Modification of the atmospheric boundary layer by a small island: observations from Nauru

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Abstract

Nauru, a small island in the tropical Pacific, generates plumes of clouds that may grow to several hundred km length. This study uses observations to examine the mesoscale disturbance of the marine atmospheric boundary layer by the island that produces these cloud streets. Observations of the surface layer were made from two ships in the vicinity of Nauru and from instruments on the island. The structure of the atmospheric boundary layer over the island was investigated using aircraft flights. Cloud production over Nauru was examined using remote sensing instruments.

During the day the island surface layer is warmer than the marine surface layer and wind speed is lower than over the ocean. Surface heating forces the growth of a thermal internal boundary layer, above which a street of cumulus clouds forms. The production of clouds results in reduced downwelling shortwave irradiance at the island surface. A plume of warm-dry air develops over the island which extends 15 – 20 km downwind.
1. Introduction

The Atmospheric Radiation Measurement program (ARM) aims to improve the parameterisation of clouds and radiation in climate models (Department of Energy 1996). The observational component of ARM comprises long-term, routine measurements of clouds, radiation, and meteorology with additional intensive field campaigns to address specific questions. Routine measurements are made in three locations: The Southern Great Plains in the USA, the North Slope of Alaska, and the Tropical Western Pacific Ocean (TWP). The TWP sites, known as Atmospheric Radiation and Cloud Stations (ARCS) house radiometers, surface meteorology instruments, cloud remote sensing equipment, and atmospheric profiling systems. Because of the quantity and nature of the instrumentation required it was necessary to place the ARM sites on land, rather than on, for example, buoys. In the TWP three sites are maintained, at Manus Island, Papua New Guinea (opened 1996), at Nauru (opened 1998), and at Darwin, Australia (opened 2002).

Nauru, a small, flat island in the western Pacific Ocean is the world’s smallest republic (Fig. 1). Most of the land area of Nauru is the central plateau, known as Topside, surrounded by a narrow coastal strip. The ARCS is situated on the west coast of Nauru. Although Nauru is a very small island, 5 km in diameter with most of the island below 30m altitude, it was anticipated that it would have some effect on the ARCS measurements. To examine this ‘island effect’ and to relate the island based measurements to data collected over the ocean, the Nauru'99 field campaign was conducted in June and July, 1999. The field campaign included instruments on the island itself, two ships stationed near the island, and measurements made by Airborne Research Australia’s Cessna 404 aircraft. This paper integrates observations from
Nauru’99 to characterise the meso-scale disturbance to the marine flow caused by the island. These results will be of use to studies that characterise the effect of the island generated circulation on ARCS measurements and seek to compensate for these effects.

Nauru’s island circulation is also an interesting meteorological phenomenon in its own right. Three types of atmospheric circulations associated with islands can be identified in the literature. The first is generated by tall islands which are mechanical obstacles to the flow and generate a wake; examples are the Aleutian Islands (Thomson et al. 1977), Hawaii (Smith and Grubišić 1993), and St Vincent (Smith et al. 1997). The second is produced by large islands in low wind speed regimes which generate meso-scale convection over the island driven by convergence of coastal sea breezes; examples are the Tiwi Islands (Keenan et al. 2000) and Puerto Rico (Malkus 1955). The third type are associated with small islands which, while they do not generate proper sea breezes, may produce convective clouds that may form long streets; examples are Anegada (Malkus 1963), Nantucket (Malkus and Bunker 1952), Barbados (De Souza 1972) and, it shall be shown, Nauru.

Both Anegada (Malkus 1963) and Nantucket (Malkus and Bunker 1952) produce cumulus clouds which form a cloud street up to 30 km in length. Plumes of heated turbulent air were observed over and downwind of the islands. Specific humidity in the boundary layer above Anegada was observed to be higher than over the surrounding ocean, while results from Nantucket were mixed. A plume of warm, dry air was observed over and 30 km downwind of Barbados in aircraft measurements reported by De Souza (1972). Analysis of pilot balloon trajectories indicate a mesoscale ‘island circulation’ with downward motion over Barbados and upward
motion downwind of the island during the day, with the reverse at night. Mahrer and Pielke (1976) have argued that De Souza neglected to account for terrain effect in divergence calculations but on the basis of model results predicted that this island circulation should be observed over a flat island. The effect of topography in flow over a small island is discussed further by Savijärvi and Matthews (2004). Nordeen et al. (2001) observed a street of cumulus clouds downwind of Nauru using satellite imagery. Cloud streets were first observed shortly after sunrise and grew to a mean length of 125 km by 1630 local time (LT). The streets were aligned with the mean wind direction and grew at one-third of the mean cloud level wind speed.

The present study builds on prior observations of island effects using a more extensive suite of surface based observations, in addition to extending aircraft measurements similar to those made by Malkus and Bunker (1952), Malkus (1963), and De Souza (1972) to a new location.

