Changes in Coral Reef Ecosystems as an Indicator of Climate and Global Change

Martin J. Attrill

Marine Biology and Ecology Research Centre, Marine Institute, University of Plymouth, Drake Circus, Plymouth PL4 8AA, United Kingdom

1. INTRODUCTION

In comparison with terrestrial systems and other components of the marine environment, relatively little is known about how climate and global change has been affecting the organisms of the seabed with one exception: tropical coral reefs. Recent reviews [1,2] and metanalyses [3,4] have pulled together all existing knowledge on how climate is impacting, for example, range shifts and phenology [4] of the world's species, but, corals aside, few examples within these overviews are from the marine seabed. In her excellent review, Parmesan [1] devotes a section to marine community shifts, but the majority of examples are from either the pelagic (Chapter 12) or intertidal (Chapter 15) zones; only two studies on fish [5,6] are associated with the subtidal seabed. Terrestrial and freshwater examples dominate these studies. A sizeable proportion of research assessing climate impact on marine systems has investigated the response to the major climate cycles, such as the El Niño Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO). These provide information on how systems respond to cooling and warming trends across the extremes of these cycles, and thus provide a model of how potentially organisms and systems may respond to climate warming [7], particularly as the occurrence and severity of ENSO events is predicted to increase under warming scenarios [8]. This future relationship between atmospheric dynamics and temperature change is, however, uncertain, so there also needs to be some caution about how past responses of biological systems to these climatic cycles reflect ongoing and future climate change [1]. Nevertheless, such studies provide much of the information available on climate responses of marine systems.

In contrast to other subtidal benthic systems, the impact of global warming-related issues on coral reefs has had one of the highest profiles in recent years, particularly following the worldwide impact of the 1997–1998 extreme El Niño event [9], the extensive public concern about this ecosystem and recent reports predicting widespread losses of reef and extinction of species [10,11]. Climate change can potentially impact coral reefs through several key mechanisms, in particular increasing sea surface temperature (SST), ocean acidification, increasing storminess and sea level rise [12,13]. The latter three mechanisms are dealt with specifically in other chapters, so this chapter will focus on the impact of rising sea temperatures on coral reef ecosystems, particularly the effect of mass bleaching of the corals themselves.

2. TROPICAL CORAL REEF ECOSYSTEMS

Concern about the human impact on coral reefs has existed for decades and, until comparatively recently, the major threats to the integrity of reef systems have been considered to be overfishing and pollution [12,14]. Such impacts can be potentially managed at the local level, but any such management will be unsuccessful when put into the context of more recent recognised effects of global climate change [12]. Similarly, climate impacts may be exacerbated by the additional effect of these other local anthropogenic factors, which have made coral reefs systems in some areas of the world more susceptible to damage. The link between climate change and region-scale mass bleaching of corals is now incontrovertible [12,13], in particular the direct link between bleaching and SST anomalies [15]. There are no records of mass bleaching prior to the 1980s, though it is unclear how extensive such bleaching was earlier in the twentieth century before widespread reporting [16]; it is unlikely, however, that bleaching of the scale seen in recent years would have gone unnoticed. In the Great Barrier Reef, for example, bleaching events have become more widespread since the 1980s (Fig. 1a), coinciding with a decline in coral cover over this time [17]; globally, mass coral bleaching has become more frequent and intense in recent decades [11].

Bleaching is due to a whitening of the corals following the expulsion of the symbiotic zooxanthellae, the algae providing most of the coral's pigment. Loss of the zooxanthellae, therefore, leaves comparatively colourless coral tissue plus the white calcareous reef skeleton. The process is often considered as a response to increasing ambient temperatures above a threshold, ~0.8–1 °C above summer average temperatures for at least 4 weeks [18,19].

