errors in calculated longwave exitance are less than 2 W m\(^{-2}\).

Data from RV Meteor were sampled at two-second intervals and averaged into ten-minute means. MV Endurer data were sampled at 33 Hz and directed into a micro-processor where ten-minute means and variances were recorded. These ten-minute means were then averaged into hourly values centred on the hour.

3. SHORTWAVE IRRADIANCE

Measurements of shortwave irradiance were compared with model estimates using Lumb (1964) for RV Meteor and MV Endurer. Lumb's model uses cloud observations and past and present weather reports in the hourly surface weather observation as criteria to fit each report into one of his nine cloudiness categories. Lumb empirical fitted curves relating zenith angle, solar constant and shortwave irradiance to each of his categories as

\[ E_s = E_0 (a + bS)S \]  

(3)

where \( E_0 \) is solar constant and \( S \), mean cosine of zenith angle for each hour. Constants \( a \) and \( b \) were empirically derived by Lumb for each category. Lumb's solar constant of 1350 W m\(^{-2}\) was modified to 1380 W m\(^{-2}\) (Wallace and Hobbs 1977), reflecting current ideas. This change introduces a maximum difference of 2% in estimates while not affecting the relationship between \( E_s \) and \( S \) (Lumb 1964).

Comparisons between Lumb's model and measurements from RV Meteor and MV Endurer are shown in Fig. 2. Model – measurement differences are within 10% for most 5-day periods. Model – measurement differences were 17 W m\(^{-2}\) for RV Meteor and -3 W m\(^{-2}\) for MV Endurer averaged over both phases of JASIN.

Differences between measurements and Lumb estimates can be attributed to scatter within each Lumb category, cloud reporting errors, and natural variability of cloud conditions over the reporting hour. Of these, small reporting differences are a major problem, leading to large irradiance differences. If at the time of observation, there were five oktas high stratocumulus, the report should fit category two. If, for the same hour, an observer reported six oktas thin altostratus, the report would fit category four. With a mean cosine of solar zenith of 0.7, one finds a difference of 122 W m\(^{-2}\) for the two categories. Over longer times, such errors tend to average out and Lumb's model accuracy improves to within his specified range (±10% over periods of five days).

Largest errors tended to occur on days with mean observed irradiance between 50 and 150 W m\(^{-2}\). Most cloud reports for these days were categorized as Lumb category 2 or 6. Of the Lumb categories, categories 2 and 6 have the largest scatter about his
regression. Standard deviations between his measurements and regressions are of the order of 50 W m⁻². It is likely that this scatter is the cause of the larger errors of the model for these types of days in our study.

Lumb's model was used to estimate shortwave irradiance for HMS Hecta and RV John Murray when on station at the NE corner of the JASIN triangle. It is anticipated that errors in estimated irradiance are of the same order as found for RV Meteor and MV Endurer.

Figure 3 shows daily mean irradiance over the JASIN meteorological triangle. These were calculated by linearly averaging the three corner irradiances. The vertical lines show the range of mean values of the corners of the triangle. Relative maxima of shortwave irradiance over JASIN occur for Julian days 209–213, 236, 237 and 244. Mean daily irradiance for the JASIN area over phase I was 140·7 W m⁻². For phase II, mean irradiance was 108·7 W m⁻². Irradiances were higher over the northern portions of the JASIN meteorological triangle, indicating less cloud cover, or increased transmittance through clouds, over this region. Means and standard deviations of daily averages for each corner of the triangle and the JASIN area are listed in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Mean phase I</th>
<th>Mean phase II</th>
<th>Both phases</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Eᵣ</td>
<td>σEᵣ</td>
<td>Eᵣ</td>
</tr>
<tr>
<td>NE corner</td>
<td>139·2</td>
<td>69·0</td>
<td>111·3</td>
</tr>
<tr>
<td>NW corner</td>
<td>152·4</td>
<td>57·5</td>
<td>106·6</td>
</tr>
<tr>
<td>S corner</td>
<td>136·8</td>
<td>64·5</td>
<td>107·2</td>
</tr>
<tr>
<td>JASIN area</td>
<td>140·7</td>
<td>60·9</td>
<td>108·7</td>
</tr>
</tbody>
</table>
Figure 3. Daily mean radiative components and net balance of the JASIN triangle for both phases of JASIN 1978. Bars represent maximum and minimum values amongst the three corners of the triangle.
4. SHORTWAVE EXITANCE

