Use of albedo modelling and aircraft measurements to examine the albedo of Nauru

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A forward model has been used to examine the relationship between aircraft measurements of the albedo of Nauru and the surface albedo of the island. Measurements from five passes over Nauru, made with an instrumented aircraft during the Nauru’99 field campaign, were used to construct a first guess map of Nauru’s albedo. With these data as surface input values, the model was used to calculate the albedo along each flight leg. By a process of manual iteration the values in the surface map were adjusted until the model results reproduced the essential features of the measurements. Often, large differences between the albedo measured at a particular location and the albedo of the surface below that location were observed. A sensitivity study showed that the limited number of measurement flight legs meant that significant areas of the albedo map remained unverified. This sensitivity technique could be used in experimental planning to ensure adequate coverage of the area being investigated. The average albedo of Nauru was estimated to be 18% ± 2%.

Introduction

The small island nation of Nauru in the Tropical Western Pacific is host to the Atmospheric Radiation Measurement (ARM) program’s Atmospheric Radiation and Cloud measurement Station No. 2 (ARCS2) installation (Clements et al. 1999). Measurements from the ARCS2 are to be used to further ARM’s aim of understanding the role of clouds and radiation in climate. In June and July 1999 a
large field campaign, ‘Nauru’99’, involving two research ships and Airborne Research Australia’s Cessna 404 aircraft, Investigator 2, was conducted in the vicinity of Nauru. One of the aims of the Nauru’99 field campaign was to investigate the manner in which measurements made on Nauru differ from those made over the open ocean (ARM 1999). Understanding the manner in which Nauru modifies the marine airflow will necessarily require analysis of the surface radiation budget, of which albedo is an important component.

Gravenhorst et al. (1999) have shown that point measurements of albedo made from instrumented towers may not provide a representative estimate of albedo. Aircraft measurements overcome this problem by sampling many points along the flight path in a very short time. Although this removes the sampling problem a different problem is introduced: What is the relationship between albedo measured at a given point and the albedo that would be measured at the surface?

This study was conducted with two aims. Firstly, to obtain an estimate of the regional albedo of Nauru. Secondly, to investigate the variation of Nauru’s albedo at the hundreds of metres scale and to investigate the relationship between albedo measured at a given point and surface albedo using the forward model developed by Schwerdtfeger (2002). This was the first time that this model had been used with aircraft field-measurements. The second aim was the main motivation for this study, since estimates of regional albedo could also have been obtained from either high-altitude aircraft flights or from satellite measurements (e.g. Laine and Heikinheimo 1996).

The model

The model used in this work was developed by Schwerdtfeger (2002) and implemented using Airborne Research Australia’s data processing package ‘ARAMF’. An outline of the principles of the model are given here, the application of the model is described in the section entitled ‘Modelling’.

Consider a pyranometer at altitude $z$ above a flat plane which is illuminated by the sun. The total irradiance measured by the pyranometer is (Schwerdtfeger 1995, 2002):

$$ F = \sum_{x_{-}, y_{-}}^{x_{+}, y_{+}} \frac{K_{x}^{2}}{(x_{2}^{2} + y_{2}^{2} + z_{2}^{2})^{2}} \, dx \, dy \quad \ldots 1 $$

Where $K_{(x,y)}$ is the radiance at each point in the plane. Following the method of Schwerdtfeger (2002), we can divide the plane into square grid cells of area $dx \, dy$

and uniform radiance, thus converting the equation into a summation:

$$ F = \sum_{x_{-}, y_{-}}^{x_{+}, y_{+}} \frac{K_{x}^{2}}{(x_{2}^{2} + y_{2}^{2} + z_{2}^{2})^{2}} \quad \ldots 2 $$

This summation can be easily performed if the radiance $K_{(x,y)}$ is specified for each cell in the plane. For a radiometer located at $(x_{i}, y_{i}, z_{i})$ Eqn 2 becomes:

$$ F_{(x_{i}, y_{i}, z_{i})} = \sum_{x_{-}, y_{-}}^{x_{+}, y_{+}} \frac{K_{x_{i}}^{2}}{((x-x_{i})^{2} + (y-y_{i})^{2} + z_{i}^{2})^{2}} \quad \ldots 3 $$

