AN ECOHYDROLOGICAL MODEL OF THE GREAT BARRIER REEF

E. Wolanski, R. Brinkman, S. Spagnol, F. McAllister, K. Marshall, L. McCook, T. Done, J. Lough
Australian Institute of Marine Science,
PMB No. 3, Townsville MC, Qld. 4810,
e-mail: e.wolanski@aims.gov.au

E. Deleersnijder
Institut d'Astronomie et de Geophysique G. Lemaitre, Universite Catholique de Louvain,
2 Chemin du Cyclotron, B-1348 Louvain-La-Neuve, BELGIUM,
e-mail: ericd@astr.ucl.ac.be

SUMMARY
The major components of an ecohydrological model of the Great Barrier Reef, Australia, are described; the model predicts the health of individual coral reefs in a 400 km long domain extending from the Whitsunday Islands in the South to Lizard Island in the North. Reef health is parameterised by the spatial cover of algae and hard coral. The model incorporates hydrology, oceanography, meteorology and ecology. The calibrated model could be used to test the implications of various scenarios for increased disturbances due to climate change, or changes in management practice (e.g. improved water quality, increased abundance of herbivorous fishes).

Keywords: modelling, coral reefs, algae, human impact, Great Barrier Reef

1. INTRODUCTION

Effective management of the Great Barrier Reef (GBR) requires an adequate understanding of key biological and oceanographic processes and their interactions. An ecohydrological model of the reef that can predict reef health could help answer questions that have important management implications. Two topical questions are: (1) To what extent do changes in quality and quantity of terrestrial runoff lead to reef degradation by generating phase shifts - the process by which areas formerly dominated by corals are overgrown by algae [1,2]; and (2) Is the reef capable of sustaining or rebuilding its biodiversity by self-seeding? This paper describes key elements of such a model.

2. MODEL DESIGN

Figure 1 shows the main components of the HOME model pathways, incorporating Hydrology, Oceanography, Meteorology and Ecology [3]. In the model, reefs are individual ecosystems, each with its own coral-algae-herbivorous fish ecology. Reefs are connected via an oceanographic-driven exchange of coral and fish larvae. The reefs are disturbed by pulse-like events (eg river plumes, tropical cyclones, warm water events resulting in bleaching). As a result of land use practices (eg agriculture, land clearing) along the coast, some reefs will also experience long-term changes in nutrient supply and turbidity. The time for sub-lethally stressed reefs to recover depends on ambient water quality conditions and numbers of herbivorous fish. The extent and rate of physiological acclimatization will also affect rates of recovery. When corals are killed or damaged, the population can re-establish from remaining fragments, or through the import of coral larvae from healthy (or less impacted) reefs. Fish larvae can also be imported from healthier

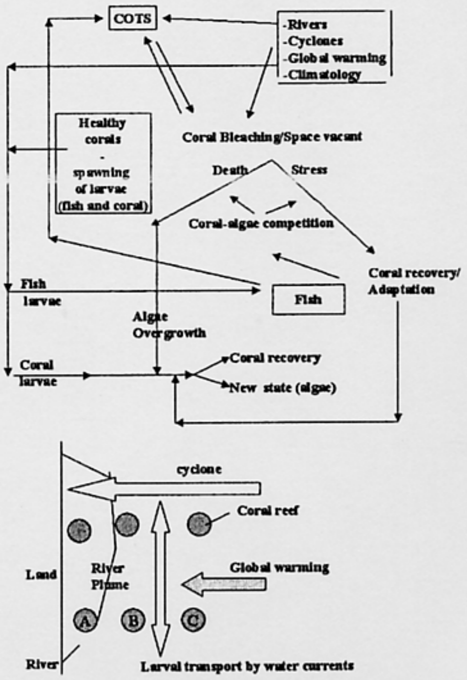

Figure 1: Model HOME pathways. A, B and C are Pandora, John Brewer and Myrmidon Reef, respectively (see location map in Figure 2).

