Vulnerability of corals to warming of the Indian seas: a projection for the 21st century

E. Vivekanandan*, M. Hussain Ali, B. Jasper and M. Rajagopalan

Central Marine Fisheries Research Institute, Cochin 682 018, India

Indian seas experienced severe warming in 1998 and 2002 that resulted in large-scale bleaching and mortality of corals. Anticipating increased warming in future, we made an attempt to project coral vulnerability in the Andaman, Nicobar, Lakshadweep, the Gulf of Mannar and the Gulf of Kachchh regions for the 21st century. To project the number of bleaching events, the thermal threshold for bleaching, degree heating month (DHM) accumulations of the sea surface temperature (SST) hotspot anomalies, and the predicted increase in SST during this century were considered. The decadal DHM values are expected to gradually increase in all the five regions in the early decades of this century, but abruptly increase after the year 2050. The results indicate that if there is no increase in thermal tolerance capacity, bleaching would become an annual or biannual event for almost all reef regions along the Indian coast in the next 30–50 years. Reef building corals may lose dominance between 2030 and 2040 in the Lakshadweep region and between 2050 and 2070 in the other four regions.

Keywords: Coral vulnerability, Indian seas, projection, seawater warming.

CORAL reefs are the most diverse marine habitat, and support an estimated 0.5 million species globally[1]. They are among the most sensitive of all ecosystems to temperature changes, exhibiting bleaching (a phenomenon in which the symbiotic zooxanthellae are expelled by coral polyps) when stressed by higher than normal sea temperatures[2,3]. Corals usually recover from bleaching, but they die in extreme cases[4]. Increased frequency of bleaching events will reduce corals' capacity to recover[5]. Large-scale bleaching episodes indicate that coral reefs are likely to be one of the first ecosystems damaged or destroyed by global climate change[6]. Sessile tropical coral reefs are uniquely threatened by global warming, because they cannot relocate to more favourable conditions[7].

Studies relating to monthly average threshold temperature values preceding bleaching in the Indo-Pacific[7] and Caribbean[8] showed that they were near or above 1 degree climatological averages in the warmest months. Surface water that equals or exceeds the widespread bleaching threshold of +1.0°C above long-term averages for the warmest month in coral reef regions is termed as a hotspot[7]. These anomalous seawater conditions are sufficient to cause most corals to bleach under experimental laboratory conditions as well as in the field[9,10]. Indian coral reefs have experienced 29 widespread bleaching events since 1989 (www.reefbase.org), but intense bleaching occurred in 1998 and 2002 (refs 11 and 12). To find out the thermal threshold for coral bleaching in the Indian seas, Vivekanandan *et al.*[13] plotted the sea surface temperature (SST) data prior to, during and after the 1998 coral bleaching events in the Andaman, Nicobar, Lakshadweep regions, the Gulf of Mannar and the Gulf of Kachchh. From these plots, they estimated the degree heating month (DHM) accumulations of the SST hotspot anomalies. They also found that coral bleaching occurred when the summer SST maxima exceeded 31°C and remained high for more than 30 days.

Bleaching events and the ambient temperature at the time of bleaching provide scope for making projections on the vulnerability of coral reefs with future warming of the seas. In this study, for projecting the likelihood of bleaching, we took advantage of DHM algorithm from the output of atmospheric–ocean general circulation model after making appropriate transformations.

To project what the future holds for the coral reefs as a consequence of warming of the Indian seas, the method used by Hoegh-Guldberg[14] was followed. This method was used for projecting the future condition of the Great Barrier Reef[15–17].

