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February 1995

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1 INTRODUCTION

In Australia, the fate of sea turtles during the first few years of their lives, particularly the Green Turtle (*Chelonia mydas*), is a major mystery. Apart from the fact that most undoubtedly perish over this period, the migratory routes taken by the survivors is largely unknown, although it is believed that mature adults eventually return to the general area of their natal rookery to breed. One such major rookery is Raine Island, located on the edge of the continental shelf in the far north of Queensland (see Figure 1). Young turtles, once hatched on Raine Island, swim towards the ocean and are not seen again in the region until adulthood is reached.

This report arose as a follow-on from the work of Dight *et al.* (1988, 1990a,b), into the dispersal of the larvae of COTS (Crown-of-Thorns starfish, *Acanthaster planci*). In that study, a numerical circulation model was used to simulate depth-averaged water currents on the continental shelf of the Great Barrier Reef (GBR) Region, chiefly in the Cairns Section of the GBR Marine Park. The circulation model was linked to an advection model, which tracked the paths of passive particles, moving with the currents and representing larvae, which were released at the locations of certain reefs within the study region. The methodology was successful in explaining a number of significant features, including the southward propagation of COTS outbreaks. Furthermore, the modelling pointed to the potential importance of the northern part of the Cairns Section to the COTS phenomenon.

Juvenile turtles are also believed to respond largely passively to ocean currents in the early stages of their life-history. Upon hatching, they swim frenziedly for the open ocean (see §2). Raine Island's location, at the very edge of a steep continental shelf, implies that hatchlings will be almost immediately influenced by the circulation regime of the deep ocean, rather than that of the continental shelf. Unlike the case of the nearly neutrally buoyant COTS, turtle hatchlings will necessarily be subjected to only the near-surface current field. Modelling the circulation of the (density-stratified) circulation of the deep ocean is a totally different and much more demanding exercise than the corresponding task on the shelf. In the planning stage for this study, therefore, there was no stated intention to apply any numerical circulation modelling to the problem of turtle hatchling dispersal. Nevertheless, an understanding of the biology of any such organism is clearly fundamental to the development of a dispersal model, whether conceptual or numerical. Accordingly, a review of the relevant biological literature on turtle dispersal has been been carried out as part of the study (§2). The design of any model, along with the interpretation of model outputs, must also take into account existing knowledge of the prevailing physical oceanography, obtained chiefly from the analysis of field data (see §3).

The main aim of the report was to review the physical oceanography of the western Coral Sea, notably the known patterns of water movement, and the relevance of these currents to the dispersal of turtle hatchlings originating from the vicinity of Raine Island. The work

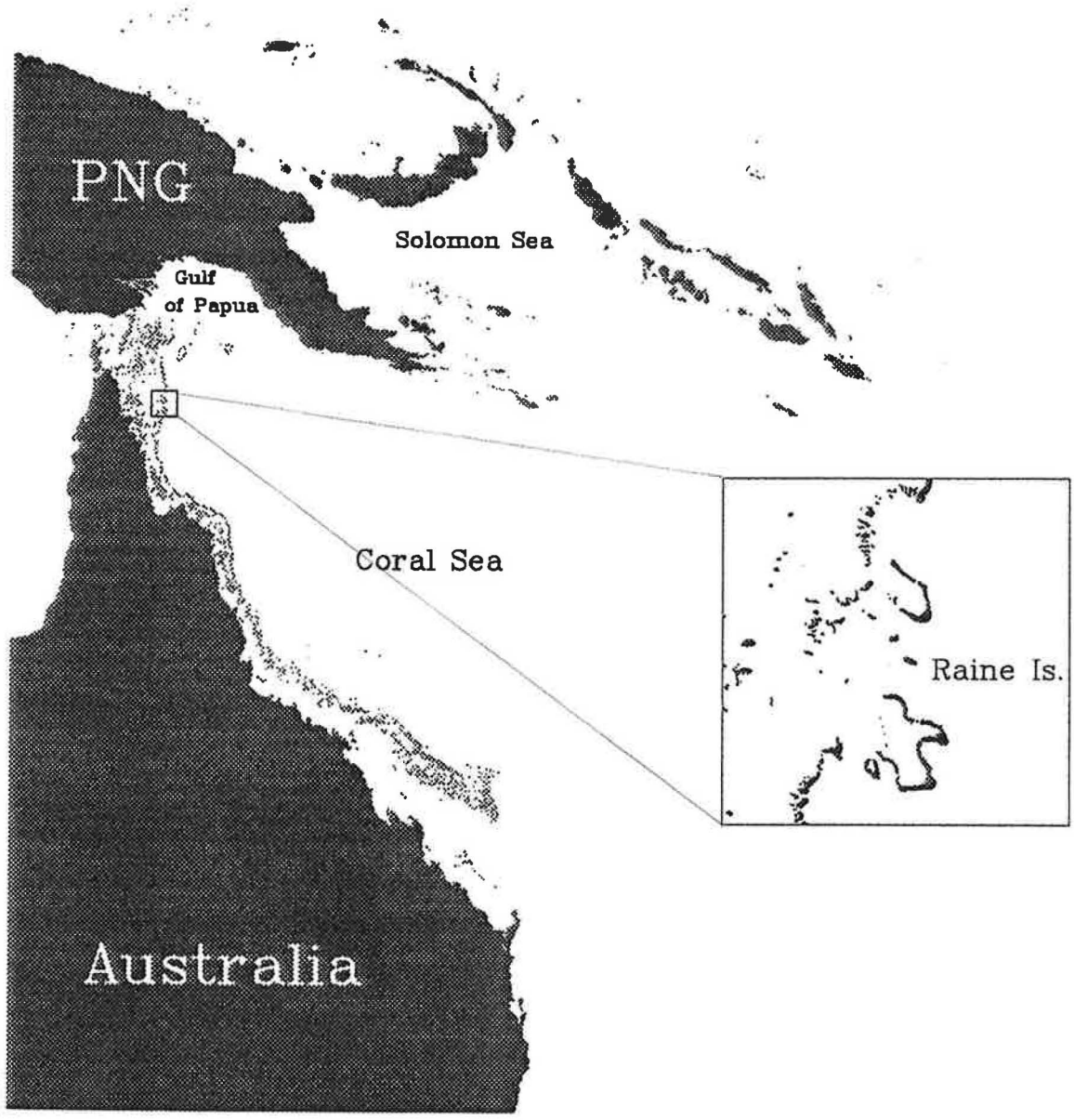

Figure 1. Map of the Coral Sea study region, also showing details of Raine Island (inset).

was essentially set up as a "desk-top" study, with the primary objective being to develop a conceptual model of hatchling dispersal, based on existing knowledge of current patterns and turtle biology. With regard to numerical modelling, the study was required to assess the potential value of physically-based modelling to any future studies, and to identify areas of research which would aid in a better understanding of turtle dispersal.

Early knowledge of the Coral Sea circulation has been summarised by Pickard *et al.* (1977). Most of the discussion of Coral Sea oceanography in this work focuses on the hydrography and general water mass properties, a knowledge of which can be used to infer large-scale currents. However, little of the field work, on which that part of the Pickard review was based, impinged on the initial area of interest, the boundary between the Coral Sea and the GBR Region. A key additional stimulus to the present work has been the recent series of cruises of the *R.V. Franklin* (in 1988, 1990 and 1991), to investigate the circulation of the western Coral Sea. Three of the authors of the present report have been involved in this work (Burrage as a Chief Investigator, Bode as an Associate Investigator, and Hughes as a postgraduate student). This work had also been pre-dated by an earlier cruise of the *Franklin* in 1985, on the basis of which a description of the large-scale Coral Sea circulation was published by Andrews and Clegg (1989).

Several features of this earlier work of Andrews were followed up and extended in the later series of Franklin cruises. These include the South Equatorial Current (SEC) bifurcation and the resulting secondary circulation in the Gulf of Papua. The region of surface bifurcation in the Coral Sea is located roughly off Cairns (Church, 1987). However, the location is known to vary, both intra- and inter-annually, in accord with fluctuations in the larger-scale oceanographic circulation. The southern leg of the SEC forms the East Australian Current (Church, 1987); there was already evidence to suggest that a current also emanated northwards from the SEC and travelled along the edge of the continental shelf in the northern GBR section, and thence around the Gulf of Papua. However, until the advent of the three *Franklin* cruises, little was known of the detailed physical oceanography of this region.