Proceedings 4th Queensland Environmental Conference (30-31 May 2002, Brisbane), Institution of Engineers (Australia) reefs; import of coral and fish larvae is controlled by oceanography.

Outside of spawning periods, individual reefs are isolated from each other. Crown-of-thorn starfish (COTS) can limit coral coverage; in turn low coral coverage and a high level of fish predation can limit COTS.

The model starts at time $t=0$ when initial conditions are set. For $t>0$, reefs are perturbed by a series of pulse-like disturbances, but there is stochastic variability among the reefs in a patch with respect to parameters influencing recovery (notably larval supply and post-larval survivorship). In time each reef thus evolves its own independent ecology. Hard coral cover on each reef is constantly changing in time and no two reefs are necessarily alike, because the import functions vary spatially. Thus every reef has its own 'health' (coral cover and fish) because the forcing functions (eg river plumes, tropical cyclones and bleaching events) vary in space and time.

The model domain (Figure 2) comprises 261 reefs and extends from Lizard Island in the North to the Whitsunday Islands in the South. The geographic extent of the model was chosen to cover a region assumed to be most susceptible to anthropogenic impacts from land runoff.

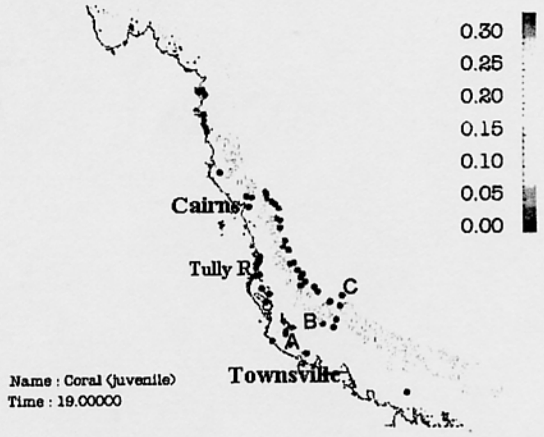

Figure 2: Model domain and an example of the model output showing the synoptic distribution of predicted, non-dimensionalised C_j. A, B and C are Pandora, John Brewer and Myrmidon Reefs respectively. Time is non-dimensionalised by the coral polyp lifetime. Because the time step is small, events such as cyclones and river floods are explicitly incorporated.

2.1 Ecology sub-model

The ecology sub-model (see Figure 3) uses hard coral cover as a measure of reef health, and is based on ecological concepts and processes described in [4]. It simplifies reef community structure to include only corals and algae, as benthic space occupants, and herbivorous fish, which consume algae. External impacts include tropical cyclones, run-off of terrestrial freshwater, nutrient and sediment, COTS and warm water-related bleaching events. Amounts of sediment and nutrient may also occur as chronic, long-term loads [5]. Algae and corals compete for limited substrate space. The model equations extend those from [2] by incorporating several new feedback processes as well as both self-seeding and connectivity of larvae. Disturbances are determined from historical records of river floods, tropical cyclones and warm water events leading to bleaching.

The ecosystem dynamics equations are:

Adult coral

$$dC_a/dt=K_{caa}C_a(1-C_a/C_{ao})\gamma/(1+K_{scaa}S) -K_dC_a(1+K_{sd}S)(1+A/(1-C_{ao})) +2K_{cjca}C_j/(1+S)$$