The radiance, $K$, in Eqn 3 can be expressed as a function of the incident radiance and the surface properties at each location. Ideally, this function would take the form of a bi-directional reflectance distribution function (BRDF) in order to account for surface anisotropy and sun-surface-sensor geometry (see for example Manalo-Smith et al. (1998)). However, even a simple semiempirical model such as that of Rahman et al. (1993) requires the recovery of three parameters for each location on the surface. Such a retrieval is not possible for the present investigation where we interpret hemispherically integrated measurements at different locations rather than multiple measurements of a single location, each with a single viewing angle, as discussed by Rahman et al. (1993) and Manalo-Smith et al. (1998). Instead, we are forced to assume that scattering effects are more important than reflection and that the surface can be treated as if it were an isotropic lambertian reflector. With this assumption the outgoing radiance can be represented in terms of the incoming irradiance, $Q$ and a single surface parameter, the albedo, $\beta$:

$$ K_{(x,y)} = \frac{\beta_{(x,y)} Q}{\pi} \quad \ldots 4 $$

This is the usual procedure for boundary-layer meteorology. Substituting for $K$ in Eqn 3 gives:

$$ F_{(x_{i}, y_{i}, z_{i})} = \sum_{x_{-}, y_{-}}^{x_{+}, y_{+}} \frac{\beta_{(x,y)} Q}{\pi} \frac{z_{i}^{2}}{((x-x_{i})^{2} + (y-y_{i})^{2} + z_{i}^{2})^{2}} \quad \ldots 5 $$

If it is assumed that $Q$ is constant over the entire surface, as is the case for a small island such as Nauru, then Eqn 5 may be expressed in terms of the albedo measured at $(x_{i}, y_{i}, z_{i})$:

$$ \beta_{(x_{i}, y_{i}, z_{i})} = \frac{F_{(x_{i}, y_{i}, z_{i})}}{Q} = \frac{1}{\pi} \sum_{x_{-}, y_{-}}^{x_{+}, y_{+}} \frac{\beta_{(x,y)} z_{i}^{2}}{((x-x_{i})^{2} + (y-y_{i})^{2} + z_{i}^{2})^{2}} \quad \ldots 6 $$

This equation can then be used to simulate albedo measurements at a particular location, given specified values of $\beta_{(x,y)}$, and forms the basis of our model.
Fig. 1(a) The coast of Nauru and location of measurement flights. The number of each flight leg is indicated at either end of the leg. The direction each pass was flown is indicated by a triangle.

Fig. 1(b) An aerial photograph of Nauru. Note the bright patches corresponding to areas of high albedo in the albedo map.

Fig. 1(c) Albedo map used as model input in final form developed by comparing model output with aircraft measurements. Each pixel in the image represents one grid cell. Unitless values are in the range 0-35%, indicated by the scale in the figure. Ocean albedo is 3%.

Since Nauru is flat, on average only 30 m above sea level with the highest point at 60 m altitude, and our measurement flights were conducted at altitudes of between 100-200 m above the surface both these conditions were met. Use of the model in areas with significant topography would require a generalised form of Eqn. 3 to account for slope and shadowing effects.

The measurements

Five overflights of Nauru, made on 2 and 4 July 1999 were used to investigate the spatial variation of the albedo of the island. Upwelling and downwelling short-wave irradiance were measured using a pair of Eppley Precision Spectral Pyranometers (PSP), one mounted on the roof of the aircraft and one in a pod under the belly.

The locations of the flight legs are shown superimposed on the outline of Nauru in Fig. 1(a). These passes were flown between the hours of 1100 and 1430, local time, at altitudes of 150 m, 150 m, 150 m, 90 m, and 180 m, respectively. Solar zenith angles (SZA) for each pass, included here to indicate the possibility of effects due to anisotropy, were 34.5°, 33.8°, 32.9°, 24.3°, and 31.6°. Further details of the measurements and flights can be found in Matthews et al. (2000).

Application of Eqn 6 requires that the area under investigation be flat and that the influence of the atmosphere on radiation in the column between the surface and the measurement platform be negligible.
PSP measurements were sampled at 20 Hz by the aircraft data logging system. The e^{-1} response time of the Eppley PSP is one second, so for a flight speed of 70 m s^{-1} only features larger than approximately 100 m could be resolved. Irradiances were averaged over two seconds, thus averaging over unresolvable small-scale features, and albedo was calculated from these averages. Two-second samples during which the sun was obscured by cloud were discarded.

