From the report accepted by Working Group II of the Intergovernmental Panel on Climate Change but not approved in detail

Cross-chapter case studies

Cross-chapter case study citation:

These cross-chapter case studies collect together material from the chapters of the underlying report. A roadmap showing the location of this material is provided in the Introduction to the report. When referencing partial material from within a specific case study, please cite the chapter in which it originally appears. When referencing a whole case study, please cite as:

Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., 2007: Cross-chapter case study. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK, 843-868.

Table of Contents

C1. The impact of the European 2003 heatwave

C1.1 Scene-setting and overview

C1.1.1 The European heatwave of 2003 (Chapter 12, Section 12.6.1)

A severe heatwave over large parts of Europe in 2003 extended from June to mid-August, raising summer temperatures by 3 to 5°C in most of southern and central Europe (Figure C1.1). The warm anomalies in June lasted throughout the entire month (increases in monthly mean temperature of up to 6 to 7°C), but July was only slightly warmer than on average (+1 to +3°C), and the highest anomalies were reached between 1st and 13th August (+7°C) (Fink et al., 2004). Maximum temperatures of 35 to 40°C were repeatedly recorded and peak temperatures climbed well above 40°C (André et al., 2004; Beniston and Díaz, 2004).

Average summer (June to August) temperatures were far above the long-term mean by up to five standard deviations (Figure C1.1), implying that this was an extremely unlikely event under current climatic conditions (Schär and Jendritzky, 2004). However, it is consistent with a combined increase in mean temperature and temperature variability (Meehl and Tebaldi, 2004; Pal et al., 2004; Schär et al., 2004) (Figure C1.1). As such, the 2003 heatwave resembles simulations by regional climate models of summer temperatures in the latter part of the 21st century under the A2 scenario (Beniston, 2004). Anthropogenic warming may therefore already have increased the risk of heatwaves such as the one experienced in 2003 (Stott et al., 2004).

The heatwave was accompanied by annual precipitation deficits up to 300 mm. This drought contributed to the estimated 30% reduction in gross primary production of terrestrial ecosystems over Europe (Ciais et al., 2005). This reduced agricultural production and increased production costs, generating estimated damages of more than €13 billion (Fink et al., 2004; see also C1.2.2). The hot and dry conditions led to many very large wildfires, in particular in Portugal (390,000 ha: Fink et al., 2004; see also C1.2.1). Many major rivers (e.g., the Po, Rhine, Loire and Danube) were at record low levels, resulting in disruption of inland navigation, irrigation and power-plant cooling (Beniston and Díaz, 2004; Zebisch et al., 2005; see also C1.2.3). The extreme glacier melt in the Alps prevented even lower river flows in the Danube and Rhine (Fink et al., 2004).

The excess deaths due to the extreme high temperatures during the period June to August may amount to 35,000 (Kosatsky, 2005); elderly people were among those most affected (WHO, 2003; Kovats and Jendritzky, 2006; see also C1.2.4). The heatwave in 2003 has led to the development of heat health-watch warning systems in several European countries including France (Pascal et al., 2006), Spain (Simón et al., 2005), Portugal (Nogueira, 2005), Italy (Michelozzi et al., 2005), the UK (NHS, 2006) and Hungary (Kosatsky and Menne, 2005).

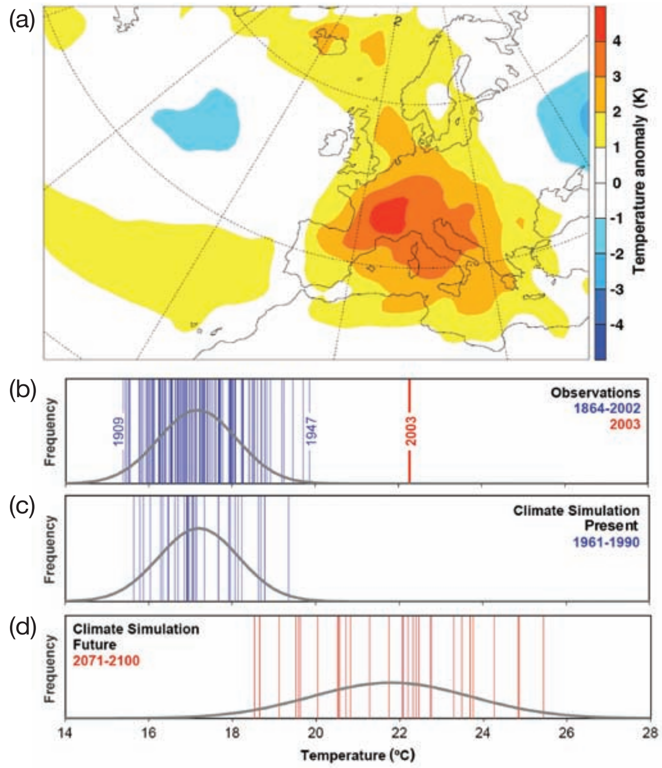

Figure C1.1. *Characteristics of the summer 2003 heatwave (adapted from Schär et al., 2004). (a) JJA temperature anomaly with respect to 1961 to 1990. (b) to (d) JJA temperatures for Switzerland observed during 1864 to 2003 (b), simulated using a regional climate model for the period 1961 to 1990 (c), and simulated for 2071 to 2100 under the A2 scenario using boundary data from the HadAM3H GCM (d). In panels (b) to (d): the black line shows the theoretical frequency distribution of mean summer temperature for the time-period considered, and the vertical blue and red bars show the mean summer temperature for individual years. Reprinted by permission from Macmillan Publishers Ltd. [Nature] (Schär et al., 2004), copyright 2004.*

C1.2 Impacts on sectors

C1.2.1 Ecological impacts of the European heatwave 2003 (Chapter 4, Box 4.1)

Anomalous hot and dry conditions affected Europe between June and mid-August 2003 (Fink et al., 2004; Luterbacher et al., 2004; Schär et al., 2004). Since similarly warm summers may occur at least every second year by 2080 in a Special Report on Emissions Scenario (SRES; Nakićenović et al., 2000) A2 world, for example (Beniston, 2004; Schär et al., 2004), effects on ecosystems observed in 2003 provide a conservative analogue of future impacts. The major effects of the 2003 heatwave on vegetation and ecosystems appear to have been through heat and drought stress, and wildfires.

Drought stress impacts on vegetation (Gobron et al., 2005; Lobo and Maisongrande, 2006) reduced gross primary production (GPP) in Europe by 30% and respiration to a lesser degree, overall resulting in a net carbon source of 0.5 PgC/yr (Ciais et al., 2005). However, vegetation responses to the heat varied along environmental gradients such as altitude, e.g., by prolonging the growing season at high elevations (Jolly et al., 2005). Some vegetation types, as monitored by remote sensing, were found to recover to a normal state by 2004 (e.g., Gobron et al., 2005), but enhanced crown damage of dominant forest trees in 2004, for example, indicates complex delayed impacts (Fischer, 2005). Freshwater ecosystems experienced prolonged depletion of oxygen in deeper layers of lakes during the heatwave (Jankowski et al., 2006), and there was a significant decline and subsequent poor recovery in species richness of molluscs in the River Saône (Mouthon and Daufresne, 2006). Taken together, this suggests quite variable resilience across ecosystems of different types, with very likely progressive impairment of ecosystem composition and function if such events increase in frequency (e.g., Lloret et al., 2004; Rebetez and Dobbertin, 2004; Jolly et al., 2005; Fuhrer et al., 2006).

