Journal of Global Environment Engineering, Vol. 4, pp. 77–89, 1998

THE ROLE OF OCEANOGRAPHIC MODELLING IN PREDICTING THE IMPACT ON CORAL REEFS FROM GLOBAL CHANGE

Eric Wolanski [1]
Keita Furukawa [2]
Stan Massel [1]

Abstract

Assuming that global change will be so rapid that the biological system will be faced with a sudden change in the physical forcing. Three scenarios for possible oceanographic effects of global change on coral reefs were proposed and modeled. 1) Flow structure on shallow water region is dominated by depth of water. Sheltered lagoonal reefs will be suffered from an increased residence time of pollutants and decrease of the upwelling of oceanic nutrients with a SLR. 2) Change of wave dynamics over a leeward coral reef following a SLR will modify coral zonation. 3) Global change may increase the frequency of tropical cyclones. It will increase the recruitment of fish and coral larvae in Ryukyu Islands, Japan. In many countries the direct impact of man on corals may obscure any impact from global change.

KEYWORDS: *Sea level rise, Coral ecosystem, residence time of pollutants, wave dynamics, tropical cyclones, recruitment*

1. Introduction

Possible future global changes are difficult to predict. The difficulties are due to limitations in the capability of numerical models of the atmospheric and oceanic circulation. They are also due to problems in extracting trends from time series of observations of atmospheric and oceanic variables (e.g., temperature, sea level), many of these series however are too short, too nosy or subject to other causes of variability than global change (Emery and Aubrey, 1991). Within large error bounds due to such effects, many possible physical global changes have been predicted (IPCC, 1990; SCCCS, 1995). Some of them may affect coral reefs. These effects include a rise in sea level, a warming of the sea and the air at sea level, an increase in the frequency of tropical cyclones (typhoons) in sub-tropical seas, and a modification of the wind field.

These effects are not necessarily independent; there may be an interaction between physics and biology. The state of knowledge of the links between physics and biology on coral reefs is still poor; hence a reliable prediction of the response of coral reefs to global change may not be possible at present.

1 Principal Senior Research Scientist, Australian Institute of Manrine Science, PMB No.3, Townsville M.C., Qld. 4810, Australia
2 Senior Research Engineer, Port and Harbour Research Institute, 3-1-1, Nagase, Yokosuka 239, Japan.

Nevertheless within such constraints, the order-of-magnitude of possible responses are attempted to describe. This work is similar attempt that adopted by Wolanski and Chappell (1996) in their predictions of the response of Australian macro-tidal tropical estuaries to a sea level rise. Namely the physical changes will be assumed in atmospheric and sea level will be very rapid so that the biological system is presented with a sudden change in the physical forcing. Three scenarios are selected from many possible scenarios and tested.

First scenario is selected from fringing coral reefs in nearly tideless oceans, an example being reefs in French Polynesia. Numerical models is used to predict possible changes in the flushing rates following a rise in sea level and/or in the wind and infer possible ecological changes. Second scenario is changing in zonation caused by predicted changes in wave dynamics over a leeward coral reef following a rise in sea level. In third scenario, advection-diffusion models is used to predict how an increase in the frequency of tropical cyclones may modify the fate and recruitment of coral larvae in the Ryukyu Islands reefs of the East China Sea.

2. Flushing of Fringing Reefs

Lagoons and fringing coral reefs such as the Tiahura lagoon in French Polynesia (Fig.1) and Shiraho coral reef, Ryukyu Islands, are flushed by water currents controlled principally by wave breaking on the reef crest, the tides, and the local wind; the offshore oceanic circulation has little influence (Nakamori et al., 1992; Wolanski et al., 1993; Wolanski, 1994). In turn this circulation determines the flushing of pollutants and nutrients.

To illustrate likely effects of global change, the water circulation at Tiahura lagoon (Fig.1) was modelled following Wolanski *et al.* (1993). The model is finite difference, centered, depth-averaged, solving the full primitive equations of motion with non-linear friction. The sea level is assumed at rest offshore with no ambient currents. The mesh size is 100 m. The domain was discretized by 61 x 43 grid points. Wave breaking implications for the water circulation are parameterized by calculating the resulting transfer of excess momentum as a radiation stress following Longuet-Higgins and Stewart (1962)

This reef has a well-developed lagoon along the coast. Water is injected over the reef flat principally by wave breaking. This water flows over the reef towards the shore, is channeled in the deeper regions and flushed out through a gap in the reef where a jet is formed. The tides are particularly small in this area which is an amphidromic point; the small tides are believed to exert little influence on the water circulation; certainly the jet in the gap in the reef is a nearly permanent feature.