Some additional details have been obtained from the paths of satellite-tracked buoys, drogued at various depths, but typically at 100 metres (Burrage, 1993). Near surface currents could be expected to still have roughly the same pattern of circulation, but must also be affected more directly by local winds. The buoy trajectories demonstrated a clear recirculation pattern in the central portion of the Gulf of Papua (one returned essentially to its release point, in the deep ocean north-east of Cairns). Another one of the buoys, which had lost its drogue, landed on a reef in the vicinity of Raine Island – presumably advected there by the combination of the large-scale currents and wind drift. However, other details of the circulation were less clear in the early stages. It was clearly possible that some of the water in the northern leg of the SEC passed northward around the Louisiade Archipelago, at the easternmost tip of

Papua New Guinea (PNG) and thence towards Indonesia, as suggested by previous data (e.g., Pickard *et al.*, 1977). Lindstrom *et al.* (1987) had already measured a significant current flowing north-westward through Vityaz Strait, between the PNG mainland and New Britain, and the most obvious source responsible for this flow was the SEC.

This research into western Coral Sea circulation formed part of the PhD program of Rowan Hughes at James Cook University (jointly supervised by Bode and Burrage). A second component of the thesis involved the development of a numerical circulation model for the region. As both the analysis of the field work, and the development of the numerical model progressed, it appeared sensible to wait for more definite information on the circulation, rather than to simply proceed with the idea of just a desk-top study. Further, it seemed possible to extend the numerical model to study particle tracking, along the lines of the earlier COTS work, something which became feasible only after the completion of Hughes' thesis (Hughes, 1993).

The remainder of the report is set out as follows. Section 2 provides a brief review of the relevant biological literature. Section 3 discusses in more detail the current state of knowledge of Coral Sea circulation, particularly based on recent field surveys and numerical modelling. Section 4 presents the results of trajectory modelling experiments. Conclusions to the report are given in Section 5.

2 BRIEF REVIEW OF RELEVANT BIOLOGICAL LITERATURE

The green turtle, *Chelonia mydas,* is one of six species of marine turtle found in Australian waters at some stage of their lifecycle, out of a total of seven found worldwide (Bustard, 1972; Hutchinson and Simmons, 1991; Limpus *et al.*, 1991). All species are endangered or threatened, and are listed in Appendix I of the Convention of International Trade in Endangered Species (CITES).

This section of the report presents a brief overview of the biological literature on *C. mydas,* relevant to the question of hatchling dispersal from Raine Island. A more comprehensive biological picture can be gained from the recent PhD thesis of Gyuris (1993). The most cited references are those of the Committee on Sea Turtle Conservation (1990) and Limpus *et al.* (1991) – hereinafter referred to as CSTC and L91, respectively.

2.1 Distribution

Adult green turtles are widely distributed in tropical and subtropical waters around the world. The major nesting areas are reported to be in the Caribbean region and Queensland, Australia (Carr *et al.*, 1978; CSTC). The Great Barrier Reef is the largest remaining green turtle nesting area in the world (Carr *et al.*, 1978; L91).

2.2 Reproduction and Life-History

The life-history of *C. mydas* is similar to that of most other species of marine turtle worldwide, including the loggerhead, *Caretta caretta,* (Carr *et al.*, 1978; CSTC) which also nests in the GBR. The life-histories and behaviour of these two species have been studied most thoroughly. The most significant differences between all species of turtle over the five genera appear to lie in their foraging habits and distribution.

In the GBR, as elsewhere worldwide, mature male and female turtles aggregate off nesting beaches during spring and early summer to mate. Nesting beaches are often described as 'high energy' (e.g., CSTC). Females emerge from the water at night where they lay clutches averaging approximately 100 eggs (although numbers are reported to vary greatly) in excavated chambers above the high tide level on sandy beaches. From one to seven clutches, but commonly two to three, may be deposited over a breeding season at intervals of approximately 12–14 days. Breeding females rarely produce clutches in successive years. Two to four years (and sometimes more) are reported to pass between breeding seasons in the Caribbean region (Bustard, 1972; Carr *et al.*, 1978; Baldwin *et al.*, 1989; CSTC), whereas five years appears to be characteristic of eastern Australian populations (L91). Data suggest that female *C. mydas* consistently return to the same beach to nest, even though they may migrate large distances to forage (Carr, 1986; L91).

Hatchlings dig their way to the surface after an incubation period of approximately two months, move across the beach and into the water. After entering the water, hatchlings swim rapidly out of the shallows and into deep water where they spend their early life near the surface in the pelagic environment (CSTC). They remain in the pelagic habitat until they reach a carapace length of approximately 20–25 cm, when they begin to appear in feeding grounds. Post-hatchling, pelagic-stage green turtles are presumed to be omnivorous, whereas sub-adult and adult turtles forage in benthic habitats, preferring seagrasses and macroalgae, and are often found around coral reefs (CSTC). The age of sexual maturity of the green turtle has been estimated to range between 20 and 50 years (Balazs, 1982; Frazer and Ehrhart, 1985). There is good genetic evidence to support the hypothesis of distinct populations of the green turtle, and also the general belief that sexually mature females return to the geographic region of their natal beach in order to nest (see Allard em et al., 1994 and other references therein).

2.3 Mortality of Eggs, Hatchlings and Adult Turtles

Survivorship of turtle hatchlings in the nest is reported to be high, provided nests have not been disturbed. However, sources of disturbance including other nesting turtles, some predators, tidal inundation, erosion, and human activities, can cause substantial mortality (CSTC, L91). Mortality of hatchlings after leaving the nest can often be severe. The major causes are

predatory fishes and in some cases birds (CSTC; L91; Gyuris, 1994). Satiation of the main predatory bird on Raine Island during periods of high hatchling density suggests that the highest productivity with respect to hatchling survivorship, as they cross the beach, should occur during peak nesting periods (see L91).

The pelagic environment is generally considered to represent a more secure habitat, one that is relatively free from predation (e.g., Fletemeyer, 1978a). As hatchlings grow, mortality due to predation is expected to diminish. Natural mortality in adult turtles is thought to be relatively low (Carr *et al.*, 1978). However, mortality of adults due to human activities, particularly those associated with various fisheries, is reported to be high (CSTC).

2.4 Behaviour of turtle hatchlings

Most research into the behaviour of turtle hatchlings has been conducted off the east coast of Central and North America, and islands of the Caribbean. The initial cues that guide turtle hatchlings from the beach nests where they emerge, appear to be quite well understood, and are attributed to photic responses (Mrosovsky, 1978; Kingsmill and Mrosovsky, 1982). Observations indicate that green turtle hatchlings engage in active, oriented travel against and beyond the waves within the surf zone for at least four hours after they enter the sea. The loggerhead turtle is reported to travel 22–28 km offshore over a period of about twenty hours while in this active, oriented travel mode (often referred to as a "swimming frenzy" – Salmon and Wyneken, 1987).

It is reported that hatchlings undertake, initially, a non-random departure course until after they move over the horizon from all fixed objects on the shore (Frick, 1976). Observations include: (i) they swim steadily on an oriented heading after crossing the surf zone and passing reefs or other shore zone obstructions; (ii) the headings are not maintained by visual reference to a fixed object on shore; (iii) the departing turtles swim steadily, near the surface, mainly at depths of 20 cm or more; and (iv) turtle hatchlings are able to dive to 3 m or more (Frick, 1976).

2.5 Pelagic dispersal of turtle hatchlings

The swimming frenzy of newly hatched turtles is considered to be an adaptive strategy which enables them to escape from the nearshore/reef environment where predation is intense, to the more secure pelagic habitat. The cues which are used during the subsequent pelagic dispersal phase are unknown. Whether post-hatchlings re-enter the coastal environment simply when currents happen to return them as juveniles, or whether an ecological or developmental signal stimulates their return by active and oriented travel, remains a mystery (Carr, 1986).

Hatchlings originating from turtle nesting beaches along the east coast of Central America

are reported to move directly offshore where they associate with Sargassum raft communities or debris (Carr and Meylan, 1980; Carr, 1986). The association of hatchlings with Sargassum raft communities is believed to afford the turtles both a degree of protection from predation and a source of food (Fletemeyer, 1978a). Hatchlings may then be transported passively within these communities, by the ocean currents, into open ocean convergence zones, or alternatively continue to cycle within the Southwest Caribbean Gyre off the southern Central American coast, or even possibly be transported eastward along the coast of South America towards Surinam (Carr and Meylan, 1980). Carr (1986) reports that Atlantic loggerhead turtles may remain for perhaps 3–5 years, circumnavigating the ocean within these Sargassum raft communities, before migrating to benthic habitats along the coast. This period has in the past been referred to as the "lost year" (e.g. Fletemeyer, 1978b). Although it is not clear how long post-hatchling green turtles may remain within such communities, it is generally assumed to be at least a year (Fletemeyer, 1978b) and most likely considerably longer (Carr, 1986).