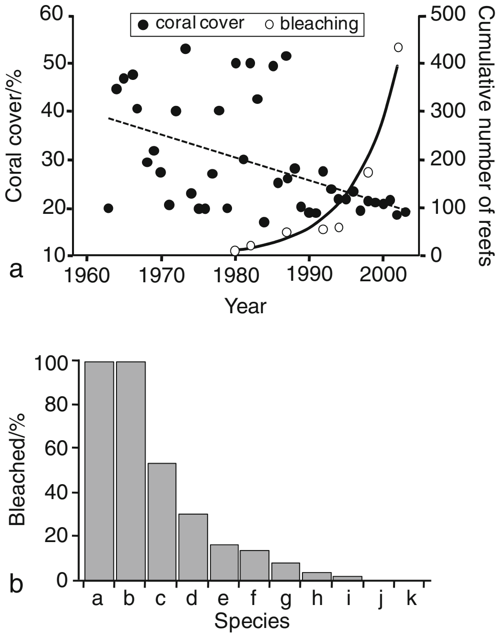

FIGURE 1 a, Trends in coral cover and number of reefs with mass bleaching on the Great Barrier Reef, Australia (Adapted by permission from Macmillan Publishers Ltd [Nature], Ref. [17]). b. Differential bleaching responses of nine species of corals in Raiatea, French Polynesia, during May 2002 (Redrawn from Ref. [12], reprinted with permission from AAAS). (a, *Acropora anthocercis*; b, *A. retusa*; c, *Montipora tuberculosa*; d, *Pocillopora verrucosa*; e, *M. caliculata*; f, *Leptastrea transversa*; g, *P. eydouxi*; h, *P. meandrina*; i, *L. bewickensis*; j, *Porites lobata*; k, *L. purpurea*).

Bleaching thresholds across coral species are likely to represent a broad spectrum of responses (Fig. 1b), however, and susceptibilities will change over time following phenotypic and genetic responses of the corals [12]. It is clear that many coral species exist over a wide biogeographical range of temperatures and individuals have subsequently different bleaching thresholds in terms of absolute temperature, indicating adaptive ability within species [20]. The key driver for bleaching, therefore, appears to be temperature increases above those generally experienced by corals in any given location. It has been hypothesised that the bleaching response is an adaptive process [21,22], the corals expelling susceptible symbionts and taking up more resistant ones; whilst there is some evidence for this [13], it does not appear to be supported by observations on the fate of bleached corals [12], perhaps being more accurately described as a stress response.

What is uncontested, however, is that major bleaching events can severely impact coral reefs in the long term: if bleaching is prolonged or exceeds 2 °C above seasonal maxima corals can die [13]. Major bleaching events were observed in 1982–1983, 1987–1988, 1994–1995, 1997–1998 [13], 2002

(GBR, [23]) and 2005 (Caribbean, [19]) and have often, but not always, been associated with intense El Niño events which enhance global sea temperatures. The 1997–1998 event was the most extreme El Niño on record [9] and resulted in extensive bleaching recorded across the world's coral reefs [24]. An estimated 16% of the world's coral was lost in this one event, in particular within the Indian Ocean/SE Asia [24] (Table 1), with only partial recovery evident. Overall, only approximately half of the reefs affected in 1998 have recovered [24]. The 2005 event, however, occurred without an El Niño and has provided evidence of the impact of the underlying increasing trend in global sea water temperatures (Chapter 19); this has been related to anthropogenic forcing in the Atlantic since the 1970s [19]. Anomalously warm temperatures were recorded across the Caribbean and tropical Atlantic [19], resulting in exceptional levels of bleaching: 90% of coral cover in the British Virgin Islands, 80% in US Virgin Islands and 66% in Trinidad and Tobago, for example [19]. Analysis of local temperature anomalies revealed that SSTs were higher than the expected annual maxima for longer than had been previously been recorded [19] (Fig. 2), resulting in the exceptional bleaching observed. It is also notable that such maxima have been exceeded every year since 1995 (Fig. 2); prior to this, such extremes were rare. The second highest value occurred in 1998, when extensive bleaching was also apparent in the Caribbean [25].

The only long-term data available on the impact of climate on coral species is from the geological record, as reviewed by Hughes et al. [12]. Many extant species of coral can be traced back in time to the Pliocene (1.8–5.3 Ma ago), so have experienced periods of extensive and rapid warming and cooling during the Pleistocene and Holocene prior to human impact [14]. In response to climatic changes, there is evidence species underwent large shifts in their distributional range [26]; for corals, this extended up to 500 km further south in Australia, for example [12]. Until very recently, there was no evidence of such shifts in response to modern climate change, but, following increasing sea temperatures, two species of *Acropora* have re-expanded their ranges 50 km northwards along the Florida Peninsula into areas where they have not been recorded for 6000 years [27].