The predicted currents in the absence of tides are used to drive an advection- dispersion model for particles (coral eggs, nutrients, pollutants) released in the downstream side of the lagoon; this area is the least flushed. The simulations (Fig.1) suggest that a rise in sea level of 0.5 m for this reef will halve the flushing rate. This will in turn enhance the trapping of pollutants. It will also halve the wave-driven upwelling and inflow on the reef crest of deep, nutrient-rich water carried upwards in the spur-and-groove system of the reef slope (Wolanski and Delesalle, 1995). Hence both from a decrease in oceanic nutrient flux and from an increase in pollutant concentrations, the reefs will be increasingly stressed. Possible effects of stressed reefs in this area, based on historical evidence, may be coral bleaching (Salvat, 1992).

This prediction is valid only for windless days. On windy days the model predicts (not shown) little change in the flushing rate as a result of a 0.5 m rise in sea level. In this case the downstream side of the lagoon are sheltered from the prevailing tradewinds by hills, so that the downstream side water of the lagoon are predicted as stressed by a rise in sea level, but

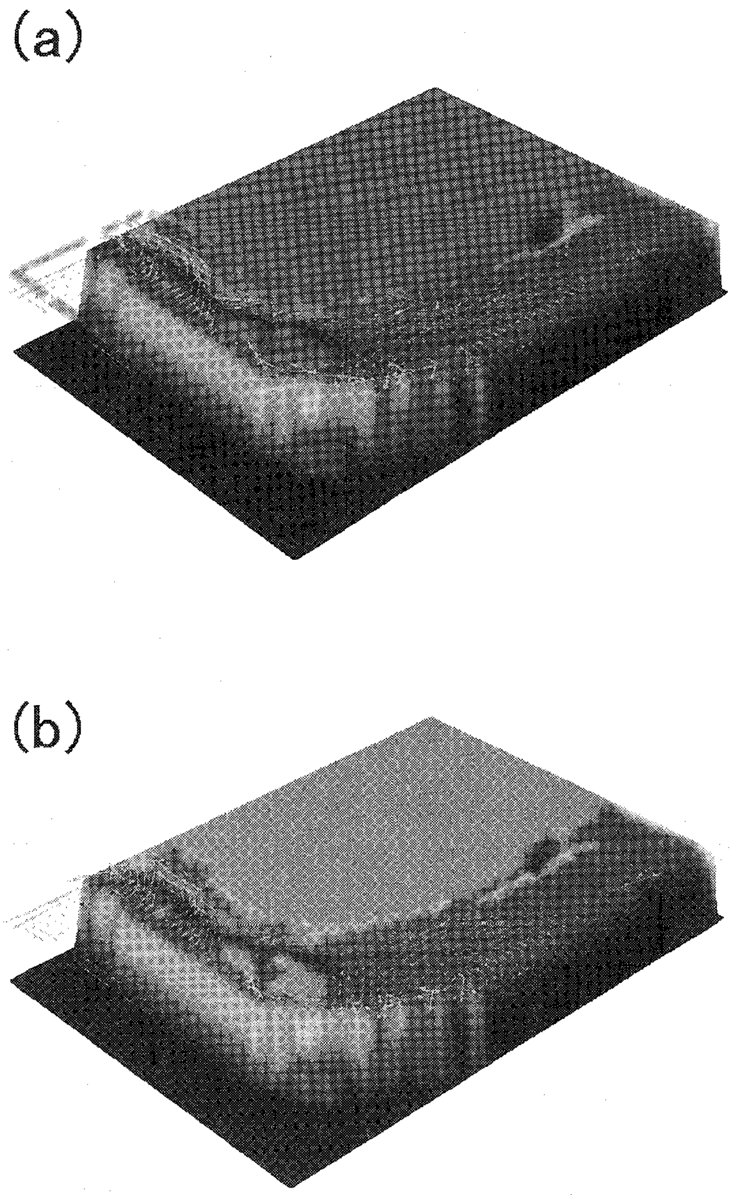

Figure 1. Three-dimensional view of the bathymetry of the Tiahura lagoon-reefsystem, Moorea Island, French Polynesia. (a) Predicted currents for a 4m swell breaking on both north and west reef crests in the absence of wind. The figure also shows the plume of a tracer 100 hours after starting a continuous released at a point in the backwater of the western (right hand side) side of the lagoon. (b) The plume for the same hydrodynamic conditions in the ocean but for a mean sea level rise of 0.5 m. Note that in (b) the plume has not yet left the lagoon. In both plots the plume is shown slightly above the water surface for better visualization.