Adult *C. mydas* which forage along the north-east coast of Brazil are known to make long-distance migrations (approximately 2,300 km) to nesting beaches on Ascension Island in the mid-Atlantic (Mortimer and Carr, 1987; Brown, 1990). Although the environmental cues which are used in open-ocean navigation are not well understood, the journey is aided by an eastward flowing South Equatorial Countercurrent during the period when adults migrate (Brown, 1990). Brown (1990) notes that the peak in hatchling emergence from their nests on Ascension Island occurs between late April and June. The onset of the southeasterly trade winds at about this time reverses the direction of surface flow, now towards the west, and presumably transports the hatchlings back towards the coast of Brazil. Subsequently, hatchlings may be transported southwards along the coast of Brazil or northwestward towards the Caribbean and Gulf Stream. Interannual variation in the onset of the trade winds is likely to lead to some variability in the initial trajectories of turtle hatchlings, the time taken for passive transportation back to the Brazilian coast (estimated to be approximately 9 months), and the percentage which may be transported eastwards to the African coast (Brown, 1990).

Carr (1986) argues that it is not the Sargassum raft *per se* which is fundamental to the pelagic stage of the sea turtle, but the passive and active aggregation of resources that occurs along convergence zones where downwelling takes place. Such zones initially accumulate buoyant objects, including debris and food, which subsequently attract a wide range of organisms from higher trophic groups.

2.6 The Raine Island nesting population

Raine Island is a relatively small (30 ha, with a circumference of approximately 1800 m) vegetated sand cay surrounded by coral reef. It lies in the Far Northern Section of the GBR Marine Park as a detached reef lying along the margin of the continental shelf (11°35′S,

144°02'E) – see Figure 1. Raine Island and the adjacent Moulter Cay represent one of the largest remaining nesting grounds for *C. mydas* worldwide (L91).

L91 report that the main concentrations of *C. mydas* nesting females in the northern GBR are found on cays lying along the outer edge of the continental shelf, between Princess Charlotte Bay in the south and Bramble Cay in the north. They report that only infrequently do *C. mydas* nest on inner shelf sand cays, continental islands and adjacent mainland beaches.

Most observations of courtship and mating of *C. mydas* in the waters surrounding Raine Island have been made during October and early November. Few are reported during December, by which time most adult male turtles have apparently disappeared (L91). However, L91 note that the observed courtship is not sufficient to account for the large nesting population on Raine Island. They report that high density courtship also occurs in shallow northern GBR and Torres Strait waters during September, October and early November, and presume that the majority of this courtship involves turtles which subsequently nest at Raine Island and Moulter Cay.

The number of green turtle females nesting on Raine Island varies markedly between years. However, L91 note that the seasonal pattern is robust. They report that sporadic nesting can occur throughout the dry season (May to August), increasing from September to a maximum in December and January. The maximum numbers of *C. mydas* nesting on Raine Island have been recorded during November 1974 and December 1984, on each occasion exceeding 11,000 on a single night (L91). Turtle nesting occurs around the entire island. In addition, most *C. mydas* at Raine Island come from feeding areas outside of Australian waters (L91).

Hatchling *C. mydas* are present in significant numbers from early December on Raine Island (Jeff Miller, QNPWS, pers. comm.). Miller reports that there is a marked increase in numbers by January, with a peak in hatchling emergence around the end of January. Significant numbers of hatchlings continue to emerge through to mid-March (J. Miller, pers. comm.). However, hatchling productivity at Raine Island is complex and not well understood (see L91).

Genetic studies show that there is considerable interchange between adjacent rookeries (islands/cays), while there is very limited interchange between the two GBR rookery regions (northern and southern GBR) and negligible interchange between the two eastern and western Australian populations of *C. mydas*. These results are in agreement with field tagging studies, which demonstrate that adult female *C. mydas* mostly return to the same beach to nest between successive seasons (L91). Although small numbers of tagged female *C. mydas* from Raine Island have been recorded nesting on other northern GBR rookeries, no interchange between the northern and southern GBR rookery region has ever been observed (L91).

3 THE PHYSICAL BACKGROUND

The basic premise adopted in this study is that turtle hatchlings can be treated as passive, near-surface drifters. That is, once clear of the continental shelf, they are advected by the prevailing ocean circulation at the sea surface. There are in fact two components of this circulation. The first is what is referred to as the 'general circulation' of the world ocean, driven by the large scale wind patterns over the ocean surfaces – mathematically, this circulation is largely determined by the *curl* of the surface wind stress. Except in the vicinity of oceanic western boundaries, this flow is linear and basically geostrophic (a balance between pressure gradients and the Coriolis parameter), so that the water flows *along,* and not perpendicular to, the isobars. The second component of the motion is related to local wind forcing. At the sea surface, currents tend locally to be driven in the direction of the wind stress. Coriolis forces cause a veering to the left (right) in the southern (northern) hemisphere. In reality, however, the extent of this veering does not approach, even closely, an angle as large as 45°, the result deduced from classical Ekman theory (Pedlosky, 1987), which relies on an idealised description of turbulent shear stress in the ocean.

A summary of the meteorological influences on the region is given by Downey (1983); see also Pickard *et al.* (1977). In the Coral Sea at the time of hatchling dispersal (chiefly January to March), the wind field is largely dominated by the summer monsoon. Winds are generally north-westerly, and of weak to moderate strength. Conversely, in the period of roughly April to November, the wind field is dominated by the south-easterly trade winds, which are the prevailing winds during the majority of the year. In the far northern part of the GBR and Coral Sea, around Torres Strait (i.e., regions which are affected more markedly by equatorial influences), the trade winds tend to blow more from the east (Downey, 1983). Given the anticipated relative weakness of the surface circulation driven by the summer monsoon, we will ignore its influence in the present discussion, and concentrate only on the first component, the large-scale ocean circulation.

3.1 Oceanic currents

As discussed in §1, an earlier and comprehensive review of the physical oceanography of the Coral Sea has been given by Pickard *et al.* (1977). The best known feature of the observed ocean circulation is the East Australian Current (EAC), which flows southwards along a large portion of the edge of the continental shelf. The EAC is, in fact, one arm of the westward flowing SEC or South Equatorial Current (Hughes, 1993), which forms part of the ocean-scale South Pacific circulation. It is less well appreciated that, in the vicinty of the sea surface, the inflowing SEC bifurcates at a latitude usually to the north of Cairns. The exact position of the surface bifurcation varies seasonally, and in a complex three-dimensional manner with depth – Burrage (1993), Hughes (1993), Hughes *et al.* (1995), Burrage *et al.* (1995). North of the bifurcation point, the currents flow clockwise around the Gulf of Papua, along the southern

coastline of PNG and exit into the Solomon Sea.

Confirmation of this second outflow branch of the SEC has been obtained only recently, following the cruises of the *R.V. Franklin* discussed in §1. Rather than describe the current patterns in great detail, we include three Appendices (given in order of increasing technical content), which provide a more comprehensive discussion. Only an abbreviated summary will be provided in this section. Appendix I (Burrage, 1993) has been written for a more general scientific audience, and it will basically suffice to refer to this work. The most comprehensive of the three is Appendix III (Hughes *et al.,* 1995), which also includes a description of the numerical modelling procedure discussed below. Some of this work is also summarised in Appendix II (Burrage *et al.,* 1995). Further details of both the analysis of field data and numerical circulation modelling for the Coral Sea can be found in the thesis of Hughes (1993).