Much evidence, therefore, exists that increasing SSTs are impacting coral reefs through extensive bleaching and subsequent mortality, particularly during exceptional years where average maximum temperatures are exceeded. Corals will also be impacted through changes in seawater pH, affecting their ability to produce calcareous reef skeletons as covered in Chapter 21 (see also Ref. [11]), and potentially further affected by severe storms [28] and sea level rise [29], other consequences of climate change [13]. Unlike past climate changes, however, coral reefs are now also markedly influenced by the synergistic effect of other anthropogenic activities, such as fishing and pollution, making them much more susceptible to changes associated with current climate warming [12].

TABLE 1 Summary of status of coral reefs in 17 regions of the world as of 2004 from Ref. [24], indicating proportion of coral reefs in each region that have been destroyed (i.e., 90% coral lost and unlikely to recover), plus proportion lost and recovered following the 1997–1998 El Niño event

Region	Coral reef area/km^2	Reefs destroyed/(%)	Reefs destroyed in 1998/(%)	Reefs recovered/(%)
The Gulfs	3800	65	15	2
South Asia	19 210	45	65	13
SE Asia	91 700	38	18	8
SW Indian Ocean	5270	22	41	20
US Caribbean	3040	16	NA	NA
S Tropical America	5120	15	NA	NA
E & N Asia	5400	14	10	3
East Africa	6800	12	31	22
East Antilles	1920	12	NA	NA
Central America	4630	10	NA	NA
Micronesian Islands	12 700	8	2	1
North Caribbean	9800	5	4	3
Red Sea	17 640	4	4	2
SW Pacific Islands	27 060	3	10	8
Australia and PNG	62 800	2	3	1
Polynesian Islands	6733	2	1	1
Hawaiian Islands	1180	1	NA	NA
TOTAL	284 803	20	16	6.4

NA = not applicable as no losses recorded in 1998.

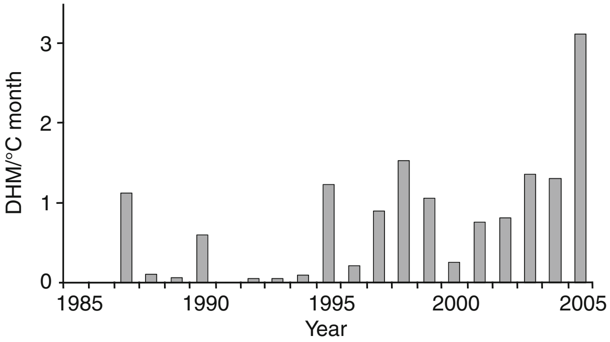

FIGURE 2 Maximum annual thermal stress on Eastern Caribbean coral reefs, presented as Degree Heating Months (DHM, °C month) since 1985. A DHM is equal to 1 month of SST that is 1 °C greater than the monthly maximum climatology for that area (Adapted from Ref. [19], copyright (2007) National Academy of Sciences, U.S.A).

3. THE ASSOCIATED FAUNA OF CORAL REEFS

Unlike the corals themselves, comparatively little research has been focused on how climate and global change may be influencing the vast biodiversity associated with coral reefs (about a quarter of all known marine species [13,30]), perhaps due to the logistic difficulties and expense of constructing long-term data sets on these organisms. Additionally, studies on changes to fish populations and their immediate prey are greatly influenced by other stresses, particularly fishing pressure [13], making it more difficult to identify signals of climate change. However, although over 4000 species of fish are associated with coral reefs [31], remarkably few studies have addressed the impact of climate change on this group. There is little current evidence of direct impact of rising temperatures on coral reef fish, due mainly to lack of data on thermal tolerance [32], although one study in the tropical eastern Pacific [33] determined that the range of Critical Thermal Maxima for 15 fish species (34.7–40.8 °C) was higher than record temperatures (32 °C) recorded during the 1997–1998 El Niño event. Similarly, evidence of distributional shifts in coral fish is lacking, despite being predicted by climate impact reviews [31]. This may be due to a lack of habitat unless coral reefs also extend their range [27].