Modelling

Because the model is underdetermined by the measurements and hence cannot be inverted it was necessary to adopt an iterative approach to estimating the surface albedo:
(a) Construct a 'first guess' albedo map;
(b) Use the model to calculate modelled albedo at each point of the five specified measurement runs;
(c) Compare the modelled and measured albedos. If these disagree, modify the albedo map and return to step (b), otherwise finish.
This process is discussed in more detail in the following sections.

Model inputs

As indicated in the preceding discussions two sets of inputs are required for the modelling process:
- aircraft location in three dimensions;
- a map specifying albedo at each point in the model domain.

Aircraft locations were readily available from the aircraft's GPS system and radar altimeter. For ease of calculation latitude and longitude were converted to metres north and east of the ARCS2 installation, on the west coast of Nauru. Altitude was specified as metres above the surface. Each of the five flight legs was kept as a separate list of (x, y) coordinates to allow simpler interpretation of the results.

Constructing the first guess albedo map was a more involved process:
(a) First, a digital atlas was used to construct a 200x200 pixel bitmap image showing only the outline of the island (Fig. 1(a)). Latitude-longitude coordinates, from the atlas, of features on Nauru's coastline allowed the real-world dimensions of each pixel to be determined and also to provide a reference point so that the real-world location of every pixel could be determined. Geo-referencing of the albedo map was performed during the model operation.
(b) Using commercial graphics software, portions of the map expected to have differing albedo were painted different colours. These divisions were made subjectively by examining a colour aerial photograph of Nauru (Fig. 1(b)) and the actual albedo measurements (Fig. 2).
(c) IDRISI GIS software (www.clarklabs.org) was used to convert the arbitrary bitmap colours to first guess albedo values. These values were selected by examining the actual measurements. Finally, the albedo map was converted to a 40,000 element list of integers and saved as a text file for import to the albedo model.

When adjusting the albedo map between iterations of the model it was necessary to begin at step (b) if the shape of any of the regions needed altering or step (c) if only the albedo values required changing.

Operation and tuning of inputs

The albedo model based on Eqn 6 was implemented in the ARAMF data processing software package. The model operation was as follows:
(a) The previously prepared albedo map was read from a file. Using the known (x, y) location of the ARCS2 installation and the real-world dimensions of each pixel the map was georeferenced.
(b) A list of (x, y, z) coordinates and corresponding albedo measurements was loaded for each aircraft leg.
(c) Looping through all aircraft coordinates (x_i, y_i, z_i) for each leg:
- the contribution of each location in the albedo map to a measurement made at (x_i, y_i, z_i) was calculated, i.e. all the terms of the summation in Eqn. 6;
- the contributions were integrated to give the modelled albedo at (x_i, y_i, z_i).

Model results for each aircraft leg were plotted against distance from the ARCS2, in either the x or y direction as appropriate. A difference between measured and predicted albedo at a given point indicated that changes to the albedo map were required. Since some large areas of uniform albedo were seen in the measurements (Fig. 2), it was possible to partly separate the problem of determining the shapes and albedos of each region within the albedo map. For such areas, only a single region of the albedo map was viewed and hence the required map albedo was precisely the measured albedo. With the albedos of these areas fixed, the albedos and then the shapes of the smaller regions were altered. For these smaller regions it was in some cases necessary to alternately modify the albedo and shape several times as the small size of the area meant that a peak in the measurements with the same albedo as the surface was not observed (for example Pass 2, which is discussed below).

The model was re-run each time the albedo map was altered, and new comparisons were made. This
Fig. 2  Model results (black solid curve) are compared with measurements (grey solid curve). The albedo below the point at which each calculation is performed (short-dashed curve) differs from both model and measurements in the vicinity of step changes in surface albedo. ‘Component’ curves indicate the contribution to model calculations by points far from the calculation point (dotted and long-dashed curves). See sub-section ‘Model sensitivity’ for further explanation.