The analysis of Andrews and Clegg (1989) showed a broad inflowing SEC, dividing into the poleward-flowing EAC, and a clockwise circulation in the Gulf of Papua. Hughes *et al.* (1995) show that this part of the return flow acts (like the EAC) as a western boundary current, and suggest it be called the Hiri Current (HC). This current flows along the edge of the shelf of the Far Northern Section of the GBR Marine Park (i.e., off Raine Island) and the southern coast of PNG. It would appear that part of the HC forms a closed gyre in the Gulf of Papua, an hypothesis which gains credence from drifter experiments – see Appendix I, Figure 7. Analysis of water properties and the results of numerical modelling strongly suggest that the portion of the HC which exits from the Gulf of Papua into the Solomon Sea, does so around the Louisiade Archipelago. The current then continues equatorward, as what is termed by Lindstrom *et al.* (1987, 1990) as the NGCU (New Guinea Coastal Undercurrent). Fluxes of the order of 8 Sverdrups (1 Sv = 10^6 m^3 s^{-1} or 1 million tonnes per second) through Vityaz Strait, between mainland PNG and New Britain, have been reported by Lindstrom *et al.* (1990). Subsequent data analysis suggests that the flux associated with this current may attain double the reported value at certain times (E. Lindstrom, pers. comm.) Hughes *et al.* (1995) suggest that the use of the term 'undercurrent' may be somewhat of a misnomer. Although model results (Hughes, 1993) show a distinct subsurface character in the horizontal velocity field in the Solomon Sea (with the peak currents occurring at around 220 m), the NGCU basically exhibits a pronounced upper ocean structure, extending down to 400 m or more. In the Gulf of Papua, however, computed peak currents are found typically at around 60 m. Observed maximum velocities in the Solomon Sea are of the order of 60 cm s^{-1} (Lindstrom *et al.,* 1987). Some of the flux into the Solomon Sea would also appear to pass through the St. George's Channel, between New Ireland and Buka/Bougainville, as well as through Vityaz Strait.

In the Coral Sea, deduction of these overall features has come from three different methods.

The first is traditional analysis of hydrographic sections (using *thermal wind* calculations) – see Appendix I, Figures 4, 6, and 8. The second comes from direct current measurements using the ADCP (Acoustic Doppler Current Profiler) on the *Franklin* – see Appendix I, Figure 3. In addition, the results of numerical modelling has been largely consistent with the measured circulation – see Appendix III and, particularly, Hughes (1993) for details.

Thus the basic current patterns which emerges from the above work suggest that any passively advected 'particles', released into the ocean off Raine Island, should travel northwards into the Gulf of Papua, proceed clockwise around the Gulf, and then exit into the Solomon Sea. After that, the major route would appear to be along the northern PNG coastline towards the equator and Indonesia. The numerical modelling conducted by Hughes (1993) includes computations of the currents in this area as well. A discussion of this modelling, as well as its subsequent application to the matter of Raine Island turtle hatchlings is presented in the following section.

4 NUMERICAL CIRCULATION MODELLING

Circulation modelling for the Coral Sea was carried out by using the MOM–1.0 model of Pacanowski *et al.* (1991), an updated version of the well-known Bryan-Cox code. Although the original intention in the work of Hughes (1993) was to concentrate on the Coral Sea domain, consideration of open boundary condition problems ultimately led to the development of a global model. Interpretation of model results, however, was essentially confined to the Coral Sea and nearby oceanic regions.

The model solves numerically the fully stratified, three-dimensional, nonlinear equations of motion, under the usual hydrostatic and Boussinesq approximations. For computational economy, MOM–1.0 employs a rigid lid, rather than a free surface boundary condition, and the spatial layout uses the 'Arakawa B' configuration. Model resolution is $1^\circ \times 1^\circ$ in both latitude and longitude. Bathymetry has been obtained from the global ETOPO–5 database, although considerable effort was taken to ensure an improved representation of ocean depths in the area of interest. The model is first spun up from an initial state (0°C temperature and 35 psu salinity) and relaxed to the Levitus (1982) hydrography; the necessary acceleration techniques are detailed in Hughes (1993). Forcing is provided by the surface wind stress field of Hellerman and Rosenstein (1983). The free thermocline stage, in which is model is allowed to adjust to seasonally-averaged forcing, is commenced after four years of simulation time. This is run for seven years, by which time an effective steady-state is attained. Finally, an eight-year seasonally varying simulation is commenced, in which wind forcing is varied on a daily basis.

Details of the model formulation and the methods of running the model are necessarily complex and specialised. It suffices to say that, within the limitations of its physical parameteri-

sations and spatial resolution, this model provides one of the most sophisticated descriptions presently available of the deep ocean circulation. Many more details can be found in Hughes (1993).

4.1 Circulation modelling results

Figures 23 and 24 of Appendix III show instantaneous stream function contours, under seasonal forcing, for the austral winter (July) and summer (January). These essentially depict the *depth-averaged* movement of water. Thus, the model shows that the overall water mass of the incoming SEC bifurcates near the Queensland shelf at a latitude of around 18°S. In fact, this picture hides the strongly three-dimensional nature of the inflow region, which is further influenced by the topography of the Queensland Plateau. In the model, surface bifurcation occurs at a latitude of around 15°S, in close agreement with the figure of 16°S, given by Church (1987). The actual bifurcation latitude is a southward increasing function of depth, and also varies seasonally. At latitudes south of about 20°S, the stream function plots show that the depth-averaged SEC inflow is directed to the south. At this latitude, the near surface waters flow to the south, to constitute part of the EAC. At depth, however, currents flow to the north to join the HC. At such latitudes, therefore, the deeper waters appear to form a counter-current to the EAC, as described in Church and Boland (1983). This is confirmed from the *Franklin* data, as seen in Figures 17 and 18 of Appendix III. Model output demonstrating more of these features can be found in Hughes (1993), as Figures 3.28 to 3.45.

The near surface flow, which of course is all that is of interest to the question of hatchling dispersal from Raine Island, is best seen from contours of modelled surface pressure – the instantaneous surface flow will tend to follow these contours, which therefore act essentially as surface streamlines. Figures 2 and 3 are taken from Hughes (1994), and show surface pressure for January and July, respectively. The corresponding currents, calculated for the first model level, are given in Figures 4 and 5. Thus, in the far northern sections of the GBR, around Raine Island (latitude 11°35'S, longitude 144°02'E), the model shows strong flow to the north, along the edge of the continental shelf. This is further confirmed by the ADCP data from the *Franklin* – see Figure 3 from Appendix I. The actual latitudinal location of the bifurcation is a matter of some conjecture and interest, which impinge on questions of the effects of low frequency ocean forcing on the continental shelf, and the consequent biological implications. The results of Church (1987), and those of Hughes (1993) – hydrography, ADCP, and modelling – all point to a surface bifurcation at between approximately 14–16°S. Additional data from a long-term current meter mooring at Jewell Reef (near latitude 14°S), suggest that the time-averaged near-surface bifurcation might be located even slightly to the north of this latitude – see Appendix II, Figure 3.

Regardless of the above details, however, it seems fairly unequivocal that the flow near Raine Island is dircted towards the north, and thence around the Gulf of Papua, before exiting into