The SST compilation for the present analysis was derived from two sources: a satellite (historical) and a forecast SST series. In the absence of continuous real time data, the United States National Oceanic and Atmospheric Administration, National Environmental Satellite Data and Information Service (NOAA/NESDIS) images are the most useful and accurate means of gaining a comprehensive data on the SST anomaly in the Indian seas[11]. Monthly SST data for the years 1985–2005 around the study sites (Table 1) were obtained by Vivekanandan *et al.*[13] from NOAA/NASA Oceans Pathfinder SST project[18], which consists of all pixel products of monthly SST derived from the 5-channel Advanced Very High Resolution Radiometers on board the NOAA polar orbiting satellites (http://podaac.jpl.nasa.gov). This was combined with the monthly SST from the year 2000 to 2099 from the UKMO HadCM3 model for each study region. The historical (satellite) dataset has a resolution of 0.045×0.045 degree latitude and longitude, while the HadCM3 data have a larger grid of 1.25×1.25 degrees. Comparisons with several other models by earlier publications suggest that HadCM3 is a substantial improvement from other models in many respects[19,20]. SRES A2 was chosen as the warming scenario as it is commonly used for 'business as usual' impact studies, projecting a 3°C increase in surface temperature by 2100 (which is an average across all the IPCC models). Moreover, SRES A2 consistently shows itself close to

*For correspondence. (e-mail: evivekanandan@hotmail.com)

Table 1. Thermal threshold and Degree Heating Months estimated for five coral reef regions in the Indian seas based on the estimates from 1998 bleaching events; mean SST is for the period 1985–2005 (modified from Vivekanandan *et al.*[13])

Region	Position	Mean SST (°C)	Max SST (°C)	Duration of high SST (days)	Thermal threshold (°C)	DHM
Andaman	11°21′N; 92°59′E	28.60	32.15	52	31.4	1.07
Nicobar	7°50′N; 93°50′E	28.70	32.00	45	31.0	1.18
Lakshadweep	10°57′N; 72°63′E	28.71	32.05	38	31.4	1.57
Gulf of Mannar	9°38′N; 79°31′E	28.28	31.00	80	31.4	1.14
Gulf of Kachchh	22°5′N; 69°33′E	26.10	30.85	33	30.0	0.75

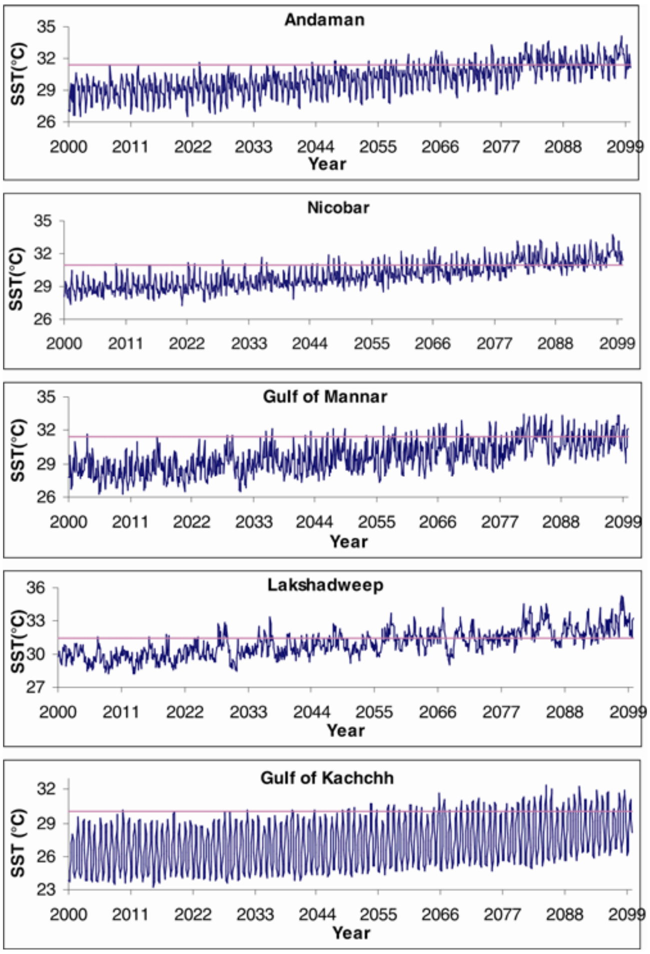

Figure 1. Predicted rise in sea surface temperature (after performing transformations) in the five coral reef regions in the Indian seas (vertical lines indicate thermal threshold for bleaching).

the trends of all climate models without unrealistic extremes.