2. Observations

The Nauru’99 field experiment was conducted from June 17th to July 17th, 1999. The main platforms participating in Nauru’99 were the ARM Atmospheric Radiation and Cloud Station (ARCS) on Nauru, the research vessels Mirai and Ronald H. Brown and Airborne Research Australia’s Cessna 404 aircraft. The observations used in this study were from two phases of Nauru’99: the big triangle phase, from June 24th to 30th, and the small triangle phase, from July 1st to 4th. During the big triangle phase, the two ships were stationed 250 km from Nauru, forming a triangle with the island (Fig. 1). During the small triangle phase the ships moved to within 50 km of the island. Throughout both phases the aircraft made measurement
flights over the ocean between the three surface platforms and also over Nauru. All data used in this study were obtained from the ARM data archive: www.archive.arm.gov.

a. Instruments on Nauru

Measurements were made at three locations on Nauru during Nauru’99: at the ARCS installation and at two locations in the interior of the island, called Topside 1 and 2 (Fig. 1). The ARCS installation is a permanent facility on the west coast of Nauru, collecting climatological data. The ARCS incorporates instruments measuring surface meteorology, broad- and narrow-band irradiances, atmospheric profiles and cloud properties. Measurements from the ARCS are processed and sorted by ARM into several data packages. This study uses measurements from four of the ARCS data packages:

- Sky radiation: downwelling long- and short-wave irradiance,
- Ground radiation: upwelling long- and short-wave irradiance, radiometric surface temperature,
- Surface meteorology: air temperature, relative humidity, and air pressure at 2 m altitude, wind speed and direction at a height of 10 m,
- Whole sky imager (WSI): cloud amount over the whole sky and in nine sub-areas: a 10° circle at the zenith, four quadrants from 0° to 45° zenith angle, centered at the cardinal points and four quadrants from 45° to 80° zenith angle.

All data were sampled at 1 minute resolution, except for WSI, sampled at 10 min intervals.
The two weather stations in the island interior measured air temperature, relative humidity, air pressure, wind speed and direction, upwelling long-wave irradiance and downwelling short-wave irradiance at 1 minute intervals. Radiometers were mounted at 2 m AGL and the remaining instruments were mounted at 3 m AGL. The towers were located at 30 m MSL. Data were recorded on self-contained data loggers and downloaded manually.

b. Ships

Both ships deployed during Nauru’99 were equipped to make a broad range of meteorological and oceanographic measurements of which this study uses only a small sub-set. Measurements used from the Mirai were:

• Air temperature, relative humidity, wind speed and direction, air pressure, rainfall and downwelling long- and short-wave irradiance from Brookhaven National Laboratory instruments mounted above the bow of the ship at 30 m ASL,
• Sea surface temperature measured by the Rutherford Appleton Laboratory Scanning Infra-red SST Radiometer,
• Vertical profiles of temperature, relative humidity and winds from Vaisala radiosondes.

Time series measurements were sampled at 1 minute intervals, radiosondes were launched every three hours. Full details of instrumentation and data processing are given in JAMSTEC (1999).

Measurements used from the Ronald H. Brown were:
• Air temperature, relative humidity, wind speed and direction, air pressure, rainfall and downwelling long- and short-wave irradiance from Environmental Technology Laboratory (ETL) instruments mounted on a staff on the bow of the ship at 18 m ASL,

• SST measured by ETL’s ‘sea snake’; a thermometer towed behind the ship at a depth of 5 cm.

All measurements were obtained as 10 minute averages. Fairall et al. (1997) describe the ETL instruments.

c. Aircraft

Measurements in the ABL were made using Airborne Research Australia’s Cessna 404 aircraft, Investigator 2. The aircraft was equipped with instruments for measuring air temperature, humidity, the 3-dimensional wind vector, radiometric surface temperature, up- and downwelling long- and short-wave irradiance and cloud liquid water content. Meteorological instruments were mounted on the nose-cone or had air intakes in the nose. Radiometers were mounted on the roof and in a pod underneath the aircraft. Full details of the instruments and data processing are given in Matthews et al. (2000).

Eight data gathering flights were made during Nauru’99. Only those flights used in this paper are described here, a complete description of all flights is given in Matthews et al. (2000). During the big triangle phase of Nauru’99 eight triangles were flown from Nauru to the Mirai, to the Ronald H. Brown, and back to Nauru (Fig. 1). Between corners of the triangle, the aircraft maintained an altitude of 30 m. During the small triangle phase a variety of flight patterns were flown near Nauru.
On July 2nd, three stacks of triangles, following the same pattern as the big triangles, were flown. Each stack consisted of up to four triangles at altitudes of 30 m, 400 m, 1200 m and 3000 m. The Mirai to Ronald H. Brown legs of the third stack were extended to pass under and through the cloud street. Three crosswind passes over Nauru at an altitude of 150 m were also flown on July 2nd. On July 4th three stacks of alongwind traverses of Nauru were made. Up to five traverses were made for each stack, at altitudes ranging from 40 m to 1100 m. The aircraft inertial navigation system failed on this day and so no wind measurements were available for July 4th.

3. Results

a. Preliminary investigations

Two questions were addressed before using the measurements from the ships and ARCS to investigate the effect of Nauru on the marine ABL: were the measurements from the platforms consistent, and what did the point measurements from the ships and ARCS represent?