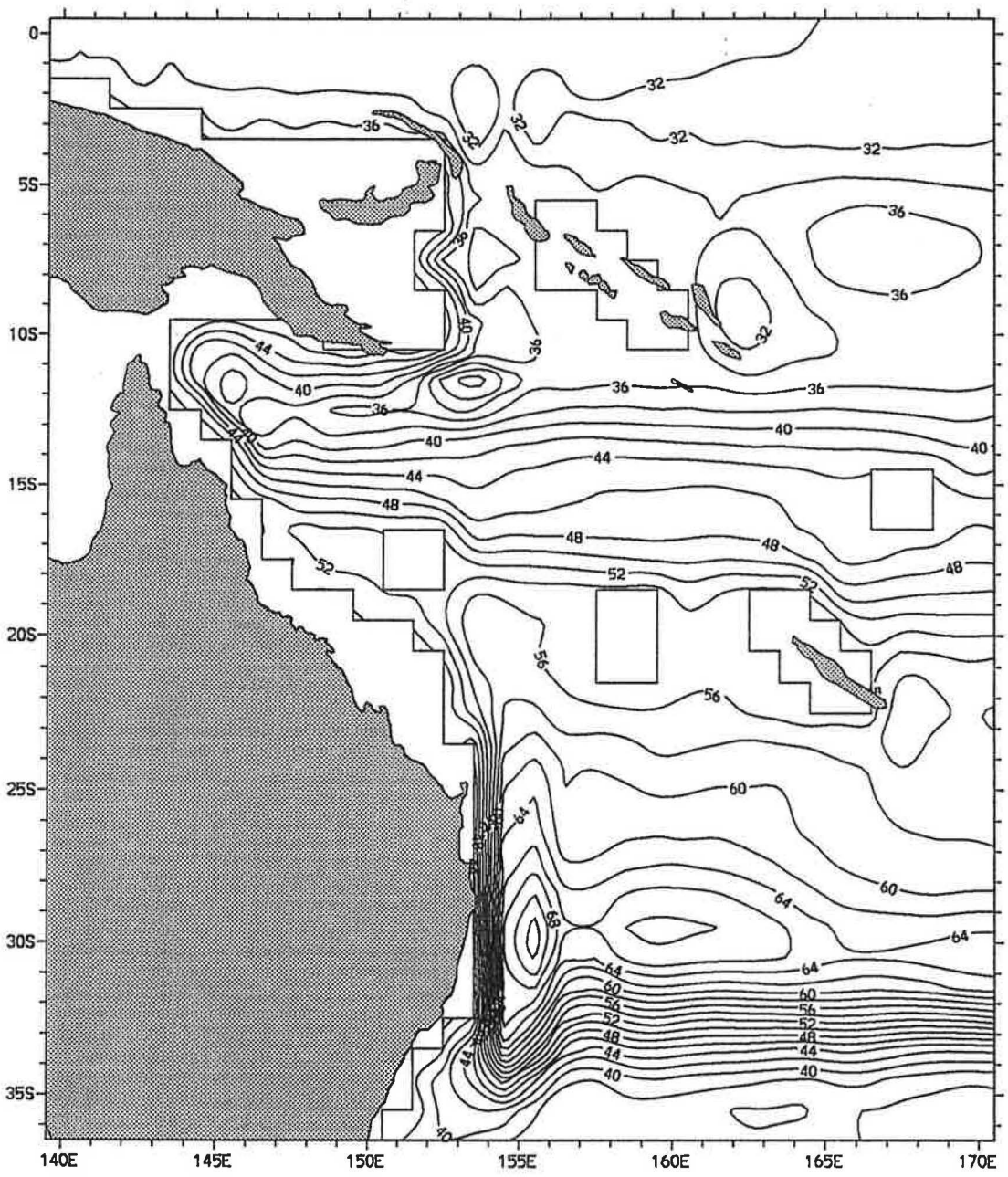

Figure 2. Modelled surface pressure for January (from Hughes, 1993). Contour interval is 2 hPa, corresponding to an approximate water level difference of 2 cm. The surface bifurcation is located close to 14.5°S at the Australian coast. The NGCU has a closed gyre near Rossel Island, at the eastern tip of Papua New Guinea.

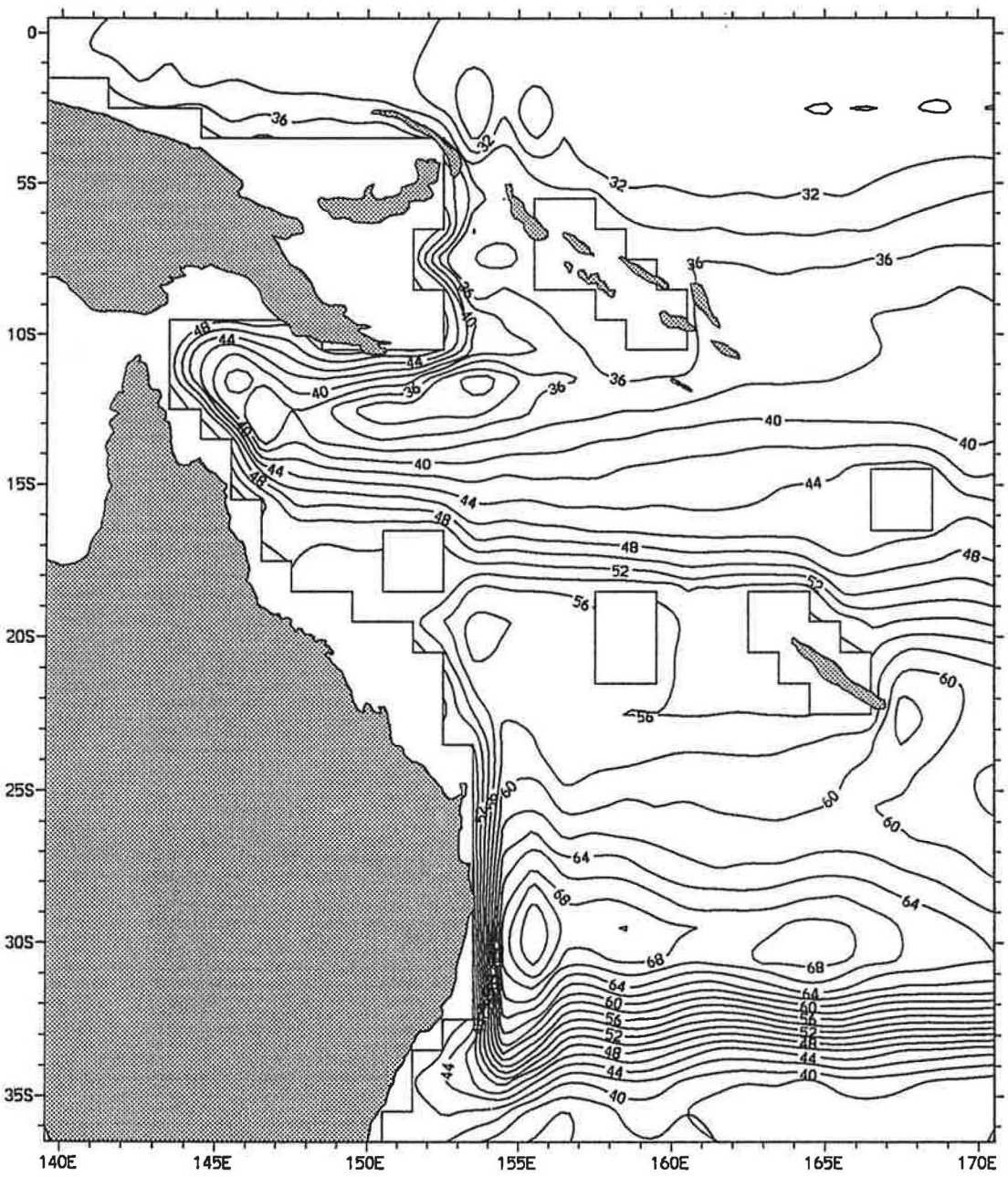

Figure 3. Modelled surface pressure for July (from Hughes, 1993). Contour interval is 2 hPa, corresponding to an approximate water level difference of 2 cm. The surface bifurcation is located close to 15.5°S at the Australian coast. The NGCU has a closed gyre near Rossel Island, at the eastern tip of Papua New Guinea.