High temperatures and greater dry spell durations increase vegetation flammability (e.g., Burgan et al., 1997), and during the 2003 heatwave a record-breaking incidence of spatially extensive wildfires was observed in European countries (Barbosa et al., 2003), with roughly 650,000 ha of forest burned across the continent (De Bono et al., 2004). Fire extent (area burned), although not fire incidence, was exceptional in Europe in 2003, as found for the extraordinary 2000 fire season in the USA (Brown and Hall, 2001), and noted as an increasing trend in the USA since the 1980s (Westerling et al., 2006). In Portugal, area burned was more than twice the previous extreme (1998) and four times the 1980-2004 average (Trigo et al., 2005, 2006). Over 5% of the total forest area of Portugal burned, with an economic impact exceeding €1 billion (De Bono et al., 2004).

Long-term impacts of more frequent similar events are very likely to cause changes in biome type, particularly by promoting highly flammable, shrubby vegetation that burns more frequently than less flammable vegetation types such as forests (Nunes et al., 2005), and as seen in the tendency of burned woodlands to reburn at shorter intervals (Vazquez and Moreno, 2001; Salvador et al., 2005). The conversion of vegetation structure in this way on a large enough scale may even cause accelerated climate change through losses of carbon from biospheric stocks (Cox et al., 2000). Future projections for Europe suggest significant reductions in species richness even under mean climate change conditions (Thuiller et al., 2005), and an increased frequency of such extremes (as indicated e.g., by Schär et al., 2004) is likely to exacerbate overall biodiversity losses (Thuiller et al., 2005).

C1.2.2 European heatwave impact on the agricultural sector (Chapter 5, Box 5.1)

Europe experienced a particularly extreme climate event during the summer of 2003, with temperatures up to 6°C above long-term means, and precipitation deficits up to 300 mm (see Trenberth et al., 2007). A record drop in crop yield of 36% occurred in Italy for maize grown in the Po valley, where extremely high temperatures prevailed (Ciais et al., 2005). In France, compared to 2002, the maize grain crop was reduced by 30% and fruit harvests declined by 25%. Winter crops (wheat) had nearly achieved maturity by the time of the heatwave and therefore suffered less yield reduction (21% decline in France) than summer crops (e.g., maize, fruit trees and vines) undergoing maximum foliar development (Ciais et al., 2005). Forage production was reduced on average by 30% in France and hay and silage stocks for winter were partly used during the summer (COPA COGECA, 2003a). Wine production in Europe was the lowest in 10 years (COPA COGECA, 2003b). The (uninsured) economic losses for the agriculture sector in the European Union were estimated at €13 billion, with the largest losses in France (€4 billion) (Sénat, 2004).

C1.2.3 Industry, settlement and society: impacts of the 2003 heatwave in Europe (Chapter 7, Box 7.1)

The Summer 2003 heatwave in western Europe affected settlements and economic services in a variety of ways. Economically, this extreme weather event created stress on health, water supplies, food storage and energy systems. In France, electricity became scarce, construction productivity fell, and the cold storage systems of 25-30% of all food-related establishments were found to be inadequate (Létard et al., 2004). The punctuality of the French railways fell to 77%, from 87% twelve months previously, incurring €1 to €3 million (US$1.25 to 3.75 million) in additional compensation payments, an increase of 7-20% compared with the usual annual total. Sales of clothing were 8.9% lower than usual in August, but sales of bottled water increased by 18%, and of ice-cream by 14%. The tourist industry in northern France benefitted, but in the south it suffered (Létard et al., 2004).

Impacts of the heatwave were mainly health- and health-service-related (see Section C1.2.4); but they were also associated with settlement and social conditions, from inadequate climate conditioning in buildings to the fact that many of the dead were elderly people, left alone while their families were on vacation. Electricity demand increased with the high heat levels; but electricity production was undermined by the facts that the temperature of rivers rose, reducing the cooling efficiency of thermal power plants (conventional and nuclear) and that flows of rivers were diminished; six power plants were shut down completely (Létard et al., 2004). If the heatwave had continued, as much as 30% of national power production would have been at risk (Létard et al., 2004). The crisis illustrated how infrastructure may be unable to deal with complex, relatively sudden environmental challenges (Lagadec, 2004).

C1.2.4 The European heatwave 2003: health impacts and adaptation (Chapter 8, Box 8.1)

In August 2003, a heatwave in France caused more than 14,800 deaths (Figure C1.2). Belgium, the Czech Republic, Germany, Italy, Portugal, Spain, Switzerland, the Netherlands