Shortwave albedo was calculated from a family of curves, due to Payne (1972), relating albedo to solar zenith angle and shortwave transmittance (ratio of incoming irradiance to irradiance assuming no attenuation by the atmosphere). Payne presented smoothed albedo observations in tabular form using increments of 2° in zenith angle and 0.05 in transmittance. Simpson and Paulson (1979) made measurements of albedo, averaging 0.074, at 35°N. They found Payne's curves to apply well for zenith angles less than 70°. Systematic differences increased with higher zenith angles, the measured albedos being smaller than those given by Payne's curves. They concluded that these differences were within the error margins of the measurement, since the cosine response of these pyranometers decreases as solar zenith angles approach 90°.

Albedos were converted to shortwave exitance by multiplying by the corresponding shortwave irradiance. Corrections for exposure were required for MV Endurer data to compare with results using Payne's curves. The hull of the ship occupied approximately 18% of the hemisphere viewed by the downlooking pyrometer. The hull of MV Endurer was black and reflection from the ship was assumed to be negligible. The ship blocked diffuse irradiance from reaching the ocean surface. The fraction of the skyward hemisphere occupied by the ship relative to a point on the surface beneath the instrument was estimated to be 0.22. Backscattered exitance was also reduced by the ship. This fraction was larger due to ship draught and estimated to be 0.36. Exitance measurements for MV Endurer were corrected by Eq. (4):

\[ E_s = 1.22 \times 1.28 M_{s(m)} + 0.005 \times 0.36 E_s \]  \hspace{1cm} (4)

where \( M_{s(m)} \) is measured exitance, 1.22 is a correction for the ship-blocked exitance, 1.28 is a correction for exitance lost due to the ship blocking diffuse irradiance and 0.005 is fraction of backscattered irradiance (Payne 1972). This correction makes shortwave exitances from MV Endurer more representative of open ocean values. In this case, ship effects reduced exitance measurements to only 65% of expected open ocean exitances.

MV Meteor exitance data were not corrected for ship effects. The mounting of the sensor over the bow significantly reduced the solid angle occupied by the ship. Corrections using the method outlined above are less than 10%. Albedos from RV Meteor, however, are significantly lower than corrected MV Endurer albedos. Cogley (1980) reported that RV Meteor albedos were consistently lower (by 0.02 to 0.07) than other investigators. A cursory comparison of clear sky albedos from Gube et al. (1980) and Payne (1972) shows RV Meteor albedos to be only 70% of Payne's measurements over solar zenith angles from 40 to 60°.

Since albedo data from RV Meteor appear too low, only corrected data from MV Endurer were used to compare with Payne's smoothed observations. MV Endurer shortwave exitances using Payne were computed and compared to mean daily measurements. Modelled shortwave exitances showed good correlation, -0.957, with corrected MV Endurer measurements.

Without measurements of shortwave irradiance for the NE corner of the triangle, a test of calculated exitances was made using transmittances calculated using the Lumb model for MV Endurer. Applying Payne's model in this fashion (using a model result as an input to another model) worked well, as seen in Fig. 4.

The relations derived from Payne were used with shortwave transmittances calculated using Lumb's model to estimate shortwave exitances for RV John Murray and HMS Hecla when on station at the NE corner of the triangle. A time series of daily mean shortwave exitance over the JASIN triangle is shown in Fig. 3. This mean was calculated
as for shortwave irradiance. Mean exitances may be somewhat low due to the inclusion of raw MV Meteor exitances. Payne's calculated climatological mean albedo for this region was 0.06 to 0.07, while our modelled and measured albedos average 0.059. Some decrease in mean albedo is expected for JASIN as mean wind speeds, averaging 7 m s\(^{-1}\), were somewhat higher than Payne's value of 3.7 m s\(^{-1}\). The relative increase in mean albedo from phase I to phase II follows Payne's climatological calculations for July through September at this latitude. Mean shortwave exitance and albedo for each corner of the triangle and the JASIN area are listed in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>Mean phase I</th>
<th>Mean phase II</th>
<th>Both phases</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(M_0)</td>
<td>(\sigma M_0)</td>
<td>(\alpha)</td>
</tr>
<tr>
<td>NE corner</td>
<td>-8.1</td>
<td>4.2</td>
<td>6.9</td>
</tr>
<tr>
<td>NW corner</td>
<td>-8.5</td>
<td>3.2</td>
<td>5.6</td>
</tr>
<tr>
<td>S corner</td>
<td>-6.0</td>
<td>3.2</td>
<td>4.3</td>
</tr>
<tr>
<td>JASIN area</td>
<td>-7.5</td>
<td>2.8</td>
<td>5.6</td>
</tr>
</tbody>
</table>