The process was followed until the differences between the model predictions and the measurements were less than two percent. This level of accuracy was achieved for 95 per cent of all island measurement points (determining the single value of albedo for the ocean being trivial) for each run except Pass 4, which is discussed below.

Final values of modelled albedo are presented in Fig. 2 as a function of distance from the ARCS2 in either a northerly or easterly direction, as appropriate. Also included in the plots are measured albedo and the value of the albedo map directly below the calculation point. The final version of the albedo map, from which these results were calculated, is shown in Fig. 1(c).
Results and discussion

All five model runs capture the essential features of the measurements, if not all the fine detail. Common features were:
- measured albedo of approximately three per cent over the ocean;
- measured albedo of 15 to 20 per cent over most of the interior of the island;
- Measured albedo of greater than 20 per cent near the coast.

These features are more or less well defined in each of the five runs. Features of interest were two bright spots observed in Pass 2 (Fig. 2(b)), which were also clearly visible in the aerial photograph (Fig. 1(b)).

The degree to which the observed features were reproduced by the model depended on two things:
(a) whether the regions defined on the albedo map were the correct shapes;
(b) whether the albedo assigned to each region was correct.

Because the surface of Nauru is of greater complexity than can be included in the present model it was not surprising that neither of these criteria were precisely met and so the model results were not in perfect agreement with measurements. In general however agreement was good: in most cases the various rises and dips were correctly located and have the correct amplitude to within two per cent. Pass 1 (Fig. 2(a)) being the simplest also gave the best results, the eastern end of Pass 4 (Fig. 2(d)) gave the worst results.

As Pass 4 was flown from east to west, the mismatches was definitely not due to problems with PSP response time. Further, it was found that the measurements could not be reproduced by the model without grossly distorting the shape of the island. Thus, the most likely explanation is that this result is a reflection on some aspect of the surface on the eastern side of Nauru, which cannot be represented in the present model. Otherwise, no effects of surface anisotropy were evident, as expected since the measurements were made over a small range of SZA and albedo is least dependent on SZA at low SZA (Manalo-Smith et al. 1998).

In the context of the present work it was more important to correctly estimate the albedo of each region than to precisely define the shape of each region. This was justified because, as is shown below, each point calculation viewed only a small area of Nauru, leaving large areas of the island unmeasured.

The unmeasured portion was effectively guessed, rendering fine tuning of the measurements beyond what has been already achieved an unprofitable enterprise.

The difference between surface albedo, as represented by the points extracted from the albedo map, and measured/modelled albedo was in some cases quite striking. Most notable were the two bright spots inland in Pass 2 (Fig. 2(b)), where to produce the measurements of approximately 24 per cent it was necessary to set the map value to 31 per cent. A similar effect can be seen near the coast where map albedos of greater than 25 per cent were needed to reproduce measurements of approximately 20 per cent. Another interesting difference between map and measured albedo was that measurements began to climb from ocean albedo well before reaching the coast. These effects were a result of using hemispheric field of view pyranometers (see also Schwerdtfeger (2002)). These results demonstrate the value of using this modelling technique to estimate the actual surface albedo, which may differ considerably from airborne measurements.

Before using the model results to calculate an area average island albedo it was necessary to examine the sensitivity of the model.

Model sensitivity

Although every point in the model domain contributed to the albedo calculated at a particular location, the contribution of surface points far from the calculation point was greatly reduced (Eqn 6). As a consequence, the limited number of aircraft measurements made in this study means that the albedo map developed cannot be assumed to have been validated over the entire model domain. To investigate the effective coverage of the five aircraft measurement flight runs an investigation of the model sensitivity as a function of distance from the measurement point was made.

For a homogeneous albedo map, contours of relative contribution (equal values of terms inside the summation, Eqn 6) will be concentric circles whose radius depends only upon the altitude of the point at which albedo is calculated. Figure 3 shows contours of relative contribution, RC for model calculations at four points contributing to Pass 4, where

\[ RC_{(x_i,y_j)} = \frac{Kz_i^2/((x-x_i)^2 + (y-y_j)^2 + z^2)^2}{\max(Kz_i^2/((x-x_i)^2 + (y-y_j)^2 + z^2)^2)} \]

where \( x_i \in [x_-x_+] \) and \( y_j \in [y_-y+] \)