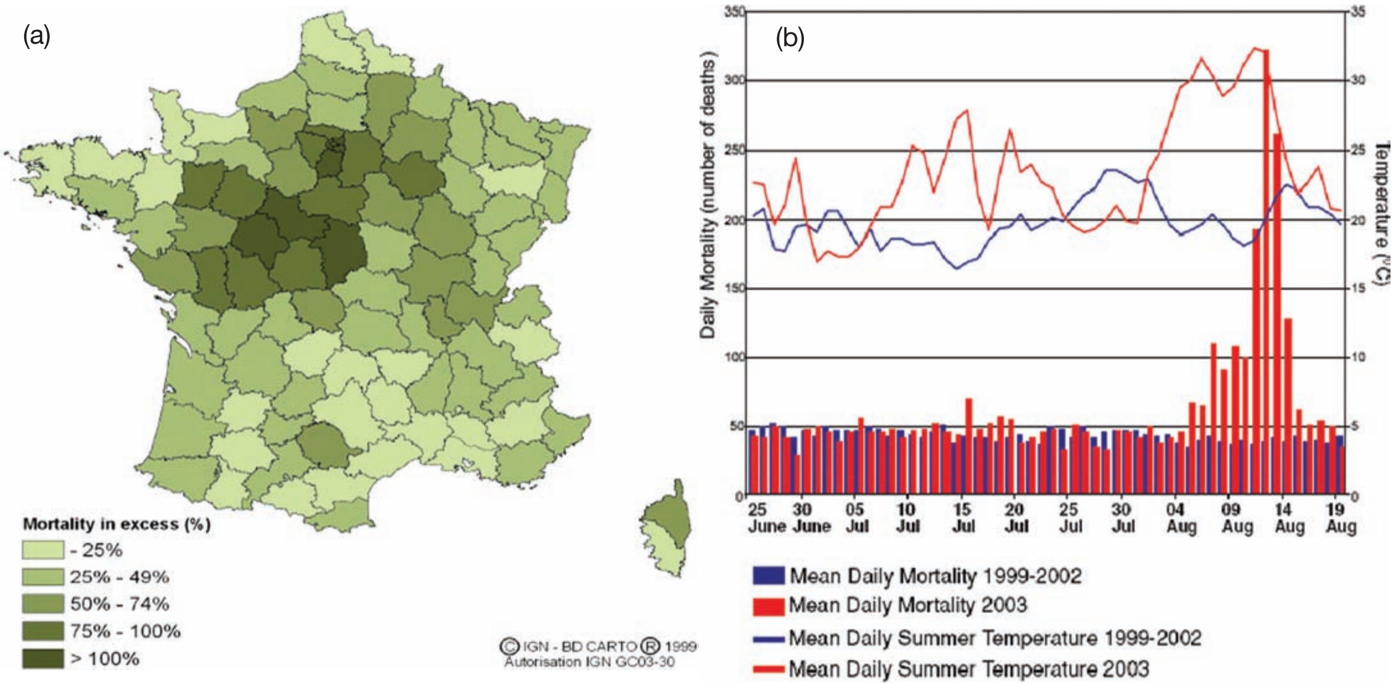

Figure C1.2. *(a) The distribution of excess mortality in France from 1 to 15 August 2003, by region, compared with the previous three years (INVS, 2003); (b) the increase in daily mortality in Paris during the heatwave in early August (Vandentorren and Empereur-Bissonnet, 2005).*

and the UK all reported excess mortality during the heatwave period, with total deaths in the range of 35,000 (Hemon and Jougla, 2004; Martinez-Navarro et al., 2004; Michelozzi et al., 2004; Vandentorren et al., 2004; Conti et al., 2005; Grize et al., 2005; Johnson et al., 2005). In France, around 60% of the heatwave deaths occurred in persons aged 75 and over (Hemon and Jougla, 2004). Other harmful exposures were also caused or exacerbated by the extreme weather, such as outdoor air pollutants (tropospheric ozone and particulate matter) (EEA, 2003), and pollution from forest fires.

A French parliamentary inquiry concluded that the health impact was ‘unforeseen’, surveillance for heatwave deaths was inadequate, and the limited public-health response was due to a lack of experts, limited strength of public-health agencies, and poor exchange of information between public organisations (Lagadec, 2004; Sénat, 2004).

In 2004, the French authorities implemented local and national action plans that included heat health-warning systems, health and environmental surveillance, re-evaluation of care of the elderly, and structural improvements to residential institutions (such as adding a cool room) (Laaidi et al., 2004; Michelon et al., 2005). Across Europe, many other governments (local and national) have implemented heat health-prevention plans (Michelozzi et al., 2005; WHO Regional Office for Europe, 2006).

Since the observed higher frequency of heatwaves is likely to have occurred due to human influence on the climate system (Hegerl et al., 2007), the excess deaths of the 2003 heatwave in Europe are likely to be linked to climate change.

References

André, J.-C., M. Déqué, P. Rogel and S. Planton, 2004: The 2003 summer heatwave and its seasonal forecasting. *C. R. Geosci.*, **336**, 491-503.

Barbosa, P., G. Libertà and G. Schmuck, 2003: The European Forest Fires Information System (EFFIS) results on the 2003 fire season in Portugal by the 20th of August. Report 20030820, European Commission, Directorate General Joint Research Centre, Institute for Environment and Sustainability, Land Management Unit, Ispra, 10 pp.

Beniston, M., 2004: The 2003 heatwave in Europe: a shape of things to come? An analysis based on Swiss climatological data and model simulations. *Geophys. Res. Lett.*, **31**, L02202, doi:10.1029/2003GL 018857.

Beniston, M. and H.F. Díaz, 2004: The 2003 heatwave as an example of summers in a greenhouse climate? Observations and climate model simulations for Basel, Switzerland. *Glob. Planet. Change*, **44**, 73-81.

Brown, T.J. and B.L. Hall, 2001: Climate analysis of the 2000 fire season. CE-FA Report 01-02, Program for Climate Ecosystem and Fire Applications, Desert Research Institute, Division of Atmospheric Sciences, Reno, Nevada, 40 pp.

Burgan, R.E., P.L. Andrews, L.S. Bradshaw, C.H. Chase, R.A. Hartford and D.J. Latham, 1997: WFAS: wildland fire assessment system. *Fire Management Notes*, **57**, 14-17. Ciais, Ph., M. Reichstein, N. Viovy, A. Granier, J. Ogée, V. Allard, M. Aubinet, N. Buchmann, C. Bernhofer, A. Carrara, F. Chevallier, N. de Noblet, A.D. Friend, P. Friedlingstein, T. Grünwald, B. Heinesch, P. Keronen, A. Knohl, G. Krinner, D. Loustau, G. Manca, G. Matteucci, F. Miglietta, J.M. Ourcival, D. Papale, K. Pilegaard, S. Rambal, G. Seufert, J.F. Soussana, M.J. Sanz, E.D. Schulze, T. Vesala and R. Valentini, 2005: Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature*, **437**, 529-533.

Conti, S., P. Meli, G. Minelli, R. Solimini, V. Toccaceli, M. Vichi, C. Beltrano and L. Perini, 2005: Epidemiologic study of mortality during the Summer 2003 heat wave in Italy. *Environ. Res.*, **98**, 390-399.

COPA COGECA, 2003a: Assessment of the impact of the heat wave and drought of the summer 2003 on agriculture and forestry. Committee of Agricultural Organisations in the European Union General Committee for Agricultural Cooperation in the European Union, Brussels, 15 pp.

COPA COGECA, 2003b: Committee of Agricultural Organisations in the European Union General Committee for Agricultural Cooperation in the European Union, CDP 03 61 1, Press release, Brussels.

Cox, P.M., R.A. Betts, C.D. Jones, S.A. Spall and I.J. Totterdell, 2000: Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature*, **408**, 184-187.

De Bono, A., P. Peduzzi, G. Giuliani and S. Kluser, 2004: *Impacts of Summer 2003 Heat Wave in Europe*. Early Warning on Emerging Environmental Threats 2, UNEP: United Nations Environment Programme, Nairobi, 4 pp.

EEA, 2003: Air pollution by ozone in Europe in summer 2003: overview of exceedances of EC ozone threshold values during the summer season April–August 2003 and comparisons with previous years. Topic Report No 3/2003, European Economic Association, Copenhagen, 33 pp. http://reports.eea.europa.eu/topic_report_2003_3/en.

Fink, A.H., T. Brücher, A. Krüger, G.C. Leckebusch, J.G. Pinto and U. Ulbrich, 2004: The 2003 European summer heatwaves and drought: synoptic diagnosis and impact. *Weather*, **59**, 209-216.

Fischer, R., Ed., 2005: The condition of forests in Europe: 2005 executive report. United Nations Economic Commission for Europe (UN-ECE), Geneva, 36 pp.

Fuhrer, J., M. Beniston, A. Fischlin, C. Frei, S. Goyette, K. Jasper and C. Pfister, 2006: Climate risks and their impact on agriculture and forests in Switzerland. *Climatic Change*, **79**, 79-102.