Juvenile coral

$$dC_j/dt=-K_{cjca}C_j+K_{cacj}C_aC_{jo}/(C_{ao}(1+K_{scj}S))R$$

Algae

$$dA/dt=-K_{caa}C_a(1-C_a/C_{ao})\gamma/(1+K_{scaa}S)+\delta_1-\delta_2$$

Herbivorous fish

$$F=F_o/(1+K_{sf}S)$$

where

t = time; F = herbivorous fish abundance; F_o = equilibrium F, function of distance offshore; S=fine sediment load ($S\geq1$); A=algal abundance; N=nutrient abundance; N_o=equilibrium N; C_a=adult coral abundance; C_{ao}=equilibrium C_a; C_j=juvenile coral abundance; C_{jo}=equilibrium C_j; $\delta_1 = C_a+A$; K_{sf}=proportional dependence of F on S; K_{caa}=at equilibrium, relative dominance of competitiveness for space of adult coral over algae; K_{scaa}=proportional dependence of K_{caa} on S; K_d=coral death rate at equilibrium; K_{sd}=dependence of K_d on S; K_{cjca}=rate at which juvenile coral mature to adulthood; K_{cacj}= recruitment rate of juvenile coral; K_{scj}=proportional dependence of K_{cacj} on S; K_{na} = equilibrium growth rate of algae from nutrients; K_{sa}=proportional dependence of K_{na} on S; $\delta=A/(1- C_a)$ = thickness of the algal mat; γ = coral growth potential= $(C_j/C_a)/(C_{jo}/C_{ao})$ if $\gamma<1$, $\gamma = 1$ otherwise; $\delta_1 =K_{na}AN(1-A)/(No(1+K_{sa}S))$; $\delta_2=K_{af}FA/F_o$ if $\delta_2> \delta_1$, $\delta_2= \delta_1$ otherwise; R=coral recruitment after mass spawning=$(S_s+C_n)M$; M=coral larvae mortality; S_s = recruitment by self-seeding;

C_n = recruitment by oceanographic import of larvae from other coral reefs in the GBR.

A coral adaptation/acclimatization module is under preparation. A module for carnivorous fish and COTS has been implemented.

The external variables are suspended sediments (S), nutrients (N) and disturbances. Disturbances are low salinity events, tropical cyclones, COTS and coral bleaching from unusually warm water in summer. Their impacts are modelled as a step decrease in cover of adult corals, providing empty space. This in turn allows for a pulse of algal growth. Since empty space is rapidly colonised by algae,

$$A = (1- C_a) H(1-A-C_a)$$

where H is the Heavyside step function.

Following a disturbance,

$$C_{a(\text{post-event})} = \alpha C_{a\ (\text{pre-event})}$$

$A_{(post\text{-}event)} = \beta - C_{a\,(post\text{-}event)}$
where α = the event transfer coefficient for coral ($\alpha < 1$) and β = the event transfer coefficient for algae ($\beta > 1$).

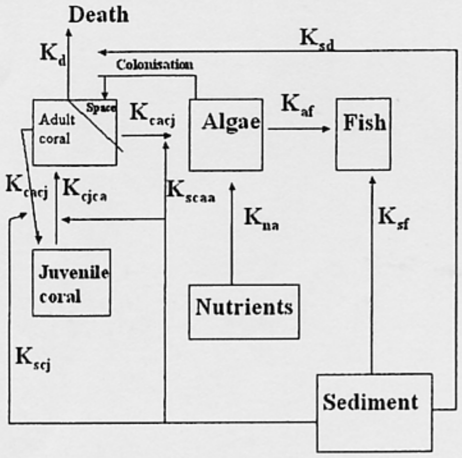

Figure 3: Ecological sub-model pathways.

For the case of a tropical cyclone impact, the parameters α and β are determined by the strength of the cyclone affecting a particular reef. For the case of river floods, α and β are determined by two parameters characterising the river plume, namely the minimum salinity and the duration of the river plume over the reef.