The first question was addressed using comparisons between measurements platforms. Side by side comparisons were used amongst the island stations, between the ships, and between the ARCS and the Ronald H. Brown. Because side by side comparisons of downwelling solar irradiance, $S_{dn}$ were not possible, an examination of clear-sky $S_{dn}$ was made. Comparisons with aircraft data were made only for surface temperature and albedo (Section 3.a.2), as no other mean quantities from the aircraft were used when contrasting the island and ocean measurements. Spatial variation of radiation and meteorology over the island and ocean were examined and used to construct representative ‘ocean’ and ‘island’ data sets.
1) Platform comparisons

The two weather stations were relocated to the ARCS compound on July 22\textsuperscript{nd}, 1999 for a 12 day comparison with the ARCS instruments. Measurements from this period were used to remove air temperature dependent differences of up to 2 K in air temperature and up to 15 % in relative humidity measurements from the Topside weather station measurements. Upwelling longwave irradiance measurements were scaled to remove 0.5 % and 0.7 % excesses from the weather station measurements. No other adjustments were required.

The \textit{Ronald H. Brown} was stationed 500m downwind of the ARCS on the night of July 4\textsuperscript{th}. Direct comparisons between the ship and island based instruments were not possible because of local effects due to the differences in physical properties between land and water. The two measurements not expected to be affected, wind direction and downwelling longwave irradiance agreed to within instrumental accuracy (Fig. 2). Specific humidity was 1 g kg\textsuperscript{-1} lower at the ARCS than at the \textit{Ronald H. Brown}. With the information available it was not possible to determine whether this was a physical effect or was due to differences in calibration. Prior to a rain shower at 0100 LT, surface temperatures, $T_{\text{surface}}$ differed by less than 1 °C. At this time potential temperature, $\theta$ also differed by less than 1 °C, indicating that the two sensors were in agreement. The different roughness lengths of the land and ocean meant that ARCS wind speed was lower than at the \textit{Ronald H. Brown} and it was not possible to test for any differences in calibrations.

On July 3\textsuperscript{rd}, the \textit{Mirai} and \textit{Ronald H. Brown} cruised side-by-side to allow comparison of the ships’ instruments (Fig. 3). With the exception of downwelling
longwave irradiance all measurements agreed to within instrumental errors, although wind measurements were disturbed during the second half of the comparison when the ships were manoeuvring. A 5 W m\(^{-2}\) difference in longwave irradiance was corrected by increasing measurements from the *Mirai*.

Downwelling shortwave irradiance, \(S_{dn}\) measurements were compared by examining clear-sky irradiance for each platform. Long and Ackerman (2000) developed a method to identify clear sky conditions from global and diffuse shortwave irradiance using four tests. The tests are based on the magnitude and rate of change of global shortwave irradiance and on the magnitude and variance of diffuse irradiance. Clear-sky \(S_{dn}\) may be compared between locations by fitting a model of \(S_{dn}\) to those measurements identified as clear sky:

\[
S_{dn} = a X^b
\]

where \(X\) is the cosine of the solar zenith angle, and \(a\) and \(b\) are regression coefficients. Because measurements of diffuse shortwave irradiance were not available from the ships, the full method could not be applied and the two global irradiance tests only were relied on to identify clear skies. Omission of the diffuse irradiance tests meant that some periods when small, scattered clouds which did not obscure the solar beam were present were erroneously identified as clear (Long and Ackerman 2000).

The omission of the diffuse irradiance tests from the ARCS measurements resulted in over estimation of \(S_{dn}\) by up to 50 W m\(^{-2}\) at zenith angles below 45\(^{\circ}\) and underestimation by up to 30 W m\(^{-2}\) at zenith angles greater than 45\(^{\circ}\) (Fig. 4). Visual inspection of data series indicated that the overestimation was due to samples with enhanced \(S_{dn}\) due to scattering from cloud being marked as clear, while the underestimation was an artefact of fitting Eq. (1) to these exaggerated values.
Estimates of clear-sky $S_{dn}$ from the ships differed by less than 1 W m$^{-2}$ at all solar zenith angles (Fig. 4) but were 30 W m$^{-2}$ below $S_{dn}$ at the ARCS at solar noon. The differences between land and sea may have been due to differences in instrument calibration, clear-sky $S_{dn}$, or the amount of cloud not detected by the algorithm. It was not possible to separate these effects, although the differences were larger than would be expected from typical differences in instrument calibration. For comparisons of mean $S_{dn}$ between land and sea differences less than 30 W m$^{-2}$ were not considered significant.

2) Spatial variation on Nauru

$S_{dn}$ in the presence of a cloud street has been investigated for the Nauru’99 period by McFarlane et al. (2005). They found that $S_{dn}$ was up to 10 % lower on the lee side of the island than on the windward side. Downwelling longwave irradiance, was 5 – 10 Wm$^{-2}$ higher on the lee side of the island than on the windward side.

The ground facing radiometers at the ARCS viewed the gravel surface of the ARCS enclosure. The albedo of this surface was 40 %. Albedo measurements from the aircraft, reported in Matthews et al. (2002), found that Nauru’s area-averaged albedo was much lower, around 18 %. Similarly, aircraft measurements of radiometric surface temperature showed the majority of the island surface to be cooler during the day than the ground viewed by the ARCS radiometers (Fig. 5). ARCS surface temperature measurements have been scaled using the least-squares line of best fit to this comparison, to give a more representative value for surface temperature. No measurements were made for ARCS temperatures in the range 25 –
30 °C (Fig. 5) and hence there is some uncertainty about the accuracy of the scaling in this range.