Gobron, N., B. Pinty, F. Melin, M. Taberner, M.M. Verstraete, A. Belward, T. Lavergne and J.L. Widlowski, 2005: The state of vegetation in Europe following the 2003 drought. *Int. J. Remote Sens.*, **26**, 2013-2020.

Grize, L., A. Huss, O. Thommen, C. Schindler and C. Braun-Fahrländer, 2005: Heat wave 2003 and mortality in Switzerland. *Swiss Med. Wkly.*, **135**, 200-205.

Hemon, D. and E. Jougla, 2004: La canicule du mois d'aout 2003 en France [The heatwave in France in August 2003]. *Rev. Epidemiol. Santé*, **52**, 3-5.

Hegerl, G.C., F.W. Zwiers, P. Braconnot, N.P. Gillett, Y. Luo, J.A. Marengo Orsini, N. Nicholls, J.E. Penner and P.A. Stott, 2007: Understanding and attributing climate change. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, Eds., Cambridge University Press, Cambridge, 663-746.

INVS, 2003: *Impact sanitaire de la vague de chaleur d'août 2003 en France. Bilan et perpectives [Health Impact of the Heatwave in August 2003 in France]*. Institut de Veille Sanitaire, Saint-Maurice, 120 pp.

Jankowski, T., D.M. Livingstone, H. Bührer, R. Forster and P. Niederhaser, 2006: Consequences of the 2003 European heat wave for lake temperature profiles, thermal stability and hypolimnetic oxygen depletion: implications for a warmer world. *Limnol. Oceanogr.*, **51**, 815-819.

Johnson, H., R.S. Kovats, G.R. McGregor, J.R. Stedman, M. Gibbs, H. Walton, L. Cook and E. Black, 2005: The impact of the 2003 heatwave on mortality and hospital admissions in England. *Health Statistics Q.*, **25**, 6-12.

Jolly, W.M., M. Dobbertin, N.E. Zimmermann and M. Reichstein, 2005: Divergent vegetation growth responses to the 2003 heat wave in the Swiss Alps. *Geophys. Res. Lett.*, **32**, L18409, doi:10.1029/2005GL023252.

Kosatsky, T., 2005: The 2003 European heatwave. *Euro Surveill.*, **10**, 148-149.

Kosatsky, T. and B. Menne, 2005: Preparedness for extreme weather among national ministries of health of WHO's European region. *Climate Change and Adaptation Strategies for Human Health,* B. Menne and K.L. Ebi, Eds., Springer, Darmstadt, 297-329.

Kovats, R.S. and G. Jendritzky, 2006: Heat-waves and human health. *Climate Change and Adaptation Strategies for Human Health,* B. Menne and K.L. Ebi, Eds., Springer, Darmstadt, 63-90.

Laaidi, K., M. Pascal, M. Ledrans, A. Le Tertre, S. Medina, C. Caserio, J.C. Cohen, J. Manach, P. Beaudeau and P. Empereur-Bissonnet, 2004: *Le système français d'alerte canicule et santé (SACS 2004): Un dispositif intégéré au Plan National Canicule [The French Heatwave Warning System and Health: An Integrated National Heatwave Plan]*. Institutde Veille Sanitaire, 35 pp.

Lagadec, P., 2004. Understanding the French 2003 heat wave experience. *J. Contingencies Crisis Manage.*, **12**, 160-169.

Létard V., H. Flandre and S. Lepeltier, 2004: La France et les Français face à la canicule: les leçons d'une crise. Report No. 195 (2003-2004) to the Sénat, Government of France, 391 pp.

Lloret, F., D. Siscart and C. Dalmases, 2004: Canopy recovery after drought dieback in holm-oak Mediterranean forests of Catalonia (NE Spain). *Global Change Biol.*, **10**, 2092-2099.

Lobo, A. and P. Maisongrande, 2006: Stratified analysis of satellite imagery of SW Europe during summer 2003: the differential response of vegetation classes to increased water deficit. *Hydrol. Earth Syst. Sci.*, **10**, 151-164.

Luterbacher, J., D. Dietrich, E. Xoplaki, M. Grosjean and H. Wanner, 2004: European seasonal and annual temperature variability, trends, and extremes since 1500. *Science*, **303**, 1499-1503.

Martinez-Navarro, F., F. Simon-Soria and G. Lopez-Abente, 2004: Valoracion del impacto de la ola de calor del verano de 2003 sobre la mortalidad [Evaluation of the impact of the heatwave in the summer of 2003 on mortality]. *Gac. Sanit.*, **18**, 250-258.

Meehl, G.A. and C. Tebaldi, 2004: More intense, more frequent, and longer lasting heatwaves in the 21st century. *Science,* **305**, 994-997.

Michelon, T., P. Magne and F. Simon-Delavelle, 2005: Lessons from the 2003 heat wave in France and action taken to limit the effects of future heat wave. *Extreme Weather Events and Public Health Responses*, W. Kirch, B. Menne and R. Bertolllini, Eds., Springer, Berlin, 131-140.

Michelozzi, P., F. de Donato, G. Accetta, F. Forastiere, M. D'Ovido and L.S. Kalkstein, 2004: Impact of heat waves on mortality: Rome, Italy, June–August 2003. *J. Am. Med. Assoc.*, **291**, 2537-2538.

Michelozzi, P., F. de Donato, L. Bisanti, A. Russo, E. Cadum, M. DeMaria, M. D'Ovidio, G. Costa and C.A. Perucci, 2005: The impact of the summer 2003 heatwaves on mortality in four Italian cities. *Euro. Surveill.*, **10**, 161-165.

Mouthon, J. and M. Daufresne, 2006: Effects of the 2003 heatwave and climatic warming on mollusc communities of the Saône: a large lowland river and of its two main tributaries (France). *Global Change Biol.*, **12**, 441-449.

Nakićenović, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grübler, T.Y. Jung, T. Kram, E. Lebre la Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, A. Roehrl, H.H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor and Z. Dadi, Eds., 2000: *Emissions Scenarios: A Special Report of the Intergovernmental Panel on Climate Change (IPCC)*. Cambridge University Press, Cambridge, 599 pp.

NHS, 2006: *Heatwave Plan for England: Protecting Health and Reducing Harm from Extreme Heat and Heatwaves*. Department of Health, London.

Nogueira, P.J., 2005: Examples of heat warning systems: Lisbon's ICARO surveillance system, summer 2003. *Extreme Weather Events and Public Health Responses*, W. Kirch, B. Menne and R. Bertollini, Eds., Springer, Heidelberg, 141-160.

Nunes, M.C.S., M.J. Vasconcelos, J.M.C. Pereira, N. Dasgupta and R.J. Alldredge, 2005: Land cover type and fire in Portugal: do fires burn land cover selectively? *Landscape Ecol.*, **20**, 661-673.

Pal, J.S., F. Giorgi and X.Q. Bi, 2004: Consistency of recent European summer precipitation trends and extremes with future regional climate projections. *Geophys. Res. Lett.*, **31**, L13202, doi:10.1029/2004GL019836.