5. LONGWAVE IRRADIANCE

Measurements of longwave irradiance from MV Endurer over the first phase of JASIN were used to develop a model (Lind and Katsaros 1982) using hourly surface weather observations and twice daily upper air data available from hemispheric analyses. Comparisons between daily mean model estimates and measurements from RV Meteor and MV Endurer are shown in Fig. 5. Mean hourly errors from both phases of
Figure 5. Daily mean measured and modelled (Lind and Katsaros 1982) longwave irradiance during JASIN for M/V Endurer and R/V Meteor.

JASIN were 3.6 W m\(^{-2}\) and \(-2.5\) W m\(^{-2}\) for MV Endurer and RV Meteor, respectively. Root-mean-square differences were 14.6 W m\(^{-2}\) for MV Endurer and 9.0 W m\(^{-2}\) for RV Meteor.

This model was used to calculate longwave irradiance for HMS Hecla and RV John Murray when on station. Table 3 lists mean longwave irradiances for each corner of the meteorological triangle and the JASIN area for each phase and for both phases of JASIN. Worst case errors in the model are expected to be less than 15 W m\(^{-2}\) for any one day. Mean longwave irradiances were largest at the south corner of the JASIN triangle. Means over the triangle are nearly constant for both phases of JASIN. During clear conditions, indicated by cloud reports of less than two oktas, MV Endurer experienced the least longwave irradiance among the ships.

<table>
<thead>
<tr>
<th></th>
<th>Mean phase I</th>
<th></th>
<th>Mean phase II</th>
<th></th>
<th>Both phases</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(E_i)</td>
<td>(\sigma E_i)</td>
<td>(E_i)</td>
<td>(\sigma E_i)</td>
<td>(E_i)</td>
<td>(\sigma E_i)</td>
</tr>
<tr>
<td>NE corner</td>
<td>345-4</td>
<td>11-5</td>
<td>334-7</td>
<td>15-2</td>
<td>341-0</td>
<td>14-7</td>
</tr>
<tr>
<td>NW corner</td>
<td>335-1</td>
<td>14-3</td>
<td>341-3</td>
<td>16-5</td>
<td>338-1</td>
<td>15-7</td>
</tr>
<tr>
<td>S corner</td>
<td>351-0</td>
<td>15-9</td>
<td>352-5</td>
<td>10-9</td>
<td>351-7</td>
<td>14-0</td>
</tr>
<tr>
<td>JASIN area</td>
<td>343-8</td>
<td>13-2</td>
<td>342-8</td>
<td>11-1</td>
<td>343-6</td>
<td>12-4</td>
</tr>
</tbody>
</table>

6. Net radiation balance

Each ship's net radiation balance was computed summing each of the four components (modelled or measured). Longwave exitance was computed using water temperature measurements from each ship (these data were not plotted, as sea surface temperature variations during JASIN were small). Mean longwave exitances increased
slightly (2 W m\(^{-2}\)) between phases for ships at the NE and NW corners, whereas the south corner experienced a decrease (2 W m\(^{-2}\)) from phase I to phase II. Longwave exitance averaged \(-375 W m^{-2}\) over JASIN. Net radiation balances for each phase, and the whole experiment, are listed in Table 4. Throughout the experiment, shortwave irradiance dominated the net radiation balance for this season and location.

### TABLE 4. MEAN NET RADIATION BALANCE AND STANDARD DEVIATION \(\sigma (W m^{-2})\) FOR EACH CORNER AND THE JASIN AREA FOR PHASE I, PHASE II AND FOR BOTH PHASES OF JASIN 1978

<table>
<thead>
<tr>
<th></th>
<th>Mean phase I</th>
<th>Mean phase II</th>
<th>Both phases</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(E_{net})</td>
<td>(\sigma E_{net})</td>
<td>(E_{net})</td>
</tr>
<tr>
<td>NE corner</td>
<td>87.5</td>
<td>16.6</td>
<td>68.6</td>
</tr>
<tr>
<td>NW corner</td>
<td>109.9</td>
<td>45.9</td>
<td>69.4</td>
</tr>
<tr>
<td>S corner</td>
<td>104.3</td>
<td>49.9</td>
<td>78.9</td>
</tr>
<tr>
<td>JASIN area</td>
<td>105.3</td>
<td>45.4</td>
<td>73.6</td>
</tr>
</tbody>
</table>