From internal boundary layer theory it would be expected that the surface layer would adjust to the change in surface forcing that the island represents, resulting in alongwind (i.e. east to west) gradients in wind speed, air temperature, and humidity until a new equilibrium is reached (Garratt 1990). Temperature, wind speed, and humidity were similar at the ARCS and at Topside 1, while at Topside 2 the wind speed was higher, the air cooler and specific humidity similar to the ARCS (Fig. 6). It is unclear whether the differences between the two Topside stations were due to local effects or differences in exposure to the marine air flow. However, it is likely that the ARCS measurements were representative of at least the western half of the island, with cooler and windier conditions near the windward coast.

For simplicity, the ARCS measurements, with modified albedo and surface temperature, are used in the remainder of this paper and are referred to as the ‘island’ data set.

3) Spatial variation over the ocean

Satellite imagery suggested that atmospheric conditions were homogenous throughout the area of the Nauru’99 experiment and so the ship measurements could serve as an estimate of the flow incident on Nauru. During the five days of big triangle flights the only measurement to show a systematic, spatial gradient was SST (Fig. 7). A pool of warmer water extending for 35-40 km north and east from the *Ronald H. Brown* was observed in aircraft measurements. The uniformity of all other measurements was reflected in the similarity of the ship data, SST and rain events
excepted, throughout the experiment. When the ships moved closer together for the small triangle phase the difference in SST closed and all measurements were in agreement. On the basis of this uniformity, it was concluded that the surface measurements from the ships were representative of the air incident on Nauru, except for local events such as rain, and SST from *Ronald H. Brown*. The *Mirai* data set was used as the ‘marine’ data set. In constructing the net radiation budget albedo was assumed to be 5%, and upwelling longwave irradiance was calculated as the sum of emitted irradiance, from surface temperature using the Stefan-Bolzmann law, and reflected irradiance from downwelling longwave irradiance, using an emissivity of 0.97.

b. The atmosphere over the ocean

Nauru’99 was characterised by suppressed convective conditions. Significant cloud clusters were not observed over the experimental area but were seen further west (Yoneyama and Katsumata 2000). Balloon soundings from the *Mirai* showed a shallow mixed layer of depth 600 - 650 m with a stable atmosphere above (Savijärvi and Matthews 2004). The free stream trade wind at Nauru averaged 10 ms\(^{-1}\) at 2 km ASL. Clouds were mostly small fair-weather cumulus (Takemi 2000) and the largest rain event was 9 mm at the *Ronald H. Brown* on June 28\(^{th}\) (Fig. 7). Mean low cloud fraction derived from ceilometer measurements on the *Mirai* was estimated to be 0.142 and cumulus fraction to be 0.122 (Takemi 2000). The median cloud base height was 750 m, 100 – 150 m above the mixed layer top and coincident with the lifting condensation level.
Surface layer conditions during Nauru’99 were quite uniform, exceptions being the rain showers at both ships on June 27th – 28th. Although most measurements showed some variability on time scales longer than one day there were not large changes and one day was much like another, with the exception of wind speed which increased steadily in the earlier part of the experiment (Fig. 7). To better reveal diurnal cycles mean series were constructed as the average of measurements from all days except June 28th, for which no downwelling solar radiation measurements were available from the Mirai (Fig. 7), divided into 1 hour segments (Fig. 8).

The most significant variation in potential temperature was the diurnal cycle, which had an average amplitude of 0.5°C. A spectral analysis by Takemi (2000) also revealed smaller temperature variations on longer time-scales, with a peak at 3.5 days.

Specific humidity increased before, and decreased after, the rain showers at both ships. Smaller variations were also observed on time scales longer than one day. A weak semi-diurnal cycle in q was observed, with peaks at midday and midnight (Fig. 8).

Wind speed increased from <2 m s⁻¹ to a peak of 9 m s⁻¹ during the period June 24th – 29th. Thereafter, wind speed varied between 5 and 9 m s⁻¹ with an average strength of 6.5 m s⁻¹. Also, a diurnal cycle with its peak at around 0800 LT was observed in the composite measurements. During Nauru’99, wind direction oscillated from ENE to ESE with a period of 4-5 days (Grachev et al. 2001). No significant diurnal cycle was observed in wind direction.

A small upward trend in SST at the Mirai was seen during the big triangle phase; Yoneyama and Katsumata (2000) report that the 28 °C isotherm deepened during this time. The diurnal cycle had an average amplitude of 0.3 °C.
Downwelling shortwave radiation deviated from a simple solar zenith angle dependence only in the presence of the ubiquitous cumulus clouds. The uniformity of the marine atmosphere was also reflected in downwelling longwave irradiance, $L_{dn}$, with day to day variations of less than 10 W m$^{-2}$. Increases in the magnitude of $L_{dn}$ due to the presence of cloud were observed throughout the field campaign, with amplitudes of up to 30 W m$^{-2}$.

c. Surface meteorology of Nauru

Nauru presented a disturbance to the marine ABL. The surface meteorology of Nauru is thus the result of the modification of the marine atmosphere by this disturbance and so surface layer meteorology on Nauru must be considered in relation to marine conditions.