Pascal, M., K. Laaidi, M. Ledrans, E. Baffert, C. Caseiro-Schönemann, A.L. Tertre, J. Manach, S. Medina, J. Rudant and P. Empereur-Bissonnet, 2006: France's heat health watch warning system. *Int. J. Biometeorol.*, **50**, 144-153.

Rebetez, M. and M. Dobbertin, 2004: Climate change may already threaten Scots pine stands in the Swiss Alps. *Theor. Appl. Climatol.*, **79**, 1-9.

Salvador, R., F. Lloret, X. Pons and J. Pinol, 2005: Does fire occurrence modify the probability of being burned again? A null hypothesis test from Mediterranean ecosystems in NE Spain. *Ecol. Model.*, **188**, 461-469.

Schär, C. and G. Jendritzky, 2004: Climate change: hot news from summer 2003. *Nature,* **432**, 559-560.

Schär, C., P.L. Vidale, D. Lüthi, C. Frei, C. Häberli, M.A. Liniger and C. Appenzeller, 2004: The role of increasing temperature variability in European summer heatwaves. *Nature*, **427**, 332-336.

Sénat, 2004: France and the French face the canicule: the lessons of a crisis. Appendix to the Minutes of the Session of February 3, 2004. Information Report No. 195, 59-62. http://www.senat.fr/rap/r03-195/r03-195.html.

Simón, F., G. López-Abente, E. Ballester and F. Martínez, 2005: Mortality in Spain during the heatwaves of summer 2003. *Euro Surveill.*, **10**, 156-160.

Stott, P.A., D.A. Stone and M.R. Allen, 2004: Human contribution to the European heatwave of 2003. *Nature*, **432**, 610-614.

Thuiller, W., S. Lavorel, M.B. Araujo, M.T. Sykes and I.C. Prentice, 2005: Climate change threats to plant diversity in Europe. *P. Natl. Acad. Sci. USA*, **102**, 8245-

8250.
Trenberth, K.E., P.D. Jones, P.G. Ambenje, R. Bojariu, D.R. Easterling, A.M.G. Klein Tank, D.E. Parker, J.A. Renwick and Co-authors, 2007: Observations: surface and atmospheric climate change. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, Eds., Cambridge University Press, Cambridge, 235-336.
Trigo, R.M., M.G. Pereira, J.M.C. Pereira, B. Mota, T.J. Calado, C.C. da Camara and F.E. Santo, 2005: The exceptional fire season of summer 2003 in Portugal. *Geophys. Res. Abstracts*, **7**, 09690.
Trigo, R.M., J.M.C. Pereira, M.G. Pereira, B. Mota, T.J. Calado, C.C. Dacamara and F.E. Santo, 2006: Atmospheric conditions associated with the exceptional fire season of 2003 in Portugal. *Int. J. Climatol.*, **26**, 1741-1757.
Vandentorren, S. and P. Empereur-Bissonnet, 2005: Health impact of the 2003 heat-wave in France. *Extreme Weather Events and Public Health Responses*, W. Kirch, B. Menne and R. Bertollini, Eds., Springer, Heidelberg, 81-88.
Vandentorren, S., F. Suzan, S. Medina, M. Pascal, A. Maulpoix, J.-C. Cohen and M. Ledrans, 2004: Mortality in 13 French cities during the August 2003 heat-wave. *Am. J. Public Health*, **94**, 1518-1520.
Vazquez, A. and J.M. Moreno, 2001: Spatial distribution of forest fires in Sierra de Gredos (Central Spain). *Forest Ecol. Manag.*, **147**, 55-65.
Westerling, A.L., H.G. Hidalgo, D.R. Cayan and T.W. Swetnam, 2006: Warming and earlier spring increase western US forest wildfire activity. *Science*, **313**, 940-943.
WHO, 2003: *The Health Impacts of 2003 Summer Heat-Waves*. Briefing Note for the Delegations of the fifty-third session of the WHO Regional Committee for Europe. World Health Organization, Geneva, 12 pp.
WHO Regional Office for Europe, 2006: 1st meeting of the project 'Improving Public Health Responses to Extreme Weather/Heat-waves'. EuroHEAT Report on a WHO Meeting in Rome, Italy, 20–22 June 2005. WHO Regional Office for Europe, Copenhagen, 52 pp.
Zebisch, M., T. Grothmann, D. Schröter, C. Hasse, U. Fritsch and W. Cramer, 2005: *Climate Change in Germany: Vulnerability and Adaptation of Climate-Sensitive Sectors*. Umweltbundesamt Climate Change 10/05 (UFOPLAN 201 41 253), Dessau, 205 pp.

C2. Impacts of climate change on coral reefs

C2.1 Present-day changes in coral reefs

C2.1.1 Observed changes in coral reefs (Chapter 1, Section 1.3.4.1)

Concerns about the impacts of climate change on coral reefs centre on the effects of the recent trends in increasing acidity (via increasing CO_2), storm intensity, and sea surface temperatures (see Bindoff et al., 2007, Section 5.4.2.3; Trenberth et al., 2007, Sections 3.8.3 and 3.2.2).

Decreasing pH (see C2.2.1) leads to a decreased aragonite saturation state, one of the main physicochemical determinants of coral calcification (Kleypas et al., 1999). Although laboratory experiments have demonstrated a link between aragonite saturation state and coral growth (Langdon et al., 2000; Ohde and Hossain, 2004), there are currently no data relating altered coral growth *in situ* to increasing acidity.

Storms damage coral directly through wave action and indirectly through light attenuation by suspended sediment and abrasion by sediment and broken corals. Most studies relate to individual storm events, but a meta-analysis of data from 1977 to 2001 showed that coral cover on Caribbean reefs decreased by 17% on average in the year following a hurricane, with no evidence of recovery for at least 8 years post-impact (Gardner et al., 2005). Stronger hurricanes caused more coral loss, but the second of two successive hurricanes caused little additional damage, suggesting a greater future effect from increasing hurricane intensity rather than from increasing frequency (Gardner et al., 2005).

There is now extensive evidence of a link between coral bleaching – a whitening of corals as a result of the expulsion of symbiotic zooxanthellae (see C2.1.2) – and sea surface temperature anomalies (McWilliams et al., 2005). Bleaching usually occurs when temperatures exceed a 'threshold' of about 0.8-1°C above mean summer maximum levels for at least 4 weeks (Hoegh-Guldberg, 1999). Regional-scale bleaching events have increased in frequency since the 1980s (Hoegh-Guldberg, 1999). In 1998, the largest bleaching event to date is estimated to have killed 16% of the world's corals, primarily in the western Pacific and the Indian Ocean (Wilkinson, 2004). On many reefs, this mortality has led to a loss of structural complexity and shifts in reef fish species composition (Bellwood et al., 2006; Garpe et al., 2006; Graham et al., 2006). Corals that recover from bleaching suffer temporary reductions in growth and reproductive capacity (Mendes and Woodley, 2002), while the recovery of reefs following mortality tends to be dominated by fast-growing and bleaching-resistant coral genera (Arthur et al., 2005).