The SST forecast from climate models rarely flow seamlessly from historical series, and errors in forecast seasonal amplitude further prevent accurate estimation when lethal mortalities might occur[21]. The construction of seamless monthly series from 1985 to 2099 needs two treatments. The first transformation is to adjust each forecast data series by the mean difference in values in the overlapping data between two datasets (n = 72 months). The second transformation scales the annual variation of each forecast data series to match that of each region's historical data (for full details see refs 21 and 22). This provides a SST monthly data set from 1985 to 2099 without any disjunction and has the same seasonal amplitude in the annual range where they overlap.

Two categories of response were studied by Hoegh-Guldberg[14] for estimating the number of catastrophic bleaching events that would occur as SST increase. This study adds two more categories objectively, thus leading to four categories of response, namely low (DHM: 0.5–1), medium (DHM: 1–1.5), high (DHM: 1.5–2.5) and catastrophic (DHM: >2.5). Each year the category was classified based on the accumulated DHM values once they exceeded DHM 0.5 for that particular year. The assumptions behind this analysis are as follows: (i) Today's thermal threshold will be similar for the entire study period and that adaptation does not occur at rates fast enough to change its tolerance. (ii) When corals are exposed to DHM 1 or more, bleaching begins, equivalent to two weeks of 2°C or four weeks of 1°C exposure above the expected long term summer maximum value at each region.

The location of study regions, temperature thresholds and DHMs for the present analysis are given in Table 1. The data show that bleaching was recorded for DHM > 1 in almost all sites except the Gulf of Kachchh where bleaching was less severe compared to other sites (0.5 < DHM < 1).

Figure 1 shows that the monthly SST is predicted to increase in all the regions of the Indian seas during 2000–99. In the Gulf of Kachchh, the annual average SST may increase from 27.0°C in 2000 to 30.5°C in 2099; and in the Lakshadweep Sea from 29.2°C to 32.2°C. This shows that the annual average SST may increase by 3.0°C to 3.5°C in the Indian seas. By the turn of this century, the annual average SST in the Gulf of Kachchh, which is located at 22.5°N, will be higher than the present SST in the Lakshadweep Sea (10.5°N). The maximum SST in summer months may rise up to 34.0°C or more. Figure 1 also shows that the thermal thresholds (Table 1) for coral bleaching in all the five regions are exceeded frequently until the middle of this century; and almost every year after 2050. This trend sets in earlier (by 2030) in the Lakshadweep region, and by the last quarter of this century,