Time series of the island and marine data sets are shown in Figs. 6 and 7. Examination of satellite images revealed two days when a cloud street did not form, June 24$^{th}$ and 30$^{th}$. These days have been excluded when examining diurnal cycles. Diurnal curves of radiation and surface meteorology were constructed as the averages of measurements from the remaining 8 days divided into 1 hour segments (Fig. 8).

In the mean diurnal data, $S_{dn}$ over Nauru was lower than over the ocean during the afternoon. Until 1300 LT the differences were less than 20 W m$^{-2}$ but in the late afternoon $S_{dn}$ at Nauru was up to 100 W m$^{-2}$ below the ocean measurements. Averaged over the course of the day the difference was 14 W m$^{-2}$. Although a difference in $S_{dn}$ was observed only during the afternoon, clouds were produced downwind of Nauru earlier in the day but did not significantly affect $S_{dn}$ measurements as they did not obscure the sun (Section 3e).
Mean $L_{dn}$ was of similar magnitude over both the island and ocean but a different diurnal pattern was observed in each location. Over the ocean there were peaks in the early morning and late afternoon with a minimum at midday. This pattern broadly matched the diurnal cycle of low cloud fraction observed from the *Mirai* (Takemi 2000). At Nauru, $L_{dn}$ was at a maximum around midday and at a minimum before dawn. Two factors acted together to influence $L_{dn}$ over Nauru: increased low cloud fraction during the day and heating of the air column above the island.

Surface temperature on Nauru exhibited a strong cycle of daytime heating and nighttime cooling with an amplitude of up to 17 °C. In the mean cycle, island surface temperature, $T_{surface}$ was at a minimum, 2.5 °C below SST, shortly before sunrise. During the morning $T_{surface}$ climed to a maximum of 36.8 °C, which was sustained for several hours. During the afternoon, the surface cooled and $T_{surface}$ dropped below SST shortly after sunset, at which time air temperature also declined below the marine air temperature. Maximum surface temperatures increased during the first four days of Nauru’99 but dropped by 8 °C after the rainfall on June 28th. Maxima then increased steadily for the remainder of the experiment. Minimum surface temperatures were less strongly affected by rain but showed similar behaviour.

As a consequence of Nauru’s higher surface temperature and albedo, net radiation at the island surface was lower than at the ocean surface during the day, by 160 W m$^{-2}$ at midday. Small day to day variations in net radiation were driven largely by variation in surface temperature on days when a cloud street formed, and by changes in $S_{dn}$ on the days when a cloud street did not form but clouds were present over the island.
The 2 m air temperature record from Nauru was dominated by a cycle of daytime heating and nighttime cooling, forced by changes in surface temperature. Throughout Nauru’99 daily maxima ranged from 1-3 °C above the marine air temperature, while minima were up to 5 °C cooler. On average, air temperature increased shortly after sunrise from a night-time minimum of 25.9 °C and exceeded the marine air temperature after 0830 LT. A maximum temperature of 29.4 °C was achieved at midday. Thereafter, air temperature dropped and was equal with the marine air temperature at sunset (1915 LT) then continued cooling throughout the night.

Specific humidity on Nauru was consistently 1 g kg\(^{-1}\) lower than over the ocean but showed day-to-day trends similar to the marine record. As has been described above, it was not possible to perform satisfactory interplatform comparisons of ship and island humidity sensors. The observed 1 g kg\(^{-1}\) difference was small enough that it may have been either due to calibration differences or of physical origin, for example, adjustment of the surface layer to the dry surface of the island.

Wind speed over Nauru was lower than over the ocean at all times and had a diurnal cycle with its maximum in the early afternoon. The average cycle had an amplitude of 2.1 m s\(^{-1}\), increasing from a minimum of 2 m s\(^{-1}\) prior to dawn to a maximum of 4.1 m s\(^{-1}\) around noon, then decaying in the evening. During the earlier part of the experiment, in which wind speed increased over the ocean, maximum wind speed over Nauru also increased but more slowly. The difference between the daily maximum wind speed at Nauru and the marine wind speed increased from <1 m s\(^{-1}\) on June 24\(^{th}\) to around 4 m s\(^{-1}\) on June 28\(^{th}\). The difference in maxima remained at 2-3 m s\(^{-1}\) throughout the rest of Nauru’99. Wind direction on Nauru closely tracked wind
direction over the ocean but was systematically 7 – 8 degrees less on Nauru than over the ocean.

d. Atmospheric boundary layer structure

Aircraft flights to examine the structure of the boundary layer above Nauru were made on July 4th. Between 1230 LT and 1430 LT two stacks of four flight legs each were flown over and downwind of Nauru (Fig. 1) to examine the structure of the boundary layer. Flight legs were at 90, 180, 360, and 710 m above sea level. During this time, cumulus clouds were forming over Nauru. A cloud plume approximately 5 km wide extended 15 - 20 km downwind of the island. Cloud base was at 750 m. Beyond this, a thinner plume extended for a further 20 – 30 km. To better reveal the mean ABL structure, measurements from the two stacks have been interpolated to a common axis and the average calculated. A 3rd stack with legs at 40, 470, and 1000 m was flown between 1040 LT and 1120 LT but is not shown here as measurements were very similar to those of the stacks with more complete coverage.