While there is increasing evidence for climate change impacts on coral reefs, disentangling the impacts of climate-related stresses from other stresses (e.g., over-fishing and pollution; Hughes et al., 2003) is difficult. In addition, inter-decadal variation in pH (Pelejero et al., 2005), storm activity (Goldenberg et al., 2001) and sea surface temperatures (Mestas-Nunez and Miller, 2006) linked, for example, to the El Niño-Southern Oscillation and Pacific Decadal Oscillation, make it more complicated to discern the effect of anthropogenic climate change from natural modes of variability. An analysis of bleaching in the Caribbean indicates that 70% of the variance in geographic extent of bleaching between 1983 and 2000 could be attributed to variation in ENSO and atmospheric dust (Gill et al., 2006).

C2.1.2 Environmental thresholds and observed coral bleaching (Chapter 6, Box 6.1)

Coral bleaching, due to the loss of symbiotic algae and/or their pigments, has been observed on many reefs since the early 1980s. It may have previously occurred, but has gone unrecorded. Slight paling occurs naturally in response to seasonal increases in sea surface temperature (SST) and solar radiation. Corals bleach white in response to anomalously high SST (~1°C above average seasonal maxima, often combined with high solar radiation). Whereas some corals recover their natural colour when environmental conditions ameliorate, their growth rate and reproductive ability may be significantly reduced for a substantial period. If bleaching is prolonged, or if SST exceeds 2°C above average seasonal maxima, corals die. Branching species appear more susceptible than massive corals (Douglas, 2003).

Major bleaching events were observed in 1982-1983, 1987-1988 and 1994-1995 (Hoegh-Guldberg, 1999). Particularly severe bleaching occurred in 1998 (Figure C2.1), associated with pronounced El Niño events in one of the hottest years on record (Lough, 2000; Bruno et al., 2001). Since 1998 there have been several extensive bleaching events. For example, in 2002 bleaching occurred on much of the Great Barrier Reef (Berkelmans et al., 2004; see C2.2.3) and elsewhere. Reefs in the eastern Caribbean experienced a massive bleaching event in late 2005, another of the hottest years on record. On many Caribbean reefs, bleaching exceeded that of 1998 in both extent and mortality (Figure C2.1), and reefs are in decline as a result of the synergistic effects of multiple stresses (Gardner et al., 2005; McWilliams et al., 2005; see C2.3.1). There is considerable variability in coral susceptibility and recovery to elevated SST in both time and space, and in the incidence of mortality (Webster et al., 1999; Wilkinson, 2002; Obura, 2005).

Global climate model results imply that thermal thresholds will be exceeded more frequently, with the consequence that bleaching will recur more often than reefs can sustain (Hoegh-Guldberg, 1999, 2004; Donner et al., 2005), perhaps almost annually on some reefs in the next few decades (Sheppard, 2003; Hoegh-Guldberg, 2005). If the threshold remains unchanged, more frequent bleaching and mortality seems inevitable (see

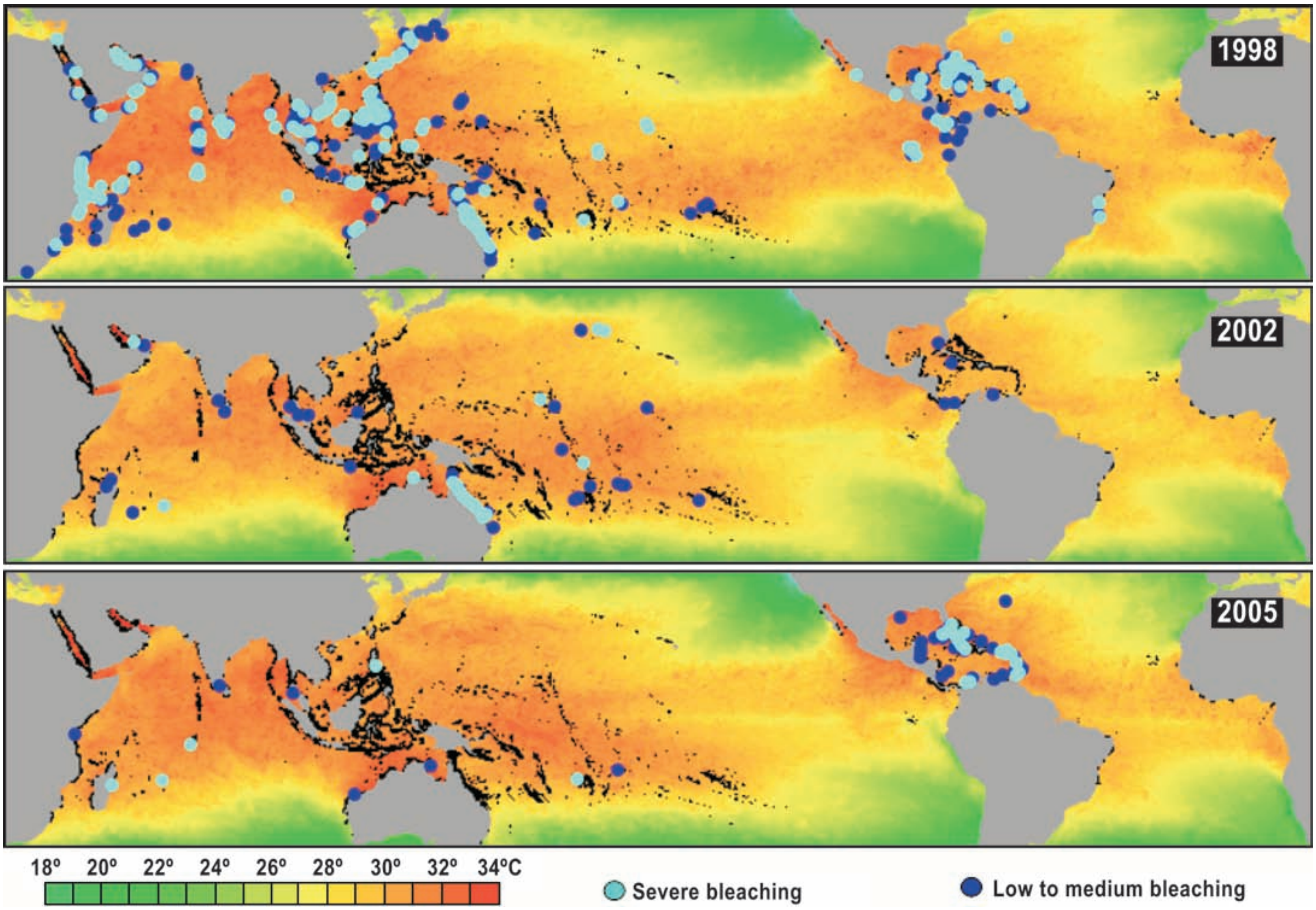

Figure C2.1. *Maximum monthly mean sea surface temperature for 1998, 2002 and 2005, and locations of reported coral bleaching (data sources: NOAA Coral Reef Watch (http://coralreefwatch.noaa.gov/) and Reefbase (http://www.reefbase.org/)).*