There is evidence, however, that coral reef fish can be impacted more severely by the indirect effects of mass coral bleaching [34–36]. In a study of Seychelles reefs following the 1997–1998 El Niño [37], intense bleaching resulted in decreased fish abundance and a shift within the assemblage from corallivores to species feeding on invertebrates. The size structure of fish also changed with an increase in large fish [38], a possible time-lag response due to a reduction in coral structural complexity affecting fish recruitment and thus the number of juveniles. However, a minimal effect of this 1997–1998 event was noted on the diversity and abundance of cryptobenthic fish species on the Great Barrier Reef [39], suggesting coral reef fishes may be comparatively resilient to short-term perturbations [39] as long as reef structure is sustained [36].

The most extensive study on the impact of a climate event on coral-associated invertebrates (>500 species) has been undertaken in Bahia, Brazil, by Kelmo and colleagues [40–42]. The 1997–1998 El Niño resulted in anomalous high temperatures and a reduction in the usual high turbidity of the area allowing more UV light to reach the reefs. All groups studied (except sponges) showed extensive reductions in diversity for several years following El Niño (Fig. 3), including the local extinction of one species of coral (*Porites astreoides*); this was most likely due to extensive neoplastic tumours on the corals following UV damage [43]. The density of the majority of species also decreased dramatically (Fig. 3), with only the urchin *Diadema antillarum* showing an opportunistic response to the changing conditions and disappearance of competitive taxa [44]. What is remarkable about this data set is the recovery of groups after 2001, with diversity returning to, or exceeding, levels prior to El Niño (Fig. 3). Reef assemblages clearly have the ability to recover from extreme climate events, but only if no further such events subsequently

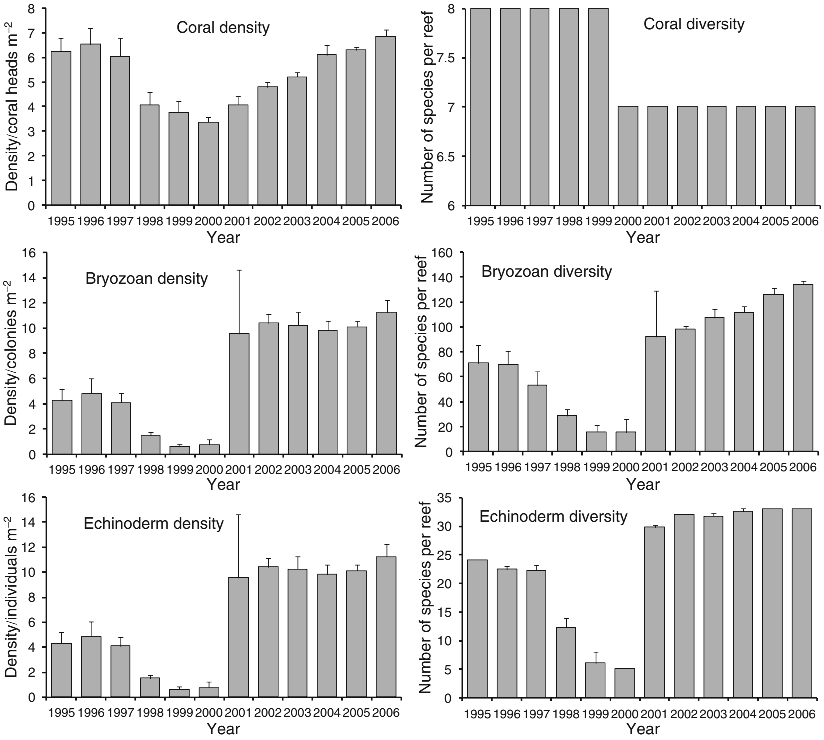

FIGURE 3 Changes in the density and diversity of three major groups of invertebrate (corals, bryozoans, echinoderms) on the patch reefs of Bahia, Brazil since 1995, indicating the impact of the 1997-8 El Niño on all measures, plus the marked recovery from three years after the event in all groups except coral diversity. Levels of echinoderm and bryozoan diversity are higher following recovery than during the pre-El Niño period.

occur; in Bahia, no major El Niño or bleaching event was evident after 1998. Models suggest ENSO events are likely to be more frequent and severe in the future [8], so this recovery ability of coral reef communities may be compromised by climate change.