A plume of warmer air extended from the surface of Nauru through the depth of the mixed layer to 20 km downwind of Nauru (Fig. 9). The core of the plume, from 0 – 15 km downwind of Nauru was 0.3 °C above the marine air temperature, with a region of stronger heating near the surface of the island. The leading edge of the plume moved downwind with increasing altitude. This is typical of a developing thermal internal boundary layer (Garratt 1990). Closer to 20 km downwind temperatures returned to the marine value as the plume dissipated. The plume was generated by a strong sensible heat flux from the surface of the island. Although flux measurements from July 4th were not available, values were available from passes
over the island made on July 2nd. These showed sensible heat fluxes of 55 - 295 W m\(^{-2}\) over Nauru, compared with < 5 W m\(^{-2}\) over the ocean. In the leg at 710 m, an upward trend in temperature west of Nauru was observed, although the trace was dominated by fluctuations. It is not possible to say from these measurements whether this sub-cloud heating was due to upward transport of heat from the island surface or enhanced downward mixing of warmer air in the wake of the island.

The region of the plume downwind of Nauru was also drier than the marine air. A region with specific humidity up to 1 g kg\(^{-1}\) below the marine value extended from Nauru to 15 km downwind of the island. This drying was not as clearly defined as the heating, due to the larger variance of the specific humidity. On July 2nd, latent heat flux at the surface of Nauru was 160 - 245 W m\(^{-2}\). This was larger than over the ocean, enhanced by increased turbulence. Without flux measurements it was not possible to identify the cause of the drying. However, a probable explanation is enhanced mixing between the mixed layer and sub-cloud layers due to increased turbulence over Nauru. As with the temperature measurements, humidity measurements in the sub-cloud layer were dominated by fluctuations but there was not a well defined trend.

The boundary layer below the cloud street, which had cloud bases at 750 m, was examined using two sets of crosswind passes flown on July 2\(^{nd}\) (Fig. 1). The aircraft flew across the cloud street at altitudes of 30 m, 400 m, and 1100 m. The lowest and highest passes did not show temperature or humidity deviating from the undisturbed marine values. The pass at 400 m, through the middle of the mixed layer, displayed two striking features. On either side of the cloud street areas of increased temperature and decreased humidity extended 6 - 7 km from the centre of the cloud.
street (Fig. 10). Potential temperature was up to 0.7 °C above values in the nearby atmosphere, while specific humidity was up to 3 g kg⁻¹ lower. This pattern was characteristic of convective rolls as observed by Brümmer (1985) and LeMone and Pennel (1976), indicating downward mixing of warm, dry air on either side of the cloud street. Further confirmation of the presence of a pair of convective rolls would best have been provided by means of vertical wind measurements. However, to reveal the mean vertical motion of convective rolls it is necessary to average over a large number of measurements, which was not possible here with only two passes under the cloud street.

**e. Clouds**

The cumulus clouds produced over Nauru were observed in whole sky imager (WSI) images and aircraft video. These clouds formed as small, individual cells separated by clear air. This type of cloud formation is typical of forced convection, whereby clouds form when thermals in the boundary layer reach the lifting condensation level (Stull 1985). Weather conditions on June 29th provided a good opportunity to examine the diurnal cycle of cloud production over Nauru. On this day clouds did not form over the ocean in the vicinity of Nauru, and thus all clouds recorded by remote sensing instruments were due to the presence of the island. Visual inspection of WSI images showed cloud production began at 0935 LT, with clouds forming in two locations, to the north and south of the ARCS approximately 5 km downwind of the island’s lee coast. During the day, cloud production intensified and moved eastwards over the ARCS then over the interior of Nauru. During this time the WSI images did not show a preferred location for cloud formation. In the late
afternoon cloud production decreased and retreated beyond the lee coast and ceased shortly before sunset.

Whole sky imager analyses of cloud cover provide a quantitative description of cloud production. Cloud amounts for quadrants of the sky centred on the cardinal directions are shown in Fig. 11. The sky was clear until 0935 LT. The apparent cloudiness in the east prior to 0935 LT was a misclassification of the sun’s aureole as cloud. This problem also exaggerated cloud amounts in the north quadrant by up to 10 % between 1200 LT and 1430 LT and in the west quadrant by up to 10 % from 1430 LT to sunset. In spite of these difficulties, a clear asymmetry was observed in the cloud field. From 1200 LT to 1700 LT cloud cover in the west ranged from 20 % to 50 %, while in the east and south cloud cover was below 20 %, except for a brief period around 1600 LT. Cloud cover in the north was more variable due to the ESE wind resulting in some island-produced clouds being located in the north quadrant. In the late afternoon cloud production collapsed, with only a very few clouds detected in the period from 1700 LT until sunset.

4. Discussion

The Nauru island circulation was driven by the change in surface properties encountered by marine air as it was advected over the island. Nauru differs from the ocean surface in two important respects: the surface was rougher and the surface was hotter during the day.

The island surface was heated by the absorption of solar radiation. Although the albedo of Nauru was larger than that of the ocean, and hence net radiation was
lower, the effective heat capacity of the soil was lower than that of the ocean mixed layer, thus allowing the surface to heat to an average 10° above SST at midday.