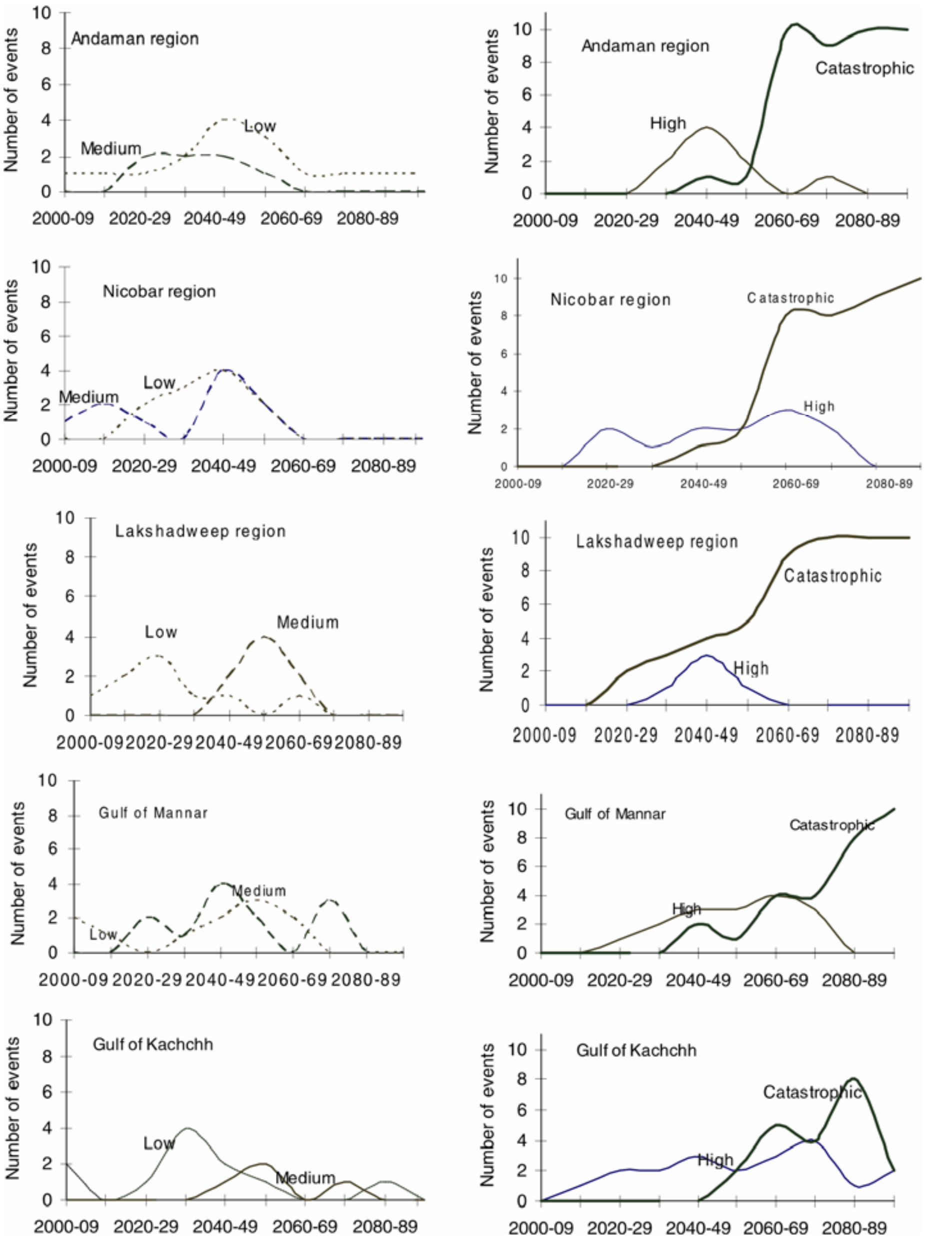

Figure 2. Projected number of coral bleaching events in the Indian seas.

the predicted SST far exceeds the thermal threshold for coral bleaching. Thus bleaching would be an annual event in these regions by the middle of this century.

The number of catastrophic events (DHM: >2.5) may increase in all the regions (Figure 2). In the Gulf of Kachchh, for instance, the number of catastrophic events will increase from 0 during 2000–09 to 2 during 2050–59; and during 2080–89, eight of the 10 bleaching events will be catastrophic events. In the Lakshadweep region, the catastrophic events will occur earlier (2020–29) and all the events in 2070–79 and thereafter will be catastrophic events. The number of bleaching events is not shown to increase more than 10 as the coral cover will become remnant by that time. This is because the corals would have experienced several catastrophic events and will begin to decline in terms of coral cover and appearance, and would have become remnant decades earlier. For example, if the summer temperatures exceed 31.4°C for even a few weeks, then bleaching will eventuate in the Andaman region. The results indicate that if there is no increase in thermal tolerance capacity, bleaching would become an annual or biannual event for almost all reef regions along the Indian coast in the next 30–50 years. By 2050, catastrophic exposure is the most likely outcome. Given that the recovery time of such an event is at least 10 years, and 50 years for full recovery[23], this scenario would mean a non-coral dominated reef structure by 2030 in the Lakshadweep region and by 2050 in the