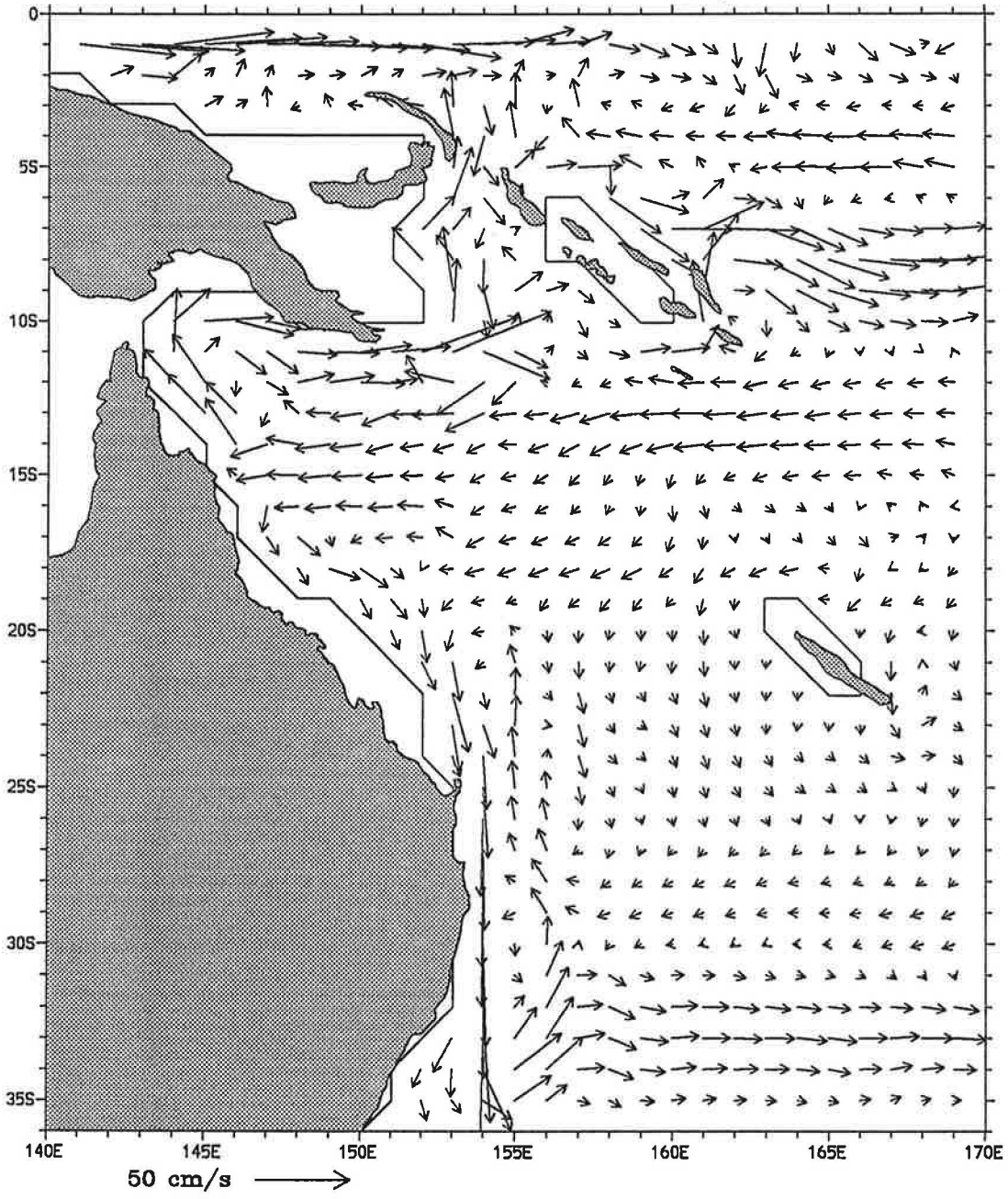

Figure 4. Computed water currents in level 1 of the model (0–27 m) for January.

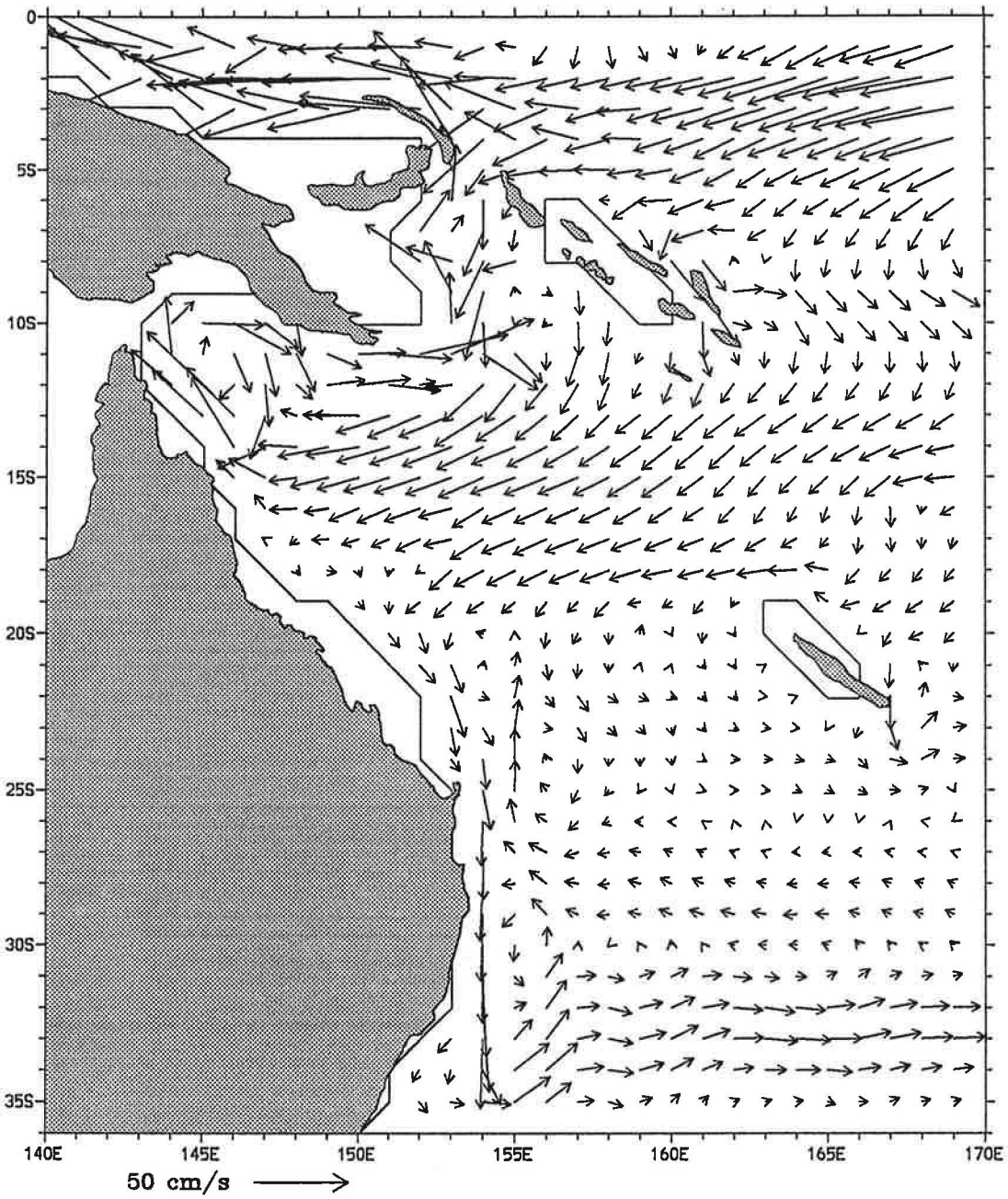

Figure 5. Computed water currents in level 1 of the model (0–27 m) for July.

the Solomon Sea. Thus, a preliminary hypothesis would suggest the likelihood that any surface-borne substances released from the vicinity of Raine Island are likely to follow such a path. Plots of instantaneous streamlines and current vectors can, nevertheless, be misleading at times. Hence, it was decided to use the model model of Hughes (1993) to determine the paths of passively drifting particles, under the influence of the computed flow fields.

4.2 Particle tracking model

The circulation model is able to produce time-histories of horizontal currents in each of the model layers, at each timestep. Such an exercise generates an unmanageably huge volume of data, and only the needed currents, from the first layer, were stored. The model's time step is 1 hour. The first (surface) layer of the model extends from the sea surface to 27 m depth. A separate program was used to track the paths of passive tracers or particles, using the computed model velocities. Groups of particles were released in the model area, adjacent to the position of Raine Island. Given the initial position of any particle, its subsequent instantaneous position can be obtained by numerical integration of the ordinary differential equations:

$$\frac{d\mathbf{x}_k}{dt} = \left(\frac{dx_k}{dt}, \frac{dy_k}{dt}\right) = \bar{\mathbf{v}}_k(\mathbf{x}_k, t) = (\bar{u}_k, \bar{v}_k),$$

where $\bar{\mathbf{v}}_k(\mathbf{x}_k, t)$ is the horizontal velocity in layer 1 at time t of particle 'k', with instantaneous vector position $\mathbf{x}_k$. The equations are integrated by a second order Runge-Kutta scheme (modified Euler). The value of $\bar{\mathbf{v}}_k(\mathbf{x}_k, t)$ is obtained by bivariate interpolation of the discrete velocity fields, provided at each time step by the hydrodynamic component of the model.

4.3 Particle tracking results

Four separate particle tracking experiments were conducted. Using seasonally-varying forcing, particles were released on the following days: 5 and 20 January, 5 and 20 February. A basic release consisted of five particles – a central particle, and one in each of the four cardinal directions, distance $0.1°$ of arc from the centre. The initial position was set east of the latitude of Raine Island – that is, seawards of the model "coastline", which is located near the edge of the continental shelf. The results are shown in Figures 6–9, in which the positions of the particles are shown every 1000 hours (approximately 6 weeks). Model and actual coastlines do not agree precisely, due to the coarseness of the model, as can be seen where trajectories appear to cross coastal boundaries.