Heating of air over the island initiated the development of a thermal internal boundary layer (TIBL). The TIBL grew rapidly into the neutral mixed layer, reaching the middle of the mixed layer over the lee coast of Nauru. The TIBL was characterised by increased temperature, strong turbulent mixing and a large upward sensible heat flux at the surface. Downwind of Nauru a plume of warm air persisted for 20 km before dissipating. This plume was also drier than the marine air. Cross-sections flown beneath the cloud street suggested that it was sustained by a pair of convective rolls. If this was the case then there must have been a transition from the heat island circulation, characterised in our observations by warming and drying of the mixed layer, to the roll circulation. Although no observations were available in the present study to investigate the transition, the modelling results of Hsu (1987) and Kang and Kimura (1997) suggest that the interaction of the mean wind with convergence in the updraft portion of the heat island circulation initiate the roll circulation.

Specific humidity in the surface layer was lower on Nauru than over the ocean. Unfortunately it was not possible to determine whether the difference was due to drying of the surface layer air or differences in instrument calibration. Adjustment of the surface layer air to the dryer surface of the island is a plausible physical explanation for the difference.

The roughness of the island acted to decrease the wind speed in the surface layer, while convective mixing above the island acted to increase the wind speed, a process described in the TIBL context by Taylor (1970). The varying intensity of
surface heating during the day modulated this increase, resulting in a diurnally varying wind speed. The net result was a diurnal cycle of 10 m wind speed that was in phase with surface temperature, with both mean and maximum speeds below the wind speed over the ocean.

Fair-weather cumulus clouds formed over Nauru during the day. Although there were insufficient measurements to investigate the vertical-velocity structure of the TIBL, the nature of the cloud formation seen in whole sky imager observations implied condensation in rising thermals (Stull 1985). In the morning and late afternoon, when surface heating was less than during the middle of the day, cloud formation often occurred over the ocean downwind of Nauru. During the middle of the day cloud formation moved upwind over the island. Clouds advected away from Nauru, forming a cloud street. The cloud feedback on the radiation budget was small. Because the clouds formed over the ocean or over the western part of the island, the sun was only obscured at the ARCS during the later part of the day when it had moved into the western part of the sky.

Models of flow over small heat islands predict the formation of a mesoscale circulation with a cell of downward motion over the upwind side of the island and a cell of upward motion downwind of the island (Savijärvi and Matthews 2004). Unfortunately, suitable wind measurements were not made during Nauru’99 to determine whether this circulation exists over Nauru. However, Hsu (1987) used a 3-dimensional model to show that the updraft cell of the circulation generated by an elongated island should have maxima in vertical velocity near the ends of the island. These areas of enhanced upward motion would be favourable for cloud formation. Sky camera imagery of clouds showed preferred locations for cloud formation to the
north and south of the ARCS during the morning and evening, when heating was too weak for widespread cloud formation, consistent with Hsu’s results. Hence, a 3D numerical simulation of the Nauru case may provide interesting insights into this type of circulation.

Noordeen et al. (2001) observed that cloud streets developed to lengths of several hundred km and that these streets grew at one third of the mean cloud-level wind speed, 35 km h\(^{-1}\). The time required for an air parcel to travel the length of the cloud street was thus much longer than the typical 30 min life of trade cumulus clouds (French et al. 1999), and so the length of the cloud street requires explanation. Kang and Kimura (1997) demonstrated that long cloud streets could be generated in the lee of coastal mountains by a pair of convective rolls originating in the convergence zone behind the mountain. Transverse aircraft passes below Nauru’s cloud street showed temperature and humidity traces characteristic of convective rolls, although conclusive evidence was not available. Also, the region downwind of a heat-island of finite width is a convergence zone (Hsu 1987). So it is possible that a pair of convective rolls was generated by Nauru and that these maintained the cloud street. Convective rolls are a thermally indirect circulation, as the temperature traces in Fig. 10 indicate, and thus if the rolls are not to decay within a short distance of Nauru they must draw energy from a source other than the heat island circulation. There are two energy sources available to sustain the rolls, mechanical production via shear instabilities in the wind profile and buoyant production via convective instability at the ocean surface (Etling and Brown 1993). Given that cloud streets were not observed over the ocean away from Nauru, and that convective rolls are very common when sufficient energy is available (Etling and Brown 1993), it is likely that the
amount of energy available was marginal. In this situation the resistance of helical flows such as convective rolls to dissipation by transfer of energy from large to small scales may also have been important in maintenance of the convective rolls and cloud street (Etling 1985). Further examination of the heat island-convective roll circulation would make an interesting subject for future study using our observations in conjunction with a model-based sensitivity study.

5. Summary

Modification of the marine ABL by Nauru has been investigated using observations from surface based instruments and an aircraft. Measurements were made during a period of suppressed convection, with a shallow mixed layer under scattered cumulus clouds.

The daily cycle of solar radiation forced a diurnal cycle of 3.5 °C in air temperature, in response to a diurnal cycle of 10.8 °C in surface temperature. The combined effects of mechanical deceleration and acceleration during the daytime due to heating of the surface produced a diurnal cycle in wind speed of 2.1 m s⁻¹.