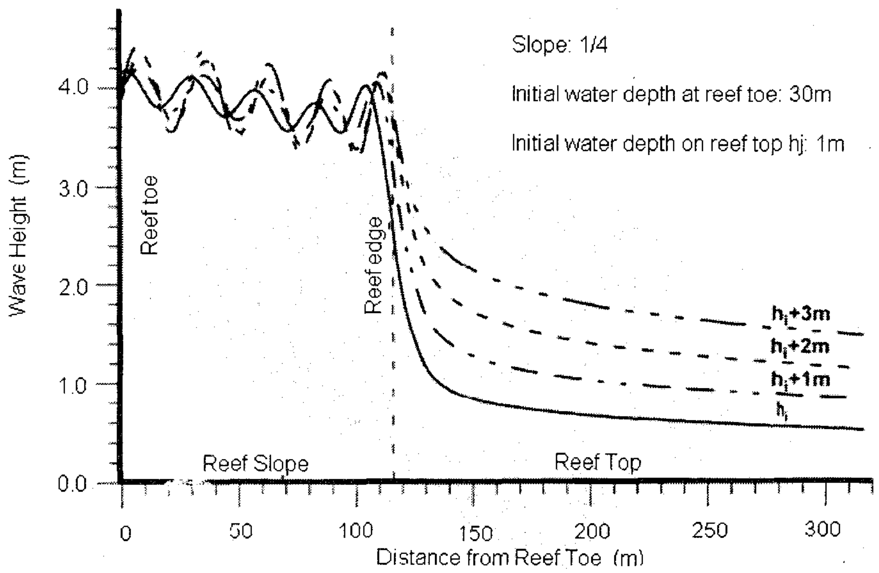

Figure 2. Predicted wave-induced sea level transect across a reef for various oceanic mean sea levels.

the flushing rates on the wind-exposed reefs near the jet are predicted as little changed. In fringing reefs elsewhere in coral reef areas where tides may the dominant forcing controlling the flushing, only small changes in the flushing rates may result from a 0.5 m sea level rise. Thus in general the first sign of stress on coral reefs from global change should be visible first in sheltered areas where micro-tides prevail.

Other effects, not considered here, may include change in temperature , tide and currents. The temperature effect believed to be minimal in the tropics. In the case of Moorea tides, it have negligible influence on the water circulation at Tiahura and this is not expected to change with global change. And, the model suggests that the oceanic circulation offshore has negligible influence on the circulation over the coral reefs, this being controlled mainly by the wind and the wave breaking.

3. Changes in Reef Zonation

A rise in sea level will not only affect flushing rates, it will also affect wave dynamics. Coral reefs exposed to oceanic swell and waves are subject to considerable wave energy from waves especially when they break. Waves shoaling over the reef slope, breaking at the reef edge and transformed on the reef platform, impose hydrodynamic forces on the coral-building organisms. In the extreme case of waves, waves directly affect the density, structure and distribution of these organisms (Done, 1992). The observed variability in coral density and size frequency distribution may be due to wave climates varying among and within reefs (Massel, 1996; Massel and Done, 1993).

The energy of oceanic waves impinging on a coral reef is partly reflected, partly transmitted over the reef flat and partly dissipated by wave breaking and bottom friction. Wave models (Massel, 1993) predict that higher reef submergence allows more wave energy to be transmitted over the reef flat. For instance when the water depth over the reef flat increases from 1 to 4 m, the wave energy will be about nine times higher (Fig.2). Rising sea water level also shift the breaking point landward.

Waves apply a forces on a individual coral structure growing on the substrate. This force can be estimated from hydrodynamic principle. It is function of the horizontal components of the orbital velocity, u, and the acceleration, a, and these are functions of wave height, H, period, T_p, and depth z. It can be assumed that individual corals growing on the substrate have little effects on the overall wave field though they certainly increase friction and enhance shoaling. This is true even for massive spherical Porites corals, because they are small compared to the incident wave length. A vector F of this force can then be represented as the vectorial sum of the inertial force F_i, the drag force F_d and the vertical lift force F_l,

$$F = F_i + F_d + F_l \tag{1}$$

For the coral structure not to be dislodged by waves, the forces must be resisted by the structure's weight and adhesion to the substrate. The threshold wave height, H, needed to overturn a coral structure of a given diameter, D, is associated with the specific return period $T(H)$ of storms or cyclone conditions which generate waves of this height. T can also be expressed as the average time between such events. If a coral structure occupies a location for L years, its probability of survival at a given water depth is

$$P = \left(1 - \frac{1}{T}\right) L \tag{2}$$

In habitats exposed to both short period, wind-driven waves, and long period swell, survival probability decreases with increasing coral age, and the decrease rate depends strongly on both locations and water depth (Fig.3).

A change of coral zonation is thus likely as a result of a rise in sea level changing the wave energy distribution. The largest change may be near the reef crest. On the reef slope, a decrease wave energy will increase the probability of a coral structure to age and grow large. Near the reef crest however, increased transmission rates of wave energy will decrease the threshold of wave height required to dislodge and damage coral structures, it will also decrease the return period of the threshold wave. Hence the probability of a coral structure to remain will decreases.