Despite the fact that seasonal forcing was used, there is relatively little variability in evidence for the particle trajectories. Essentially, the particles do what would be expected from the hydrographic and AADCP data, as well as from the computed currents. That is, they initially proceed northwards from the release point, and then clockwise around the Gulf of Papua,

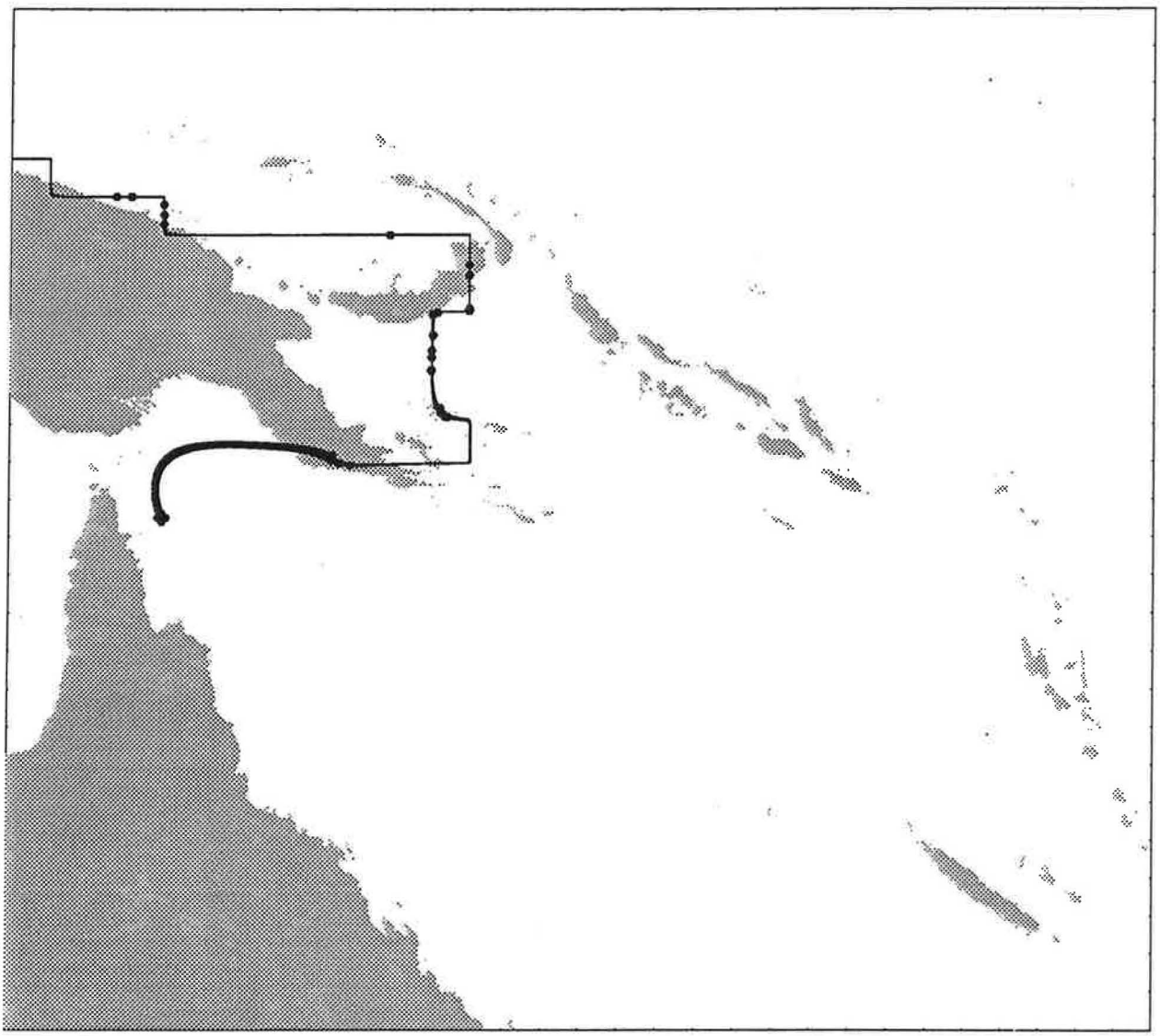

Figure 6. Paths for a single release of five particles off Raine Island on 5 January. Dots show positions attained every 1000 hours.

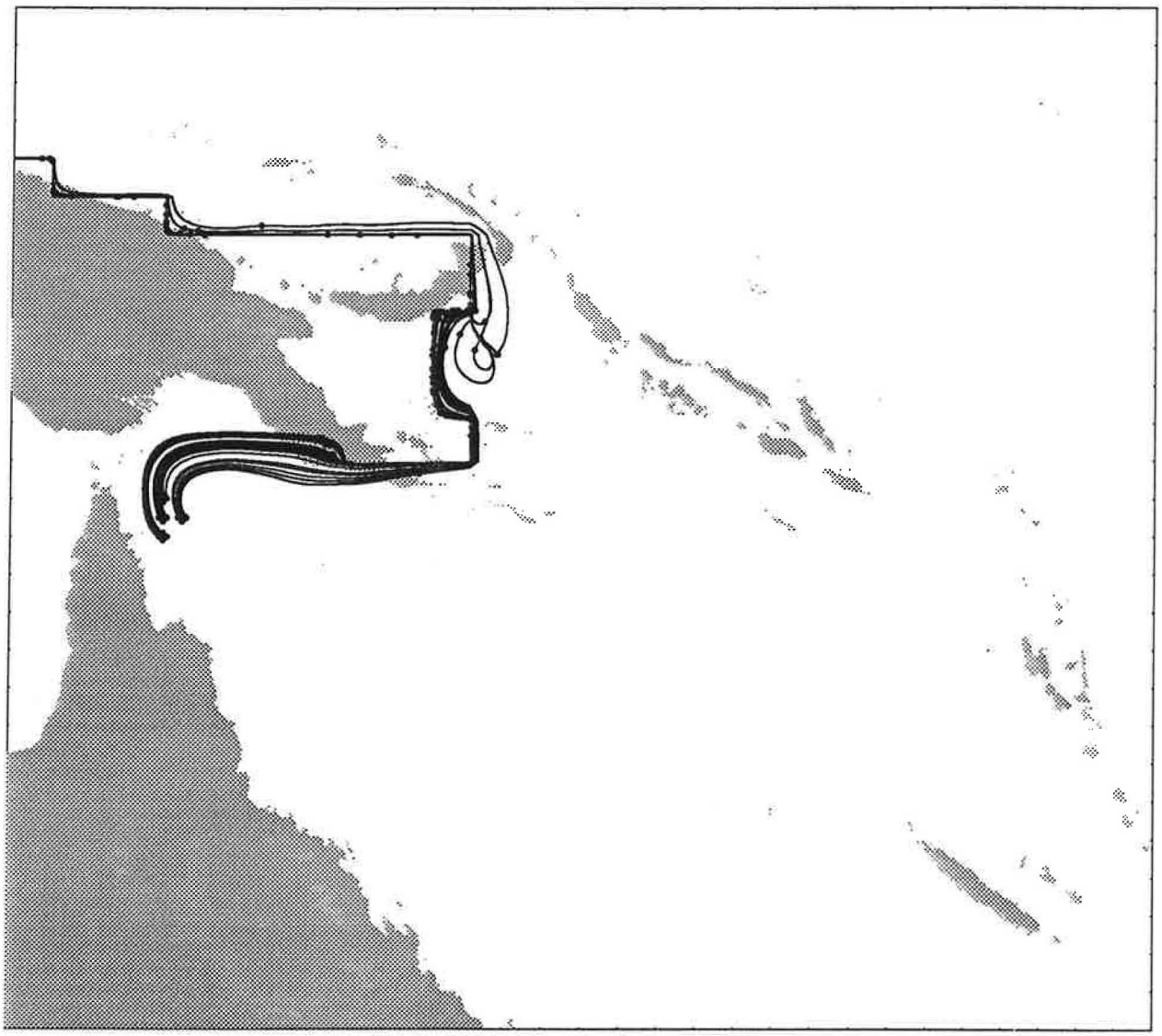

Figure 7. Paths for four simultaneous releases, each of five particles, off Raine Island on 20 January. Dots show positions attained every 1000 hours.