2.2 Low salinity events

A three-dimensional hydrodynamic model was used to describe the dynamics of river plumes. The 3-D model hydrodynamics equations are [6,7]:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

$$\frac{\partial u}{\partial t} + \frac{\partial (uu)}{\partial x} + \frac{\partial (vu)}{\partial y} + \frac{\partial (wu)}{\partial z} - fv = -\frac{1}{\rho_0}\frac{\partial p}{\partial x} + \frac{\partial}{\partial z}\left(A\frac{\partial u}{\partial z}\right)$$

$$\frac{\partial v}{\partial t} + \frac{\partial (uv)}{\partial x} + \frac{\partial (vv)}{\partial y} + \frac{\partial (wv)}{\partial z} + fu = -\frac{1}{\rho_0}\frac{\partial p}{\partial y} + \frac{\partial}{\partial z}\left(A\frac{\partial v}{\partial z}\right)$$

$$\frac{\partial p}{\partial z} = -\rho g$$

where A is the eddy viscosity. The density ρ is mainly dependent on salinity. The salinity conservation equation is:

$$\frac{\partial S}{\partial t} + \frac{\partial (uS)}{\partial x} + \frac{\partial (vS)}{\partial y} + \frac{\partial (wS)}{\partial z} = \frac{\partial}{\partial z}\left(K\frac{\partial S}{\partial z}\right)$$

where K denotes the eddy diffusivity. The eddy viscosity and diffusivity are obtained from a turbulence closure model.

The model requires daily river discharges, as well as wind speed and direction data. These historical data were available and were used by the model to calculate river flood plumes movement from 1969 onwards in the GBR in an area extending from the Whitsunday Islands to Princess Charlotte Bay. The model was calibrated using an extensive data set collected during the1981 flood [6]. An example of the predicted river plume for the 1991 flood is shown in Figure 4.

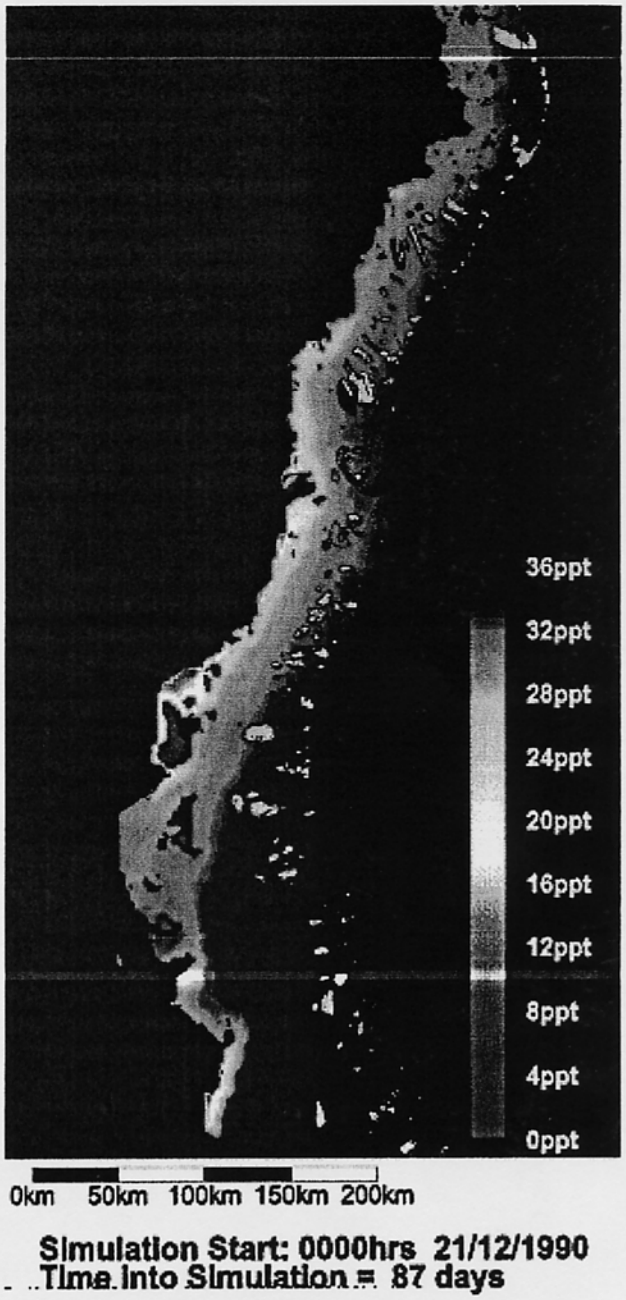

Figure 4: A snapshot of the predicted surface salinity distribution in the central region of the Great Barrier Reef during the 1991 flood.