7. DIURNAL VARIABILITY OF RADIATION DURING JASIN

Mean hourly variations of shortwave and longwave irradiance and reported cloud cover were analysed for the three corners of the JASIN triangle. To compute the hourly distribution of irradiances for the JASIN area, times at each corner were adjusted to local apparent time (\(\text{LAT}\)), and irradiances were normalized to the corner with the largest total irradiance over JASIN. The hourly cloud cover fraction was also normalized in this fashion allowing each corner to contribute equally to the average diurnal cycle of the JASIN area.

Figure 6(a, b and c) shows areal-averaged hourly shortwave irradiance, reported cloud cover fraction and longwave irradiance, respectively, averaged over all days of JASIN. Shortwave irradiance from the afternoon has been folded about local noon (shown as dotted curve) to illustrate the difference between mornings and afternoons. The meteorological triangle received about 15% more shortwave irradiance in the afternoons than during the mornings. The cycle of cloud cover fraction (Fig. 6(b)) shows good correlation with the diurnal cycle of shortwave irradiance. Fractional cloud cover was quite similar at the three corners of the triangle, with mean cover of 0.85, 0.86 and 0.88 at the NW, NE and S corners, respectively. Reported cloud cover averaged 5% higher over the period 00 to 12 \(\text{LAT}\) than from 12 to 24 \(\text{LAT}\). This difference is even larger for the hours when the sun is above the horizon.

The diurnal cycle of longwave irradiance (Fig. 6(c)) is marked by a broad peak between 08 and 13 \(\text{LAT}\), coinciding with reduced shortwave irradiance. Afternoons, with larger shortwave irradiance, experienced a slight decrease in mean longwave irradiance. The diurnal cycles of cloudiness and longwave irradiance are not well correlated, however. This may be due to nonlinear effects of total cloudiness on longwave irradiance. Longwave irradiance is strongly dependent on temperature and humidity in the lower layers of the atmosphere, as well as on cloud cover. Variations of longwave irradiances with mean cloud cover of 7 octas are bound to be small in any case due to the isotropic nature of \(E_i\) and the nearly constant characteristics of the air mass over JASIN.

A more detailed listing of the radiation components from the three corners of the JASIN meteorological triangle may be found in a technical report (Lind et al., 1983) available upon request from RJL or KBK.
Figure 6. Mean hourly distribution of shortwave irradiance (a); reported cloud cover fraction (b); and deviation from mean longwave irradiance (c); averaged over the JASIN triangle for all days of JASIN. Each corner's value has been normalized by the corner with the largest value before averaging. The dotted curve in (a) is afternoon irradiance folded about noon to show the difference between mornings and afternoons.

8. DISCUSSION

The models used in this study are found to work well. Conditions in JASIN were similar to those for which the models were developed. Lumb’s model was developed with ocean weather ship data from the North Atlantic. The Lind and Katsaros model was developed with data obtained on MV Endurer over the first phase of JASIN. Each was found to give satisfactory results when compared with independent observations. Payne’s smoothed albedo observations were found to verify well with corrected MV Endurer data.

Before application of these models to complete the radiation data set for the third corner of the JASIN triangle, they were first tested against measurements from JASIN. Used in this fashion, the accuracy of these models, over periods of a few days, approaches what is obtainable by direct measurement. Errors introduced by using model values in this way can be easily computed.
ACKNOWLEDGMENTS

We appreciate the assistance of the captains and crews of RV Meteor and MV Gardline Endurer and the help of Drs Peter K. Taylor, Trevor Guymet and Arthur Fisher of the Institute of Oceanographic Sciences, Wormley, England and Prof. Erhard Raschke of Cologne University. The research was supported by the Office of Naval Research under contract N00014-80-C-0252 TASK NR-083-012. NATO also provided assistance with travel and shipping.

REFERENCES

Lind, R. J., Katsaros, K. B. and Gube, M. 1983 'The radiation budget and parameterizations in JASIN'. Contribution No. 643, Dept. of Atmos. Sciences, AK-40, Univ. of Washington