This quantity indicates the relative importance of each grid cell to the albedo calculation. Over the ocean the contours were circular. Over the middle of Nauru, where the sample calculation point was in the centre of a large area of constant albedo this was also almost the case. On the other hand, for the measurement points near the coast the contours expanded to...
Four examples of relative contribution by points in the model domain to albedo calculations. Calculations are performed to model albedo at each of the locations marked with a dot. All points outside the solid (dashed) contour surrounding each point make a relative contribution of less than 0.1 (0.01). See text for a detailed explanation of relative contributions. Note the change of the contours from circular to fan like patterns in the vicinity of contrasting changes in surface albedo.

All points within the solid (dashed) contour fell within a 0.1 (0.01) relative contribution contour (of which Fig. 3 shows four examples) for at least one model calculation. Points outside the dashed contour did not significantly contribute to any model calculations. The albedo of these points is therefore untested.

Cover those areas of higher albedo at and near the coast. Included in Fig. 2 are curves which indicate the contribution to the albedo calculation at each point due to points outside the 0.01 and 0.1 relative contribution contours. The contribution by points outside the 0.01 contour was typically around one per cent and never more than two per cent (Fig. 2(b)). This means that if the value of all points outside the 0.01 contour were set to zero (or doubled) the albedo calculation would only decrease (increase) by one percent. Since the agreement between calculated and measured albedo was only two per cent, this implies that the model results must be considered insensitive to points outside the 0.01 contour. The contribution by points outside the 0.1 contour was typically at least five per cent over land and hence the contribution by points between the 0.1 and 0.01 contours was typically four per cent, which was significant. So, we conclude that the model was insensitive to points outside the 0.01 relative contribution contour and sensitive to those points within it. Thus only those points which fell inside a 0.01 contour for at least one of the aircraft measurements points can be considered to have been verified by the model results, since points outside this area do not significantly affect model calculations. The total area of Nauru which fell within these bounds is shown in Fig. 4. From this figure it can be seen that there are large areas of the island which were not covered, and there is no reason to suppose that the values assigned to these areas are correct other than that their visual appearance is similar to that of the areas measured.

In future work this type of sensitivity analysis could be used in planning experiments, given some reasonable assumptions about the surface albedo, e.g. using textbook values for grass, sand etc. to construct an albedo map from a photograph. Alternatively, the area viewed by a radiometer at height z may be estimated by analysis of Eqn 7 (we are indebted to an anonymous reviewer for this point). If constant albedo is assumed then contours of relative contribution will be circles and Eqn 7 reduces to:
Where \( R \) is the radius of the contour having relative contribution \( RC \). For \( z \) equal to 150 m, say, the 0.1 and 0.01 contours have radii of 220 m and 450 m, respectively. Hence, for a flight at 150 m, parallel passes should not be more than 900 m apart.

### Mean island-albedo
An estimate of the average albedo of Nauru was simply calculated from the partially verified albedo map (Fig. 1(c)) as the average albedo of all pixels in the model domain which were not ocean. In this manner, the albedo was estimated to be 17.9 per cent. Estimating the accuracy of this calculation is hindered by the lack of measurements for those areas not sampled. Certainly the estimated albedo cannot be more accurate than the agreement between those areas which were measured, two percent in this case. Since albedo is known to increase greatly at high solar zenith angles as a consequence of surface anisotropy (e.g. Manalo-Smith et al. 1998, Fig. 12), albedo estimated here will not apply at all times of the day. Further measurements would be required to determine the solar zenith angle dependence of Nauru’s albedo.

### Conclusions
Measurements made from an instrumented aircraft have been used to measure the albedo of Nauru. Because hemispheric field-of-view radiometers were used to make these measurements it was necessary to investigate the relationship between measured albedo and surface albedo. A forward model was used to iteratively estimate the surface albedo required to reproduce the observations. Over some areas of Nauru surface albedo differed considerably from measured albedo, particularly near step changes in surface albedo. A sensitivity analysis of the model revealed that large areas of the island did not contribute significantly to the model calculations. These areas were effectively unmeasured and this introduced uncertainty into the area averaged estimate of albedo. This aspect of the model could be used when planning experiments to ensure that flight paths do provide adequate coverage of surface features.

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