2.3 Nutrient and sediment input from land runoff

Time series covering a thirteen-year period are available for the Tully River (see location map in Figure 2) in the wet tropics [8]. Increased concentrations of nitrogen in the river that may be a consequence of agricultural activity is incorporated in the model. The resulting increases in concentration of N and S are parameterised semi-empirically in the model. These increases reflect an observation that the impact of reduced salinity on massive coral skeletons show a strong inverse relation to (1) the percentage distance of a reef across the shelf and (2) the average water depth between a reef and the mainland (Lough, Barnes and McAllister, unpublished data).

2.4 Tropical cyclones

Historical data on the trajectory and intensity of tropical cyclones are available from 1969 onwards. The impact on each reef is then determined for each cyclone during this period and these data are used in the model as an external forcing.

2.5 Unusually warm water in summer

The incidence of lethal coral bleaching events can be correlated to anomalously high sea surface temperature (SST) [9]. The synoptic distribution of SST, as measured by satellite, is available for recent years, including the 1998 mass-bleaching event [9].

2.6 Coral recruitment

The transport of coral spawn material may be modelled by the two-dimensional, depth-averaged equation

$$\frac{\partial(hc)}{\partial t} = \frac{\partial}{\partial x}\left(kh\frac{\partial c}{\partial x} - uhc\right) + \frac{\partial}{\partial y}\left(kh\frac{\partial c}{\partial y} - vhc\right)$$

where $c(t,x,y)$ denotes the concentration of the material under study, while k (>0), h and (u,v) represent the horizontal diffusivity, the depth of the water column and the depth-averaged horizontal velocity vector along the (x,y) axes, respectively.

Accurate numerical solutions of this equation are not easy to obtain, for want of appropriate Eulerian discretisations of the advection operator. This is why a Lagrangian approach is adopted instead. At time $t_n = n\Delta t$ (n=0,1,2,...), where Δt is a suitable time increment, the position (X_n, Y_n) of a particle of coral spawn material is updated by means of the Lagrangian algorithm

$$(X_{n+1}, Y_{n+1}) = (X_n, Y_n) + (U,V)\Delta t + \sqrt{\frac{2k\Delta t}{r}}(R_{x,n}, R_{y,n})$$

where $R_{x,n}$ and $R_{y,n}$ are zero-mean random numbers with variance equal to r. The velocity components U and V are defined to be

$$(U,V) = (u,v) + \frac{1}{h}\left[\frac{\partial(kh)}{\partial x}, \frac{\partial(kh)}{\partial y}\right]$$

The velocity to be used is the sum of the water velocity (u,v) and the correction velocity $(1/h)[\partial(kh)/\partial x, \partial(kh)/\partial y]$. The correction velocity is a key aspect of the Lagrangian algorithm, and the failure to include it leads to a spurious accumulation of particles in regions where the water depth or the diffusivity is smallest [10].

2.6.1 *Oceanographic sub-model*

An oceanographic sub-model is used to obtain the velocity vector (u,v) in the coral recruitment sub-model. It is based on the 2-D barotropic equations of motion and parameterises explicitly the influence of the Coral Sea in generating the large-scale circulation in the GBR [7,11]:

$$\frac{\partial uH}{\partial t} + \frac{\partial u^2 H}{\partial x} + \frac{\partial uvH}{\partial y} - fvH + gH\frac{\partial(\bar{\eta} + \eta')}{\partial x} + \frac{gu|\mathbf{u}|}{C^2} - \frac{\tau_{sx}}{\rho} - \beta\nabla^2(vH) = 0$$