The zonation of the coral communities on the reef slope and reef top can be expected to change.

This prediction may be valid under the assumption of a constant storm/cyclone frequency. It may be however that storms and tropical cyclones will become more frequent, the decreased return period T of storm waves may accelerate the predicted coral zonation changes.

4. Recruitment of Fish and Coral Larvae

The Ryukyu Islands, Japan have well-developed fringing coral reefs, their coral fauna is very diverse appears to depend on seeding from reefs in the Philippines (Veron and Hodgson, 1989). The seeding is believed to be due to larvae being transported by the global circulation of the North Equatorial Current followed by Kuroshio Current; this current (Fig.4) path through near Luzon, Philippines, enters the East China Sea, flows northward along the continental shelf edge of eastern Asia, and reaches around Ryukyu Island. Larval transport in the global circulation is uni-directional with a speed of about 1-2 knots, this enables a larva to travel

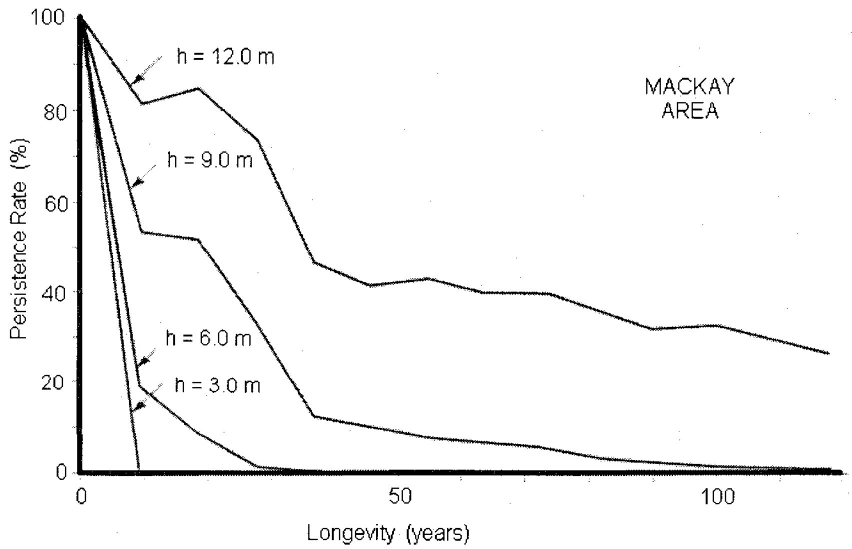

Figure 3. Survival probability of corals in the Mackay area of the Great Barrier Reef for various longevity and water depth

from Luzon to the Ryukyu Islands in 30 days. Further the surface waters are warm, with temperatures greater than 20°C (Tchernia, 1980), which is warm enough for the Japanese species of coral which require minimum water temperatures of about 18°C to survive(Veron and Minchin, 1992). The survival of the coral larva north of the Ryukyu islands is decreased by decreasing water temperature. Hence the global circulation is believed to play the role of a conveyor belt in transporting and distributing coral larvae in the East China Sea.

The coral spawning season is in summer, late spring and early fall, this is also the typhoon season. The typhoons affect the conveyer belt in at least two ways, firstly they generate strong near-surface, wind-driven current, and secondly they increase horizontal turbulent mixing.

The frequency of typhoons in the East China Sea is predicted to increase by 30 to 50% following global change (Daniels, 1992; Haarsma *et al.*, 1993). This prediction is tentative because different models produce quite different results (IPCC, 1990).

In follows discussions, an advection dispersion numerical model is used to study likely coral larva dispersion in the East China Sea. The model suggests that an increase in typhoon frequency may increase the probability of coral larvae recruitment in the Ryukyu Islands.

A typical typhoon in this region has maximum wind speed of about 30 ms^{-1} velocity, and the radius of wind exceeding 15 ms^{-1} is about 100 km. About 20 to 30 such storms move rapidly through the East China Sea, *i.e.* about 4 to 5 typhoons per month during the season (National Astronomical Observatory, 1994; SCCCS, 1995). There are three typical typhoon paths crossing the global circulation and these are called here typhoons 1, 2 and 3 (Fig.5). Typhoon 1 passes near Luzon and is swept out to the eastern side of Japan, Typhoon 2 passes far from Luzon and moves towards the Ryukyu Islands, and Typhoon 3 crosses the circulation north of Luzon and heads for Taiwan (Algue, 1904).