4. CONCLUSION

There is clear, unequivocal evidence that climate change is affecting coral reef systems [12], with a particular concern about mass coral bleaching due to rising temperatures and the subsequent effects this will have on coral survival and thus the associated organisms. Whilst corals have an innate ability to acclimatise to such change [45], as evidenced in the past [12], severe and regular El Niño events coupled with the modern synergistic impact of other human activities such as fishing, pollution (including comparatively fast ocean acidification [11]) and tourism make coral reefs amongst the most vulnerable of the world's ecosystems under current scenarios of future climate change.

REFERENCES

1. C. Parmesan, Ann. Rev. Ecol. Evol. Syst. 37 (2006) 637–669.
2. G.R. Walther, E. Post, P. Convey, A. Menzel, C. Parmesan, T.J.C. Beebee, J.M. Fromentin, O. Hoegh-Guldberg, F. Bairlein, Nature 416 (2002) 389–395.
3. C. Parmesan, Glob. Change Biol. 13 (2007) 1860–1872.
4. C. Parmesan, G. Yohe, Nature 421 (2003) 37–42.
5. A.L. Perry, P.J. Low, J.R. Ellis, J.D. Reynolds, Science 308 (2005) 1912–1915.
6. S.J. Holbrook, R.J. Schmitt, J.S. Stephens, Ecol. Appl. 7 (1997) 1299–1310.
7. C.D.G. Harley, A.R. Hughes, K.M. Hultgren, B.G. Miner, C.J.B. Sorte, C.S. Thornber, L.F. Rodriguez, L. Tomanek, S.L. Williams, Ecol. Lett. 9 (2006) 228–241.
8. A. Timmermann, J. Oberhuber, A. Bacher, M. Esch, M. Latif, E. Roeckner, Nature 398 (1999) 694–697.
9. M.J. McPhaden, Nature 398 (1999) 559–562.
10. K.E. Carpenter, M. Abrar, G. Aeby, R.B. Aronson, S. Banks, A. Bruckner, A. Chiriboga, J. Cortes, J.C. Delbeek, L. DeVantier, G.J. Edgar, A.J. Edwards, D. Fenner, H.M. Guzman, B.W. Hoeksema, G. Hodgson, O. Johan, W.Y. Licuanan, S.R. Livingstone, E.R. Lovell, J.A. Moore, D.O. Obura, D. Ochavillo, B.A. Polidoro, W.F. Precht, M.C. Quibilan, C. Reboton, Z.T. Richards, A.D. Rogers, J. Sanciangco, A. Sheppard, C. Sheppard, J. Smith, S. Stuart, E. Turak, J.E.N. Veron, C. Wallace, E. Weil, E. Wood, Science 321 (2008) 560–563.
11. O. Hoegh-Guldberg, P.J. Mumby, A.J. Hooten, R.S. Steneck, P. Greenfield, E. Gomez, C.D. Harvell, P.F. Sale, A.J. Edwards, K. Caldeira, N. Knowlton, C.M. Eakin, R. Iglesias-Prieto, N. Muthiga, R.H. Bradbury, A. Dubi, M.E. Hatziolos, Science 318 (2007) 1737–1742.
12. T.P. Hughes, A.H. Baird, D.R. Bellwood, M. Card, S.R. Connolly, C. Folke, R. Grosberg, O. Hoegh-Guldberg, J.B.C. Jackson, J. Kleypas, J.M. Lough, P. Marshall, M. Nystrom, S.R. Palumbi, J.M. Pandolfi, B. Rosen, J. Roughgarden, Science 301 (2003) 929–933.
13. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, C.E. Hanson, Cross-Chapter Case Study, Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC, Cambridge University Press, Cambridge, UK, 2007, pp. 843–868.