Heating of the island’s surface during the day generated a thermal internal boundary layer (TIBL) over Nauru within the 600 m deep mixed layer. The warmer air was advected away from the island and formed a plume 15 – 20 km long and up to 0.3°C warmer than the undisturbed mixed layer. This plume of warm air was also up to 1 g kg⁻¹ drier than the undisturbed mixed layer. Enhanced convection in the TIBL produced cumulus clouds over Nauru. These clouds, with bases at 750 m, formed long streets, up to several hundred km long in some instances. The time required for an air parcel to travel the length of the cloud street was longer than the lifetime of a
typical cumulus cloud. Limited observations suggest that the cloud street may have been maintained by a pair of convective rolls, but further investigation would be required to confirm this. These characteristic features of Nauru’s island circulation, a warm-dry plume and the production of cumulus clouds, were similar to those previously observed over Anegada (Malkus 1963), Nantucket (Malkus and Bunker 1952) and Barbados (De Souza 1972). All four island circulations appear to be driven by the same mechanism, enhanced convection over the island due to surface heating.

The modification of the boundary layer by Nauru, most notably enhanced cloud production, will affect climate measurements made by ARM on the island. Studies such as those being pioneered by McFarlane et al. (2005) will be required to correct for these island effects.
Acknowledgements

The ARM data were obtained from the Atmospheric Radiation Measurement Program, sponsored by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research, Environmental Sciences Division. Airborne Research Australia was established with funding from the Australian Commonwealth’s Major National Research Facilities Scheme. Investigator 2 was piloted by Noel Roediger and the aircraft radiometers were maintained by David Pethick. Dr. Long acknowledges the support of the Climate Change Research Division of the U.S. Department of Energy as part of the ARM Program.
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Figure captions

Figure 1. Location Map. Main panel, the locations of the ships during the small triangle and aircraft traverses of the island circulation and cloud street. Inset, the locations of the ship during the big triangle. All distances are km from the ARCS, located at 0°16’S, 166°54’E.

Figure 2. Comparison of ARCS and Ronald H. Brown sensors on the night of July 4th, 1999. The ship was anchored 500 m downwind of the ARCS. Trace rain (<0.2 mm) fell around 0100 LT. From top to bottom, series are: potential temperature, θ, specific humidity, q, wind speed, wind direction, downwelling longwave irradiance, L_{dn}, and surface temperature, T_{surface}.

Figure 3. Side by side comparison of ship sensors on July 3rd, 1999. During the first half of the comparison the ships travelled into the wind. In the second half both ships were manoeuvring, disturbing the wind measurements. From top to bottom, series are: potential temperature, θ, specific humidity, q, wind speed, wind direction, downwelling longwave irradiance, L_{dn}, and sea surface temperature, SST.

Figure 4. Estimates of clear-sky global solar irradiance. Curves are the deviation of the model of Long and Ackerman (2000) fitted using only global irradiance from the same model fitted using global and diffuse irradiance to determine clear-sky conditions.
Figure 5. Comparison of island surface temperature measured at the ARCS and the average of aircraft traverses of the island. Vertical bars are 1 standard deviation. In addition to the low level passes shown in Figure 1, passes of the island made during big triangle flights have been included to increase the sample size.

Figure 6. Time series of radiation and surface meteorology from the 3 stations on Nauru. Downwelling longwave irradiance and rainfall were measured at the ARCS only. From top to bottom, series are: potential temperature, $\theta$, specific humidity, $q$, wind speed, wind direction, downwelling shortwave irradiance, $S_{dn}$, downwelling longwave irradiance, $L_{dn}$, surface temperature, $T_{surface}$, net radiation, $R_{net}$, and rainfall amount.

Figure 7. Time series of radiation and surface meteorology from the Mirai and Ronald H. Brown. The big triangle phase (Figure 1) lasted from June 24$^{th}$ to June 30$^{th}$, 1999. The small triangle phase was from July 1$^{st}$ to July 5$^{th}$, 1999. From top to bottom, series are: potential temperature, $\theta$, specific humidity, $q$, wind speed, wind direction, downwelling shortwave irradiance, $S_{dn}$, downwelling longwave irradiance, $L_{dn}$, sea surface temperature, SST, net radiation, $R_{net}$, and rainfall amount.

Figure 8. Comparison of diurnal cycles of radiation and surface meteorology over the ocean and island. Curves are averages of all days divided into one hour segments. 2 days when a cloud street did not form have been excluded. From top to bottom, series are: potential temperature, $\theta$, specific humidity, $q$, wind speed, wind direction,
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Figure 9. Temperature and humidity of the mixed layer above and downwind of Nauru. Curves are the average of 2 sets of traverses interpolated onto a common axis. Results are offset for clarity, with dashed lines indicating the mean mixed layer potential temperature, 27.8°C, and specific humidity, 17.0 g kg$^{-1}$. Flight altitudes were, from top to bottom, 710 m, 360 m, 180 m, and 90 m. Successive temperature traces are offset by 1 K, humidity traces are offset by 2 g kg$^{-1}$, except the 710m trace which is offset by 5 g kg$^{-1}$. Distances are measured from the ARCS. The location of Nauru is indicated by the thick line.

Figure 10. Cross section of the mixed layer below the cloud street at 400 m altitude. Distance is measured relative to the ARCS. The centre of the cloud street was located at -7 km. Top, potential temperature, $\theta$. Bottom, specific humidity, q.

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