The oceanic circulation in surface waters was modelled using a two dimensional model VORTEX (Furukawa and Hosokawa, 1996; Furukawa and Wolanski, 1997). The model assumes

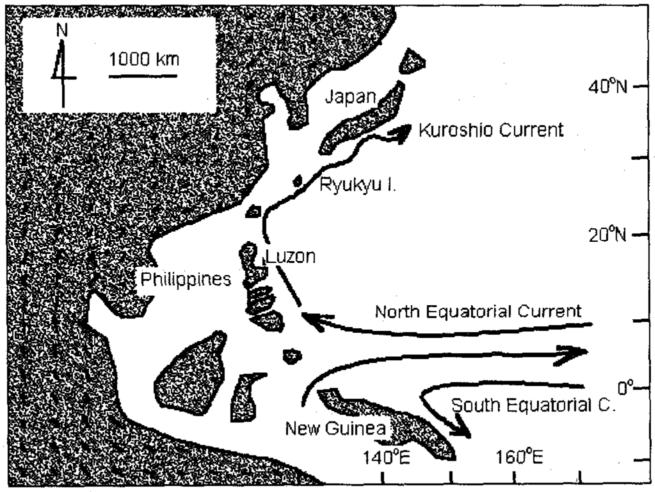

Figure 4. Sketch of the circulation in north Pacific ocean.

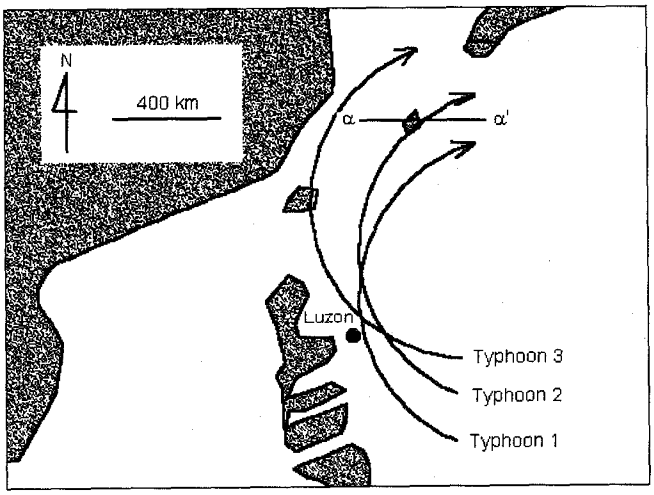

Figure 5. Typical typhoon trajectories and location of transect line $\alpha - \alpha'$ at the Ryukyu Islands.

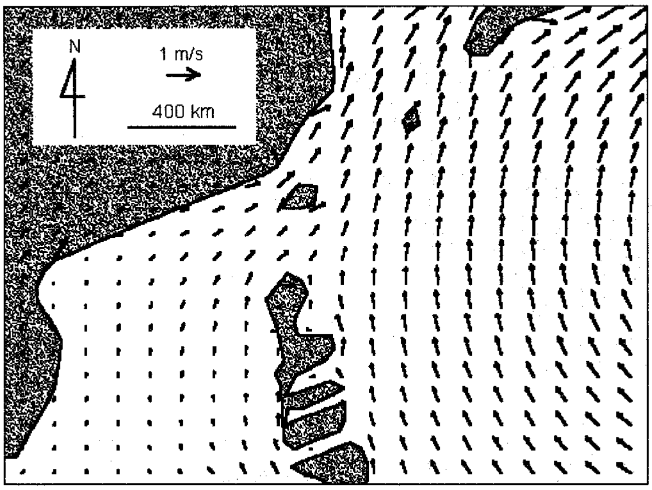

Figure 6. Synoptic distribution of predicted currents.

that the mean circulation carrying surface water from the Philippines to Japan is not modified by global change. We focus on the role of individual typhoons in redistributing the plume of coral fish larvae during their sea transfer from Philippines to Japan. The model domain covers the whole north Pacific Ocean. One large gyre (Fig.6) drives the North Pacific circulation of which the Kuroshio is part.

The tangential wind speed V_r generated by a typhoon is modelled as (WMO, 1978),

$$V_r = V_m \frac{2 r_m r}{r_m^2 + r^2} \tag{3}$$

where V_m is the maximum wind velocity, r_m is the radius of maximum wind and r is the distance from the center of the typhoon. For a typical typhoon is assumed as $V_m = 30\mathrm{ms}^{-1}$ and $r_m = 100\mathrm{km}$, this corresponds to $V_r = 15\mathrm{ms}^{-1}$ at $r = 400\mathrm{km}$.

The typhoon-driven surface current u_t is assumed to be equal to 2% of the wind velocity V_r. The total surface current carrying the coral larva is calculated as the vector sum of the current-driven by global circulation u_c and the typhoon-driven current u_t.