Figure C2.2a), but with local variations due to different susceptibilities to factors such as water depth. Recent preliminary studies lend some support to the adaptive bleaching hypothesis, indicating that the coral host may be able to adapt or acclimatise as a result of expelling one clade[1] of symbiotic algae but recovering with a new one (termed 'shuffling', see C2.2.1), creating 'new' ecospecies with different temperature tolerances (Coles and Brown, 2003; Buddemeier et al., 2004; Little et al., 2004; Rowan, 2004; Obura, 2005). Adaptation or acclimatisation might result in an increase in the threshold temperature at which bleaching occurs (Figure C2.2b). The extent to which the thermal threshold could increase with warming of more than a couple of degrees remains very uncertain, as are the effects of additional stresses, such as reduced carbonate supersaturation in surface waters (see C2.2.1) and non-climate stresses (see C2.3.1). Corals and other calcifying organisms (e.g., molluscs, foraminifers) remain extremely susceptible to increases in SST. Bleaching events reported in recent years have already impacted many reefs, and their more frequent recurrence is very likely to further reduce both coral cover and diversity on reefs over the next few decades.

C2.2 Future impacts on coral reefs

C2.2.1 Are coral reefs endangered by climate change? (Chapter 4, Box 4.4)

Reefs are habitat for about a quarter of all marine species and are the most diverse among marine ecosystems (Roberts et al., 2002; Buddemeier et al., 2004). They underpin local shore protection, fisheries, tourism (see Chapter 6; Hoegh-Guldberg et al., 2000; Cesar et al., 2003; Willig et al., 2003; Hoegh-Guldberg, 2004, 2005) and, although supplying only about 2-5% of the global fisheries harvest, comprise a critical subsistence protein and income source in the developing world (Whittingham et al., 2003; Pauly et al., 2005; Sadovy, 2005).

Corals are affected by warming of surface waters (see C2.1.2; Reynaud et al., 2003; McNeil et al., 2004; McWilliams et al., 2005) leading to bleaching (loss of algal symbionts; see C2.1.2). Many studies incontrovertibly link coral bleaching to warmer sea surface temperature (e.g., McWilliams et al., 2005), and mass bleaching and coral mortality often results beyond key temperature thresholds (see C2.1.2). Annual or bi-annual exceedance of

[1] A clade of algae is a group of closely related, but nevertheless different, types.

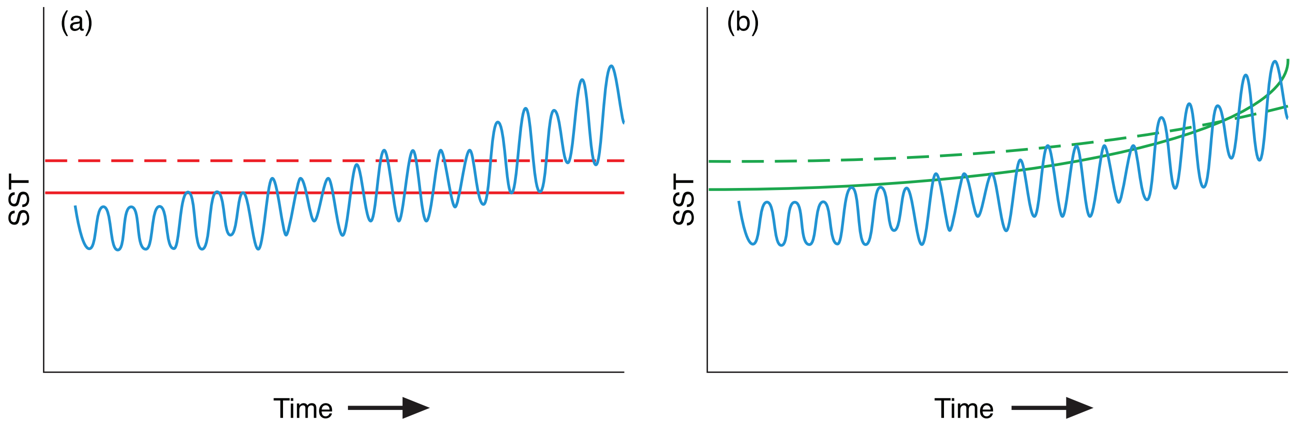

Figure C2.2. *Alternative hypotheses concerning the threshold SST at which coral bleaching occurs: (a) invariant threshold for coral bleaching (red line) which occurs when SST exceeds usual seasonal maximum threshold (by ~1°C) and mortality (dashed red line, threshold of 2°C), with local variation due to different species or water depth; (b) elevated threshold for bleaching (green line) and mortality (dashed green line) where corals adapt or acclimatise to increased SST (based on Hughes et al., 2003).*

bleaching thresholds is projected at the majority of reefs worldwide by 2030 to 2050 (Hoegh-Guldberg, 1999; Sheppard, 2003; Donner et al., 2005). After bleaching, algae quickly colonise dead corals, possibly inhibiting later coral recruitment (e.g., McClanahan et al., 2001; Szmant, 2001; Gardner et al., 2003; Jompa and McCook, 2003). Modelling predicts a phase switch to algal dominance on the Great Barrier Reef and Caribbean reefs in 2030 to 2050 (Wooldridge et al., 2005).

Coral reefs will also be affected by rising atmospheric CO_2 concentrations (Orr et al., 2005; Raven et al., 2005; Denman et al., 2007, Box 7.3) resulting in declining calcification. Experiments at expected aragonite concentrations demonstrated a reduction in coral calcification (Marubini et al., 2001; Langdon et al., 2003; Hallock, 2005), coral skeleton weakening (Marubini et al., 2003) and strong temperature dependence (Reynaud et al., 2003). Oceanic pH projections decrease at a greater rate and to a lower level than experienced over the past 20 million years (Caldeira and Wickett, 2003; Raven et al., 2005; Turley et al., 2006). Doubling CO_2 will reduce calcification in aragonitic corals by 20%-60% (Kleypas et al., 1999; Kleypas and Langdon, 2002; Reynaud et al., 2003; Raven et al., 2005). By 2070 many reefs could reach critical aragonite saturation states (Feely et al., 2004; Orr et al., 2005), resulting in reduced coral cover and greater erosion of reef frameworks (Kleypas et al., 2001; Guinotte et al., 2003).