Table 2. Projected vulnerability of corals in the Indian seas

Region	Decade in which corals may begin to decline	Decade in which reef building corals would lose dominance
Andaman	2030–2040	2050–2060
Nicobar	2020–2030	2050–2060
Lakshadweep	2020–2030	2030–2040
Gulf of Mannar	2030–2040	2050–2060
Gulf of Kachchh	2030–2040	2060–2070

other reef regions. By 2050, the likelihood of a catastrophic exposure is every 10 years. Given the implication that reefs will not be able to sustain catastrophic events more than three times a decade[23], reef building corals may begin to decline between 2020 and 2040 and the reef building corals would lose dominance between 2030 and 2040 in the Lakshadweep region and between 2050 and 2060 in the Andaman and Nicobar regions and the Gulf of Mannar (Table 2). Some coral types are hardier[3,11] and may last longer. However, these periods are likely to be short as sea temperatures will continue to increase rapidly and the threshold of even these hardy species will be exceeded[15]. The delays in response to warming, and differences between the most vulnerable and hardier coral types may be at most a couple of decades[23]. Using similar method of analysis, and by creating different scenarios, coral regions in the Great Barrier Reef are projected to become remnant by 2040–50 (refs 23 and 24).

These projections on coral reef vulnerability have taken into consideration only the warming of seawater. McClanahan *et al.*[25] suggested that the rate of temperature rise is less important than SST background variation in predicting coral survival. They also found that bleaching was positively correlated with speed of waterflow. For the present analysis, these factors, and other factors such as increasing acidity of seawater, which would make it harder for the corals to form exoskeleton, have not been considered. Scientists are of the opinion that if the acidification continues as it is now, it would seriously affect coral calcification in the world oceans[26]. Furthermore, as ocean warming coincides with sea level rise and perhaps more frequent storms and El Niños, reefs are likely to experience greater coastal erosion, sedimentation and turbidity, which would quicken their demise[27]. In the changed scenarios of less or no coral cover, it is difficult to project the fate of organisms that are serviced and the contiguous ecosystems that are supported by the reefs.