Typhoons also influence horizontal mixing and diffusion in surface waters. Horizontal mixing is parameterised using a horizontal surface diffusion coefficient K_h. In the absence of typhoons, K_h is assumed as equals to $K_{h0} = 100\mathrm{m}^2\mathrm{s}^{-1}$, a typical value for oceanic diffusion (Okubo, 1974). Under a typhoon following diffusion coefficient is assumed, in the absence of field data,

$$K_h = K_{h0}\left(1 + \alpha \frac{V_r}{V_m}\right) \tag{4}$$

where $\alpha = 10$.

Horizontal mixing of coral larvae in the advection-dispersion model is simulated by a random walk method.

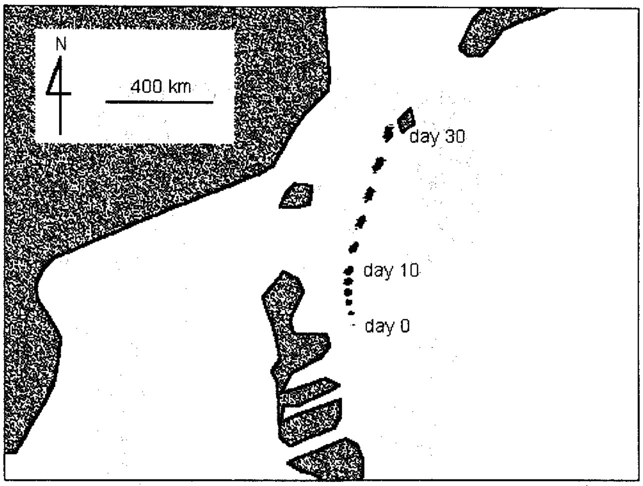

Figure 7. Predicted trajectory and patch size of coral larvae spawned at coral reefs in the Philippines off Luzon and transported towards the Ryukyu Islands by the current. This simulation assumes no typhoons. The patch is shown in 2 days intervals at 0-10 days, and 4 days intervals at 10-30 days.

In the model the coral larvae are injected offshore Luzon. They are tracked in the model for 40 days.

Predictions of the fate of coral larvae in the absence of typhoons (Fig.7) show a mean northward current of about 0.5-1.0 ms^{-1}, the coral larvae reaching the Ryukyu Islands area in about 30 days. The larval cloud is relatively small and the larvae are likely to miss the islands, recruitment depending strongly on local, random meanders of the current. Recruitment in this case would be small with large inter-annual variability.

The presence of typhoons result in doubling, in some cases even tripling, the size of the coral larvae patch arriving near the Ryukyu Islands (Fig.8); the travel time is reduced. A reduction of the travel time is expected to decrease the loss of larvae from mortality due to starvation and predation. Further the trajectory of the center of the larval cloud is also changed by typhoons. Typhoon 1 (Fig.8a) pushes the coral larvae right unto the Ryukyu Islands and decreases their travel time by 13 these two effects combined should increase recruitment. Typhoon 2 also reduce travel time by a similar amount, but the coral larvae are swept away to west side of Ryukyu Islands. Typhoon 3 has little effect on the travel time, and steers the larvae west of the Ryukyu Islands.

Typhoons are quasi-random events and the model results for reef recruitment may be best interpreted using average predictions (Fig.9). In the absence of typhoons, the coral larvae cloud is about 30 km wide and 31 days old; reef recruitment is at the mercy of random fluctuations of the current and in some years reef recruitment may even not occur. The width of the coral larvae cloud increases with increasing number of typhoons. For instance with 8 typhoons, *i.e.* doubling the present number of typhoons, the larval cloud reaching the Ryukyu area is 120 km wide and 26 days old. Reef recruitment is thus enhanced and regular recruitment is more likely.

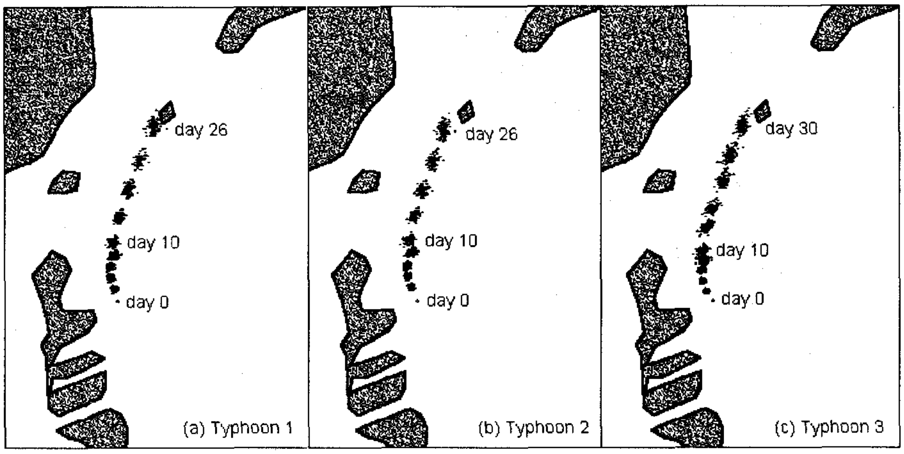

Figure 8. Same as in Figure 7, for four typhoons per month in the whole model domain for three types of typhoons as defined in Figure 5.