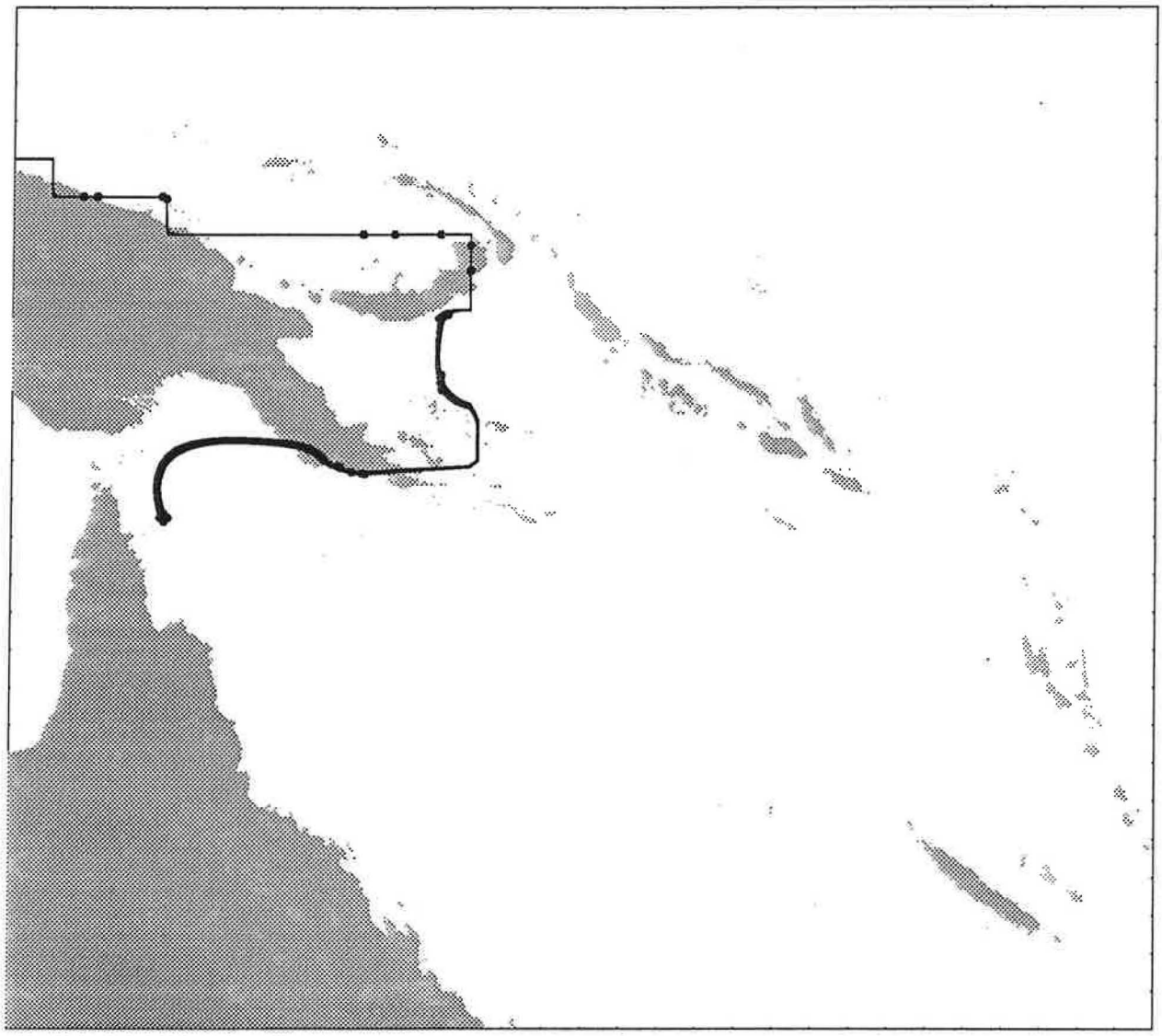

Figure 8. Paths for a single release of five particles off Raine Island on 5 February. Dots show positions attained every 1000 hours.

Figure 9. Paths for four simultaneous releases, each of five particles, off Raine Island on 20 February. Dots show positions attained every 1000 hours.

following the (model) coastline closely. Their passage in this area, before they proceed into the Solomon Sea, is relatively rapid. Currents in the Solomon Sea are weaker, as evidenced by the increased time taken to traverse this region. After this, the particles are advected through St. George's Channel and thence along the northern coast of PNG towards Indonesia. In order to determine if the trajectories were sensitive to the location of the release point, four separate releases were conducted for the experiments of 20 January and 20 February – Figures 7 and 9. Some extra variability is seen, but nothing dramatic.

Before reading too much into the results of these numerical experiments, caution should be exercised. The particle paths, and the corresponding speeds of movement, could possibly be taken as an indication of what *may* happen, but nothing much stronger than that. Firstly, the model resolution, at 1° of arc, is extremely coarse. As a result, the complex coastal features of PNG are represented very poorly, e.g., in the Louisiade Archipelago. The most notable problem is with Vityaz Strait, between New Britain and the PNG mainland, which is physically too narrow to be resolved by the model geometry. However, it should be recalled that Lindstrom *et al.* (1987) measured strong currents through this gap. In addition, there is no allowance made for any deliberate or random movement on the part of the juvenile turtles, represented by the particles. The surface currents, shown in Figures 4 and 5 (as well as the results of the TEW cruise – see Hughes, 1993), indicate some potential for clockwise movement around the Solomon Sea, especially if the juveniles were sufficiently mature by the time they reached such locations to modify their positions deliberately.

The final point that came out of the particle tracking experiments was that the particles showed a very strong tendency to remain right on the model coastline – i.e., at the edge of the continental shelf. There were no instances in which they exhibited any drift away from the margins of oceanic basins.

5 DISCUSSION AND CONCLUSIONS

This basic aim of this report was investigate possible physical influences on the paths taken by juvenile green turtles from the Raine Island hatchery. At the present time, the fate of these juveniles remains a mystery. It is believed that those which survive to adulthood tend to return there to breed. However, there is no direct evidence of even this, let alone the intermediate life-history of the turtles. Overseas research, as summarised in §2, suggests that the juveniles are transported away from hatcheries by large-scale oceanic currents. The report provides some background on the biology of the species, although there are other more extensive sources listed there which can be consulted. A very recent work is the thesis of Gyuris (1993).

The main part of the report is provided by §3 and the three Appendices. These detail the present state of knowledge on the physical oceanography of the western Coral Sea, largely

as a result of recent cruises of the *Franklin*, but also the 1987 TEW data obtained from the *Oceanographer*. These data sets have provided concrete information about the northwards emanating arm of the South Equatorial Current, the NGCU (or Hiri Current). Complementing the field data are the results of the numerical circulation model of Hughes (1993). This model uses a relatively coarse spatial resolution but, nevertheless, its results are largely in agreement with the data, so far as the main features of the circulation are concerned.

The available evidence from these sources suggests that turtle hatchlings, if indeed they behave as passive drifters, would tend to be advected clockwise around the Gulf of Papua, into the Solomon Sea, and then along the northern coastline of Papua New Guinea towards Indonesia.[4] A secondary hypothesis is that there may also be some tendency for increased residence times within the Solomon Sea, due to the circulation patterns in this region. Both data and model results (Figures 4 and 5) show currents flowing south-eastwards along the western coast of the Solomons, in the direction of Vanuatu. However, it is not clear what would be the consequences of a continued movement in this direction. Advection back towards the Queensland coast, with the prevailing South Equatorial Current, might be a possibility, but this would involve a major open ocean traversal of thousands of kilometres.

In §4, the numerical model is used in a particle tracking mode to determine the paths taken by passive drifters released from the vicinity of Raine Island during January and February. The results of these experiments are in accord with the main hypothesis. It should be emphasised that, in all of this work, the hatchlings are treated as totally passive drifters. We have not attempted to address the question of the possible effects of hatchling mobility.

One matter which has not been addressed in the report is the question of possible return paths for mature turtles, assuming they eventually return to the general vicinity of their birthplace to breed. Both available oceanographic data and the particle tracking have suggested the possibility of advection towards Indonesia. The prevailing winds and currents are such that it may be difficult for them to return to Raine Island along their outward path. We have no evidence, nor any expertise to offer firm suggestions about this return path. However, a route from Indonesia, through the Arafura Sea and Torres Strait cannot be ruled out.

In summary, therefore, the physical data and model results provide some definite suggestions about pathways for juvenile turtles. It needs to be stressed that there are no guarantees that these will provide detailed or accurate answers to the main question of where the turtles disappear to for so many years. If future numerical modelling work proves to be practicable at a much finer spatial resolution than is possible at present, definitive hypotheses on migratory paths could be advanced with more confidence. In spite of the necessary cautions, we believe

[4] It should be noted that the *coastline* of the open ocean model used in the present work is located essentially at the edge of the continental shelf, and not at the coastline proper. Secondly, the coarse rectangular coastline of the model tends to produce the rectilinear particle paths of Figures 6–9.

that the report does offer some physically feasible ideas about likely migratory pathways, and could therefore suggest places where it may be sensible to search for green turtles prior to the attainment of adulthood.

ACKNOWLDEGEMENTS

We would particularly like to thank Emma Gyuris of JCUNQ, as well as Suzy Davies of GBRMPA, for their help in recovering bibliographic items, when many of our records disappeared 'in transit'. Helpful discussions on turtle biology with Emma and with Jeff Miller of QNPWS are also much appreciated.

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