1. Spalding, M. D., Ravilious, C. and Green, E. P., *World Atlas of Coral Reefs*, UNEP World Conservation Monitoring Centre, Univ. of California Press, Berkeley, 2001, p. 424.
2. Jokiel, P. and Coles, S., Effect of temperature on the mortality and growth of Hawaiian reef corals. *Mar. Biol*., 1977, **43**, 201–208.
3. McClanahan, T. R., Ateweberhan, M., Sebastian, C. R., Graham, N. A. J., Wilson, S. K., Guillaume, M. M. M. and Bruggemann, J. H., Western Indian Ocean communities: bleaching responses and susceptibility to extinction. *Mar. Ecol. Prog. Ser*., 2007, **337**, 1–13.
4. McClanahan, T. R., The relationship between bleaching and mortality of common corals. *Mar. Biol*., 2004, **144**, 1239–1245.
5. Lough, J. M., Sea surface temperature variations on coral reefs: 1903–1998. *Aust. Inst. Mar. Sci. Rep*., 2000, **31**, 110.
6. Hayes, R. L. and Goreau, T. J., The tropical coral reef ecosystem as a harbinger of global warming. *World Res. Rev*., 1991, **3**, 306–322.
7. Goreau, T. J. and Hayes, R. L., Coral bleaching and ocean hotspots. *Ambio*, 1994, **23**, 176–180.
8. Goreau, T. J., Hayes, R. L., Clark, J. W., Basta, D. J. and Robertson, C. N., Elevated sea surface temperatures correlate with Caribbean coral reef bleaching. In *A Global Warming Forum: Scientific, Economic, and Legal Overview* (ed. Geyer, R. A.), CRC Press, Boca Raton, Florida, 1993, pp. 225–255.
9. Hoegh-Guldberg, O. and Smith, G. J., Light, salinity, and temperature and the population density, metabolism, and export of zooxanthellae from *Stylophora pistillata* and *Seriatopora hystrix*. *J. Exp. Mar. Biol. Ecol*., 1989, **129**, 279–303.
10. Glynn, P. W., Imai, R., Sakai, K., Nakano, Y. and Yamazoto, K., Experimental response of Okinawan (Ryukyu Islands, Japan) reef corals to high sea temperature and UV radiation. Proc. 7th International Coral Reef Symposium, 1992, pp. 73–82.
11. Arthur, R., Coral bleaching and mortality in three Indian reef regions during an El Nino southern oscillation event. *Curr. Sci*., 2000, **79**, 1723–1729.
12. Kumaraguru, A. K., Jayakumar, K. and Ramakritinan, C. M., Coral bleaching 2002 in the Palk Bay, southeast coast of India. *Curr. Sci*., 2003, **85**, 1787–1793.
13. Vivekanandan, E., Hussain Ali, M., Jasper, B. and Rajagopalan, M., Thermal thresholds for coral bleaching in the Indian Seas. *J. Mar. Biol. Assoc. India*, 2008, **50**, 209–214.
14. Hoegh-Guldberg, O., The future of coral reefs: Integrating climate model projections and the recent behaviour of corals and their dinoflagellates. Proc. 9th International Coral Reef Symposium, Bali, Indonesia, 2001, pp. 172–180.
15. World Wildlife Fund, Great Barrier Reef 2050. Implications of climate change for the Australia's Great Barrier Reef. WWF Report, Australia, 2004, p. 345.
16. Phinney, J. T., Hoegh-Guldberg, O., Kleypas, J., Skirving, W. and Al Strong, *Coral Reefs and Climate Change: Science and Management, Coastal and Estuarine Studies*, American Geophysical Union, Washington DC, 2006, vol. 61, p. 244.
17. Johnson, J. E. and Marshall, P. A. (eds), *Climate Change and the Great Barrier Reef. A Vulnerability Assessment*, Great Barrier Reef Marine Park Authority and Australian Greenhouse Office, Australia, 2007, p. 810.
18. Vazquez, J., Perry, K. and Kilpatrick, K., NOAA/NASA AVHRR 1998 Oceans Pathfinder sea surface temperature data set user's reference manual, Version 4.0, JPL Technical Report, D14070, http://podacc jpl.nasa.gov/sst, 1998.
19. Cubasch, U. *et al*., *Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change* (eds Houghton, J. T.

et al.), Cambridge University Press, Cambridge, UK, 2001, pp. 525–582.
20. Sheppard, C. R. C. and Loughland, R., Coral mortality and recovery in response to increasing temperature in the southern Arabian Gulf. *Aquat. Ecosyst. Health Mgmt.*, 2002, **5**, 395–402.
21. Sheppard, C. R. C., Predicted recurrences of mass coral mortality in the Indian Ocean. *Nature*, 2003, **425**, 294–297.
22. Sheppard, C. R. C. and Rioja-Neito, R., Sea surface temperature 1987–2099 in 38 cells in the Caribbean region. *Mar. Environ. Res.*, 2005, **60**, 389–396.
23. Done, T. J. *et al.*, Testing bleaching resistance hypotheses for the 2002 Great Barrier Reef bleaching event. *Aust. Inst. Mar. Sci. Rep.*, 2003, p. 95.
24. Hoegh-Guldberg, O., Coral bleaching. Climate change and the future of the world's coral reefs. *Mar. Freshwat. Res.*, 1999, **50**, 839–866.
25. McClanahan, T. R., Ateweberhan, M., Muhando, C., Maina, J. and Mohammed, S. M., Effects of climate and seawater temperature variation on coral bleaching and mortality. *Ecol. Monogr.*, 2007, **77**, 503–525.
26. Gattuso, J.-P., Frankignoulle, M., Bourge, I., Romaine, S. and Buddemeier, R. W., Effect of calcium carbonate saturation of seawater on coral calcification. *Glob. Planet Change*, 1998, **18**, 37–46.
27. Hodgson, G., A global assessment of human effects on coral reefs. *Mar. Poll. Bull.*, 1999, **38**, 345–355.