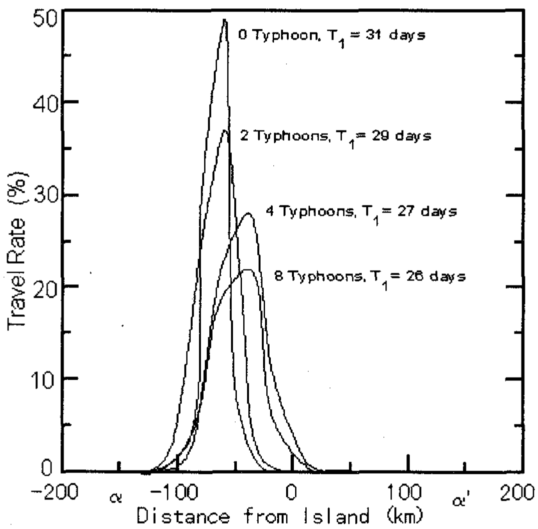

Figure 9. Predicted 'travel rate' distribution along the control line $\alpha - \alpha'$ near the Ryukyu Islands shown in Figure 5. The 'travel rate' is defined as the ration of the number of coral larvae along the transect line $\alpha - \alpha'$ to the number of coral larvae spawned in he Philippines. Coral larvae looses by predation, starvation and other causes, are ignored. The predictions vary according to the numbers of typhoons. The number next to each line shows the number of typhoons. Only typhoons type 1 (see Figure 5) are assumed. T_i is the age of the coral larvae after spawning in coral reefs of the Philippines off Luzon.

5. Discussions and Conclusions

Predictions of the physics-induced biological changes in coral reefs from global changes are difficult because quantitative data on likely changes of wind, storm frequencies and oceanic circulation are lacking. Also the links between biology and physics in coral reefs are complex and still poorly known. It is thus not only difficult but even maybe 'fuzzy' science to attempt to make predictions on how coral reefs may change. Nevertheless, three scenarios were examined with these qualifications. The physical changes in atmospheric and sea level were assumed as a very rapid processes, and the biological system will be faced with a sudden change in the physical forcing.

Firstly, SLR was modelled on the hydrodynamics of a nearly tideless, fringing coral reefs-lagoon system at Moorea Island, French Polynesia. The numerical models was used to predict possible changes in the flushing rates following a rise in sea level and infer possible ecological changes. The prediction said that the areas sheltered from the wind will suffer from an increased residence time of pollutants and a decrease in upwelling of oceanic nutrients.

Secondly, the prediction said that changes in coral zonation on reef slopes will result from changes in wave dynamics over a leeward coral reef following a rise in sea level. Such changes will be accelerated by a possible increase in the frequency of tropical cyclones (typhoons).

Thirdly, the prediction showed that global change, by increasing the frequency of typhoons, may increase coral larvae recruitment in the Ryukyu Islands. Presumably increased recruitment of fish larvae is also likely as both reef fish and coral larvae have an initial pelagic phase after spawning. Because of the ability of reef fish larvae to swim, their recruitment rate is much larger than that of coral larvae (Wolanski and Doherty, 1996) and may be further enhanced by global change.

The three examples shown here may appear non related. They are used to show that oceanographic modelling may be useful in predicting likely impacts on coral reefs from global change and to possibly direct the atttention of biologists to ask specific, practical questions at specific sites. They also show that a number of likely impacts may be subtle and at first glance possibly counter-intuitive.

The choice of scenarios was limited by necessity. There are many more scenarios that could be developed to study the effect of global change on coral reefs. Since coral reefs have survived previous climatic changes, albeit with changes, none of these global change effects were suspected that will have anywhere near the impact on corals as the present devastation and destruction by man of coral reefs and its fisheries in many countries (*e.g.*, Wilkinson, 1992; Dayton, 1995). At the present rate of destruction, global change may have few coral reefs left to affect by the time it comes around. The direct impact of man on corals may be the dominant cause for coral reef changes in many places and may obscure any impact from global change.

6. Acknowledgments

This study was supported by the Australian Institute of Marine Science, the Port and Harbour Research Institute of Japan, the Research Development Corporation of Japan, and the IBM International Foundation. This paper was presented at the workshop on "Response of Coral Reefs to Global Change", Tsukuba Research Center, 1996

References

Algue, J (1904): The cyclones of the Far East, *Special Report of the Director of the Philippine Weather Bureau*, Bureau of Public Printing, Manila, pp.89-93.