$$\frac{\partial vH}{\partial t} + \frac{\partial vuH}{\partial x} + \frac{\partial v^2 H}{\partial y} + fvH + gH\frac{\partial(\bar{\eta} + \eta')}{\partial y} + \frac{gv|\mathbf{u}|}{C^2} - \frac{\tau_{sy}}{\rho} - \beta\nabla^2(vH) = 0$$

$$\frac{\partial \eta'}{\partial t} + \frac{\partial uH}{\partial x} + \frac{\partial vH}{\partial y} = 0$$

where $\bar{\eta}$ is the mean sea surface elevation determined by the large scale circulation in the Western Coral Sea, η' is a time varying fluctuation about $\bar{\eta}$, h is water depth below mean sea level, H is total water depth (h + η), f is the Coriolis parameter; g is acceleration due to gravity; C is the Chezy coefficient, $C = H^{1/6}/n$ where n is the Manning coefficient; τ_{sx} and τ_{sy} are wind stress components in the x and y directions, respectively; ρ is fluid density; β is horizontal eddy viscosity; and ∇^2 is the Laplacian operator $\nabla^2 = (\partial^2/\partial x^2 + \partial^2/\partial y^2)$.

The model domain is that shown in Figure 4. The annual coral spawning date from 1969 onwards was calculated from the lunar phase. Historical wind data during the spawning events were obtained from the Commonwealth Bureau of Meteorology (before 1980) and from the AIMS weather database (after 1980). The oceanographic model was used to calculate the water circulation during and just after mass coral spawning subsequently used these historical wind data.

2.7 Model verification

The predicted values of C_a can be compared against historical observations of C_a at reefs that have been monitored over long periods [12]. The longest data sets (20 years long) available for verification are that (Figure 5) of C_a from three reefs located in a cross-shore transect off Townsville in the central GBR, these are Pandora Reef (inshore), John Brewer reef (mid-shelf) and Myrmidon Reef (offshore; see a location map in Figure 2). Initial comparison of time-series of observed and predicted C_a is very encouraging.

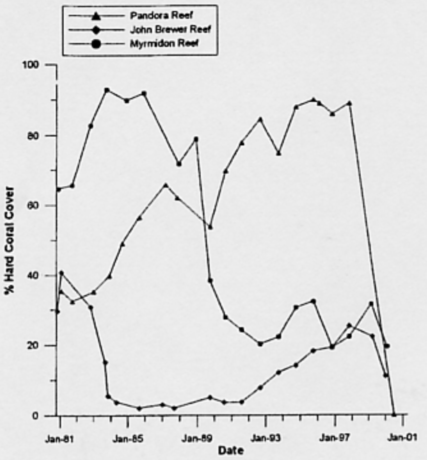

Figure 5: Time-series plot of C_a at three reefs off Townsville (see location map in Figure 2).

2.8 Model visualization

The model output is visualized using OpenDX (an open source scientific data visualization package originally released by IBM as Data Explorer). The data are displayed as stacked cylindrical glyphs of C_j, A and C_a over the model domain (Figure 6). The bathymetry data is displayed in 3-D. In addition, current data can be added as moving arrows. Single frames can be concatenated to construct an animation. This technology enables a simplified "immersive visualization" experience that makes it easier for the user to interpret the data. Alternatively, the 2-D synoptic distribution of reef health as parameterised by one of the three parameters C_j, A and C_a, can be visualised (see an example in Figure 2).

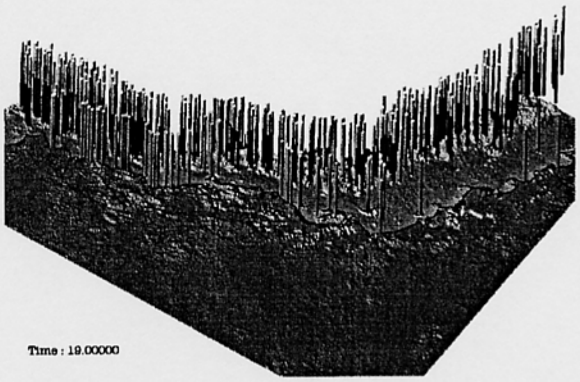

Figure 6: A snapshot from a time-series of the predicted distribution of non-dimensionalised A (top bar in the glyph) and C_a (bottom bar). The bar height =1.