ACKNOWLEDGEMENTS. We are thankful to the Director, Central Marine Fisheries Research Institute, Cochin for providing facilities; Dr Pramod Kumar Aggarwal, National Professor, Indian Agricultural Research Institute, New Delhi for valuable suggestions; and Mr K. S. S. M. Yousuf for help in preparation of the manuscript. The work was carried out under the ICAR Network Project 'Impact, Adaptation, Vulnerability of Indian Agriculture to Climate Change'.

Received 25 February 2009; revised accepted 5 November 2009

Prevention of mammary adenocarcinoma and skin tumour by *Ganoderma lucidum*, a medicinal mushroom occurring in South India

B. Lakshmi, N. Sheena and K. K. Janardhanan*

Department of Microbiology, Amala Cancer Research Centre, Amala Nagar, Thrissur 680 553, India

***Ganoderma lucidum* (Fr.) P. Karst. is considered as a panacea in Chinese medicine. This mushroom has been reported to have a number of novel biological activities. Our previous investigations have demonstrated the antioxidant, anti-inflammatory and antitumour activities of aqueous-methanolic extract of *G. lucidum* occurring in South India. We extended our studies to evaluate the effect of this mushroom extract on the prevention of mammary adenocarcinoma in rats and skin tumour in mice. Mammary tumours were induced by oral administration of 7,12-dimethyl benz[*a*]anthracene (DMBA) in female Sprague Dawley rats. Skin tumours were induced by topical application of DMBA and promoted by croton oil on Balb/c mice. The experimental results indicated that *G. lucidum* showed significant tumour reducing activity against DMBA induced mammary and skin tumours in a dose-dependent manner. The administration of the mushroom extract showed profound effect on tumour induction, tumour latency period and tumour proliferation of both mammary tumour as well as skin tumours. The results thus reveal that the aqueous-mehanolic extract of *G. lucidum* possessed significant protective effect against DMBA induced mammary and skin tumours. Findings suggest the potential therapeutic use of *G. lucidum* in cancer chemoprevention.**

Keywords: *Ganoderma lucidum*, mammary adenocarcinoma, medicinal mushroom, skin tumour.

BREAST cancer is one of the most frequent malignancies among women and the incidence is increasing at an alarming rate. It is the major cause of cancer deaths in women worldwide, both in developed and developing countries[1,2]. Hope for treating cancer lies in four modules, surgery, radiation, chemotherapy and a combination of all the three[3]. Despite abundant information on the etiopathogenesis and early detection, effective therapeutic modalities for patients with advanced stages of the disease are still needed. Adjuvant therapy after ablative surgery is effective only when the tumour is detected early. The role of polycyclic aromatic hydrocarbons (PAH) is clearly implicated in the process of carcinogenesis especially 7,12-dimethylbenz[*a*]anthracene (DMBA), which is one of the most potent skin and breast carcinogens known. Most of the metabolically activated PAHs are mutagenic to DNA[4]. 12-*O*-tetradecanoylphorbol-13-acetate (TPA) is a tumour promoter isolated from seed oil of *Croton tiglium* and has been extensively studied in DMBA-induced mouse skin tumour model. Inflammation and free radicals have been associated with cancer in various tissues including skin tumour, bladder, stomach and colon. The experimental evidence strongly suggests the role of free radical mediated tumour promotion in phorbol ester promoted papilloma on the skin[5]. Application of croton oil has been shown to reduce antioxidant enzymes in both epidermal and inflammatory cells[6]. Inhibition of ROI (reactive oxygen intermediates) generation can serve as an important system for the identification of agents that can inhibit oxidative DNA damage as well as tumour promotion.

Several nonnutritive phytochemicals found in natural products associated with pharmacological attributes reveal that they inhibit/delay and or reverse cancer

*For correspondence. (e-mail: kkjanardhanan@yahoo.com)