Daniels, R.C. (1992): Sea-Level Rise on the South Carolina Coast: Two Case Studies for 2100, *Journal of Coastal Research*, **8**(1), pp.56-70.

Dayton, L. (1995): The killing reefs, *New Scientist*, **148**, pp.14-15.

Done, T.J. (1992): Effects of tropical cyclone waves on ecological and geomorphological structures on the Great Barrier Reef, *Continental Shelf Research*, **12**, pp.859-872.

Emery, K.G. and D. Aubrey (1991): *Sea levels, land levels and tide gages*, Springer- Verlag, Berlin, 237 pp.

Furukawa, K. and Y. Hosokawa (1996): Parameter fitting on a discrete vortex method with wake simulation behind an inclined flat plate, *Computational Fluid Dynamics Journal*, **5**(1), pp.89-105.

Furukawa, K. and E. Wolanski (1997): Shallow water frictional effects in island wakes, *Estuarine, Coastal Shelf Science*, submitted.

Haarsma, R.J, J.F.B. Mitchell and C.A. Senior (1993): Tropical disturbances in a GCM. *Climate Dynamics*, **8**, pp.247-257.

IPCC. (1990): *Climate Change, The IPCC Scientific Assessment*, edts Houghton, J.T., G.J. Jenkins and J.J. Ephraums, Cambridge University Press, Oxford, pp.131-170.

Longuet-Higgins, M.S. and R.W. Stewart (1962): Radiation stress and mass transport in gravity waves with applications to "surf beats". *Journal of Fluid Mechanics*, **13**, pp.481-504.

Massel, S.L. (1993): Extended refraction-diffraction equations for surface waves. *Coastal Engineering*, **19**, pp.97-126.

Massel, S.L. (1996): *Ocean surface waves: their physics and predictions.* World Scientific Publ., Singapore, in press, 1996.

Massel, S.L. and T. Done (1993): Effects of cyclone waves on massive coral assemblages on the Great Barrier Reef: meteorology, hydrodynamics and demography, *Coral Reefs*, **12**, pp.153-166.

Nakamori, T., A. Suzuki and Y. Iryu (1992): Water circulation and carbon flux on Shiraho coral reef of the Ryukyu Islands, Japan, *Continental Shelf Research*, **12**, pp.357-368.

National Astronomical Observatory (ed.). (1994): *Chronological Scientific Tables*, Maruzen, Japan, pp.393-394.

Okubo, A. (1974): Some speculations on oceanic diffusion diagrams, *Rapp. P.-V. Reunion Conseil Int. Exploration de la Mer*, **167**, pp.77-85.

Salvat, B. (1992): Blanchissement et mortalite des scleractinaires sur les recifs de Moorea (archipel de la Societe) en 1991. *Comptes Rendus de l'Academie des Sciences, Paris*, T. **314**, Serie III, pp.105-111.

(SCCCS) Steering Committee of the Climate Change Study. (1995): *Climate Change Science: current understandings and uncertainties*, Australian Academy of Technological Sciences and Engineering, p.17.

Tchernia, P. (1980): *Descriptive Regional Oceanography*, Pergamon Press, England, pp.216-238.

Veron, J.E.N. and G.A. Hodgson (1989): Annotated checklist of the hermatypic corals of the Philippines, *Pacific Science*, **43**(3), pp.234-287.

Veron, J.E.N. and P.R. Minchin (1992): Correlations between sea surface temperature, circulation patterns and the distribution of hermatypic corals of Japan, *Continental Shelf Research*, **12**, pp.835-857.

Wilkinson, D. (1992): Coral reefs of the world are facing widespread devastation: can we prevent this through sustainable management practices. Plenary Address, Biology. *Proc. 7th International Coral Reef Symposium*, June 1992, Guam.

WMO (1972): *Present Techniques of Tropical Storm Surge Prediction*, Reports on Marine Science Affairs, Report No. **13**, World Meteorological Organisation, Switzerland, pp.8-23.

Wolanski, E. (1994): *Physical oceanographic processes of the Great Barrier Reef*, CRC Press, Boca Raton, Florida, 194 pp.

Wolanski, E., B. Delesalle, V. Dufour and A. Aubanel (1993): Modelling the fate of pollutants in the Tiahura lagoon, Moorea, French Polynesia. *Proc. 11th. Australasian Conference on Coastal and Ocean Engineering*, pp.23-27

Wolanski, E. and B. Delesalle (1995): Upwelling by internal waves, Tahiti, French Polynesia. *Continental Shelf Research*, **15**, pp. 357-368.

Wolanski, E. and J. Chappell (1996): The response of tropical Australian estuaries to a sea level rise. *Journal of Marine Systems*, in press.

Wolanski, E. and P. Doherty (1996): Predicting the dispersion of fish larvae in the Great Barrier Reef. *Australian Institute of Marine Science*.