14. J.B.C. Jackson, M.X. Kirby, W.H. Berger, K.A. Bjorndal, L.W. Botsford, B.J. Bourque, R.H. Bradbury, R. Cooke, J. Erlandson, J.A. Estes, T.P. Hughes, S. Kidwell, C.B. Lange, H.S. Lenihan, J.M. Pandolfi, C.H. Peterson, R.S. Steneck, M.J. Tegner, R.R. Warner, Science 293 (2001) 629–638.
15. J.P. McWilliams, I.M. Cote, J.A. Gill, W.J. Sutherland, A.R. Watkinson, Ecology 86 (2005) 2055–2060.
16. A.D. Barton, K.S. Casey, Coral Reefs 24 (2005) 536–554.
17. D.R. Bellwood, T.P. Hughes, C. Folke, M. Nystrom, Nature 429 (2004) 827–833.
18. O. Hoegh-Guldberg, Mar. Freshw. Res. 50 (1999) 839–866.
19. S.D. Donner, T.R. Knutson, M. Oppenheimer, Proc. Natl. Acad. Sci. USA 104 (2007) 5483–5488.
20. S.D. Donner, W.J. Skirving, C.M. Little, M. Oppenheimer, O. Hoegh-Guldberg, Glob. Change Biol. 11 (2005) 2251–2265.
21. A.C. Baker, Nature 411 (2001) 765–766.
22. R.W. Buddemeier, D.G. Fautin, Bioscience 43 (1993) 320–326.
23. R. Berkelmans, G. De'ath, S. Kininmonth, W.J. Skirving, Coral Reefs 23 (2004) 74–83.
24. C. Wilkinson (Ed.), Status of Coral Reefs of the World: 2004, vol. 1, AIMS, Townsville, Australia, 2004, p. 316.
25. R.B. Aronson, W.F. Precht, M.A. Toscano, K.H. Koltes, Mar. Biol. 141 (2002) 435–447.
26. K. Roy, D. Jablonski, J.W. Valentine, Ecol. Lett. 4 (2001) 366–370.
27. W.F. Precht, R.B. Aronson, Front. Ecol. Environ. 2 (2004) 307–314.
28. T.A. Gardner, I.M. Cote, J.A. Gill, A. Grant, A.R. Watkinson, Ecology 86 (2005) 174–184.
29. N. Knowlton, Proc. Natl. Acad. Sci. USA 98 (2001) 5419–5425.
30. C.M. Roberts, C.J. McClean, J.E.N. Veron, J.P. Hawkins, G.R. Allen, D.E. McAllister, C.G. Mittermeier, F.W. Schueler, M. Spalding, F. Wells, C. Vynne, T.B. Werner, Science 295 (2002) 1280–1284.
31. P.L. Munday, G.P. Jones, M.S. Pratchett, A.J. Williams, Fish Fish. 9 (2008) 261–285.
32. J.M. Roessig, C.M. Woodley, J.J. Cech, L.J. Hansen, Rev. Fish Biol. Fish. 14 (2004) 251–275.
33. C. Mora, A.F. Ospina, Mar. Biol. 139 (2001) 765–769.
34. D.J. Booth, G.A. Beretta, Mar. Ecol. Prog. Ser. 245 (2002) 205–212.
35. K.C. Garpe, S.A.S. Yahya, U. Lindahl, M.C. Ohman, Mar. Ecol. Prog. Ser. 315 (2006) 237–247.
36. U. Lindahl, M.C. Ohman, C.K. Schelten, Mar. Pollut. Bull. 42 (2001) 127–131.
37. M.D. Spalding, G.E. Jarvis, Mar. Pollut. Bull. 44 (2002) 309–321.
38. N.A.J. Graham, S.K. Wilson, S. Jennings, N.V.C. Polunin, J. Robinson, J.P. Bijoux, T.M. Daw, Conserv. Biol. 21 (2007) 1291–1300.
39. D.R. Bellwood, A.S. Hoey, J.L. Ackerman, M. Depczynski, Glob. Change Biol. 12 (2006) 1587–1594.
40. M.J. Attrill, F. Kelmo, M.B. Jones, Clim. Res. 26 (2004) 151–158.
41. F. Kelmo, M.J. Attrill, R.C.T. Gomes, M.B. Jones, Biol. Conserv. 118 (2004) 609–617.
42. F. Kelmo, M.J. Attrill, M.B. Jones, Coral Reefs 22 (2003) 541–550.
43. F. Kelmo, Ecological Consequences of the 1997–98 El Niño Southern Oscillation on The Major Coral Reef Communities From Northern Bahia, Brazil, University of Plymouth, Plymouth, 2002, p. 245.
44. M.J. Attrill, F. Kelmo, Estuar. Coast. Shelf Sci. 73 (2007) 243–248.
45. P.J. Edmunds, R.D. Gates, Mar. Ecol. Prog. Ser. 361 (2008) 307–310.