3. CONCLUSION

The HOME model links physical and biological oceanography as well as reef ecological processes in the GBR. It could prove useful in helping to attribute causality between natural and human influences, on declines in coral cover. The model can help investigate the extent to which anthropogenic effects, via land-runoff and climate changes, may be responsible for the failure of reefs to recover after disturbance, with a consequent long-term decline in reef health.

The model thus can overcome problems with a classical, short-term environmental impact assessment, which would demonstrate mainly the inherent variability in reef communities. The HOME model, once finalized, would overcome this problem and be used to forecast (with error bars) both levels and variability of key indicators of reef health, such as coral cover, over the next 50 years under various management strategies and external influences.

4. ACKNOWLEDGMENTS

AIMS, CRC-Reef, IBM-Australia, the Catholic University of Louvain and UNESCO IHP Project on Ecohydrology supported this study. Eric Deleersnijder is a Research Associate with the National Fund for Scientific Research of Belgium (FNRS). It is a pleasure to thank M. Wakeford and Dr. B. King.

5. REFERENCES

[1] Done, T.J.: Phase shifts in coral reef communities and their ecological significance. Hydrobiologia 247 (1992), 121-132.
[2] McCook, L.J.: Wolanski, E.J.: Spagnol, S.: Modelling and visualizing interactions between natural disturbances and eutrophication as causes of coral reef degradation. In: Oceanographic Processes of Coral Reefs: Physical and Biological Links in the Great Barrier Reef. Ed. Wolanski: CRC Press 2001, 113-125.
[3] E. Wolanski: Oceanographic Processes of Coral Reefs. Physical and Biological Links in the Great Barrier Reef. CRC Press, Boca Raton, 2001.
[4] McCook, L. J.: Macroalgae, nutrients and phase shifts on coral reefs: Scientific issues and management consequences for the Great Barrier Reef. Coral Reef 18 (1999), 357-367.
[5] Russ, G.R.: McCook, L.J.: Potential effects of a cyclone on benthic algal production and yield to grazers on coral reefs across the central Great Barrier Reef. Journal of Experimental Marine Biology and Ecology 235 (1999), 237-254.
[6] King, B.: McAllister, F.: Wolanski, E.: Done, T.: Spagnol, S.: River plume dynamics in the central Great Barrier Reef. In: Oceanographic Processes of Coral Reefs: Physical and Biological Links in the Great Barrier Reef. Ed. Wolanski: CRC Press 2001, 145-160
[7] E. Wolanski: Physical oceanographic processes of the Great Barrier Reef. CRC Press. Boca Raton, 1994.
[8] Mitchell, A.W: Reghenzani, J.R.: Furnas, M.J.: Nitrogen levels in the Tully River – a long term view. Water Science and Technology 43 (2001), 99-105.
[9] Skirving, W.: Guinotte, J.: The sea surface temperature story on the Great Barrier Reef during the

coral bleaching event of 1998. In: Oceanographic Processes of Coral Reefs: Physical and Biological Links in the Great Barrier Reef. Ed. Wolanski: CRC Press, 301-313.
[10] Spagnol, S.: Wolanski, E.: Deleersnijder, E.: Brinkman, R.: McAllister, F.: Cushman-Roisin, B.: Hanert, E.: A method to correct negative diffusion effects on depth-averaged, advection-diffusion models of coral reefs. Marine Ecology Progress Series, in press.
[11] Brinkman, R.: Wolanski, E.: Delersnijder, E.: McAllister, F.: Skirving, W.: Mass flux from the Coral Sea into the Great Barrier Reef. Estuarine Coastal and Shelf Science, in press.
[12] Done, T.J.: Wakeford, M.: Unpublished estimates made in photographic stations.