Adaptation potential (Hughes et al., 2003) by reef organisms requires further experimental and applied study (Coles and Brown, 2003; Hughes et al., 2003). Natural adaptive shifts to symbionts with +2°C resistance may delay the demise of some reefs until roughly 2100 (Sheppard, 2003), rather than mid-century (Hoegh-Guldberg, 2005) although this may vary widely across the globe (Donner et al., 2005). Estimates of warm-water coral cover reduction in the last 20-25 years are 30% or higher (Wilkinson, 2004; Hoegh-Guldberg, 2005) due largely to increasing higher SST frequency (Hoegh-Guldberg, 1999). In some regions, such as the Caribbean, coral losses have been estimated at 80% (Gardner et al., 2003). Coral migration to higher latitudes with more optimal SST is unlikely, due both to latitudinally decreasing aragonite concentrations and projected atmospheric CO_2 increases (Kleypas et al., 2001; Guinotte et al., 2003; Orr et al., 2005; Raven et al., 2005). Coral migration is also limited by lack of available substrate (see C2.2.2). Elevated SST and decreasing aragonite have a complex synergy (Harvell et al., 2002; Reynaud et al., 2003; McNeil et al., 2004; Kleypas et al., 2005) but could produce major coral reef changes (Guinotte et al., 2003; Hoegh-Guldberg, 2005). Corals could become rare on tropical and sub-tropical reefs by 2050 due to the combined effects of increasing CO_2 and increasing frequency of bleaching events (at 2-3 × CO_2) (Kleypas and Langdon, 2002; Hoegh-Guldberg, 2005; Raven et al., 2005). Other climate change factors (such as sea-level rise, storm impact and aerosols) and non-climate factors (such as over-fishing, invasion of non-native species, pollution, nutrient and sediment load (although this could also be related to climate change through changes to precipitation and river flow; see C2.1.2 and C2.2.3; Chapter 16)) add multiple impacts on coral reefs (see C2.3.1), increasing their vulnerability and reducing resilience to climate change (Koop et al., 2001; Kleypas and Langdon, 2002; Cole, 2003; Buddemeier et al., 2004; Hallock, 2005).

C2.2.2 Impacts on coral reefs (Chapter 6, Section 6.4.1.5)

Reef-building corals are under stress on many coastlines (see C2.1.1). Reefs have deteriorated as a result of a combination of anthropogenic impacts such as over-fishing and pollution from adjacent land masses (Pandolfi et al., 2003; Graham et al., 2006), together with an increased frequency and severity of bleaching associated with climate change (see C2.1.2). The relative significance of these stresses varies from site to site. Coral mortality on Caribbean reefs is generally related to recent disease outbreaks, variations in herbivory,[2] and hurricanes (Gardner et al., 2003; McWilliams et al., 2005), whereas Pacific reefs have been particularly impacted by episodes of coral

[2] Herbivory: the consumption of plants by animals.

bleaching caused by thermal stress anomalies, especially during recent El Niño events (Hughes et al., 2003), as well as non-climate stresses.

Mass coral-bleaching events are clearly correlated with rises of SST of short duration above summer maxima (Douglas, 2003; Lesser, 2004; McWilliams et al., 2005). Particularly extensive bleaching was recorded across the Indian Ocean region associated with extreme El Niño conditions in 1998 (see C2.1.2 and C2.2.3). Many reefs appear to have experienced similar SST conditions earlier in the 20th century and it is unclear how extensive bleaching was before widespread reporting post-1980 (Barton and Casey, 2005). There is limited ecological and genetic evidence for adaptation of corals to warmer conditions (see C2.1.2 and C2.2.1). It is very likely that projected future increases in SST of about 1 to 3°C (Section 6.3.2) will result in more frequent bleaching events and widespread mortality if there is no thermal adaptation or acclimatisation by corals and their symbionts (Sheppard, 2003; Hoegh-Guldberg, 2004). The ability of coral reef ecosystems to withstand the impacts of climate change will depend on the extent of degradation from other anthropogenic pressures and the frequency of future bleaching events (Donner et al., 2005).

In addition to coral bleaching, there are other threats to reefs associated with climate change (Kleypas and Langdon, 2002). Increased concentrations of CO_2 in seawater will lead to ocean acidification (Section 6.3.2), affecting aragonite saturation state (Meehl et al., 2007) and reducing calcification rates of calcifying organisms such as corals (LeClerq et al., 2002; Guinotte et al., 2003; see C2.2.1). Cores from long-lived massive corals indicate past minor variations in calcification (Lough and Barnes, 2000), but disintegration of degraded reefs following bleaching or reduced calcification may result in increased wave energy across reef flats with potential for shoreline erosion (Sheppard et al., 2005). Relative sea-level rise appears unlikely to threaten reefs in the next few decades; coral reefs have been shown to keep pace with rapid postglacial sea-level rise when not subjected to environmental or anthropogenic stresses (Hallock, 2005). A slight rise in sea level is likely to result in the submergence of some Indo-Pacific reef flats and recolonisation by corals, as these intertidal surfaces, presently emerged at low tide, become suitable for coral growth (Buddemeier et al., 2004).

Many reefs are affected by tropical cyclones (hurricanes, typhoons); impacts range from minor breakage of fragile corals to destruction of the majority of corals on a reef and deposition of debris as coarse storm ridges. Such storms represent major perturbations, affecting species composition and abundance, from which reef ecosystems require time to recover. The sequence of ridges deposited on the reef top can provide a record of past storm history (Hayne and Chappell, 2001); for the northern Great Barrier Reef no change in frequency of extremely large cyclones has been detected over the past 5,000 years (Nott and Hayne, 2001). An intensification of tropical storms (Section 6.3.2) could have devastating consequences on the reefs themselves, as well as for the inhabitants of many low-lying islands (Sections 6.4.2 and 16.3.1.3). There is limited evidence that global warming may result in an increase of coral range; for example, the extension of branching Acropora polewards has been recorded in Florida, despite an almost Caribbean-wide trend for reef deterioration (Precht and Aronson, 2004), but there are several constraints, including low genetic diversity and the limited suitable substrate at the latitudinal limits to reef growth (Riegl, 2003; Ayre and Hughes, 2004; Woodroffe et al., 2005).

The fate of the small reef islands on the rim of atolls is of special concern. Small reef islands in the Indo-Pacific formed over recent millennia during a period when regional sea level fell (Dickinson, 2004; Woodroffe and Morrison, 2001). However, the response of these islands to future sea-level rise remains uncertain, and is addressed in greater detail in Chapter 16, Section 16.4.2. It will be important to identify critical thresholds of change beyond which there may be collapse of ecological and social systems on atolls. There are limited data, little local expertise to assess the dangers, and a low level of economic activity to cover the costs of adaptation for atolls in countries such as the Maldives, Kiribati and Tuvalu (Barnett and Adger, 2003; Chapter 16, Box 16.6).

C2.2.3 Climate change and the Great Barrier Reef (Chapter 11, Box 11.3)

The Great Barrier Reef (GBR) is the world's largest continuous reef system (2,100 km long) and is a critical storehouse of Australian marine biodiversity and a breeding ground for seabirds and other marine vertebrates such as the humpback whale. Tourism associated with the GBR generated over US$4.48 billion in the 12-month period 2004/5 and provided employment for about 63,000 full-time equivalent persons (Access Economics, 2005). The two greatest threats from climate change to the GBR are (i) rising sea temperatures, which are almost certain to increase the frequency and intensity of mass coral bleaching events, and (ii) ocean acidification, which is likely to reduce the calcifying ability of key organisms such as corals. Other factors, such as droughts and more intense storms, are likely to influence reefs through physical damage and extended flood plumes (Puotinen, 2006).

Sea temperatures on the GBR have warmed by about 0.4°C over the past century (Lough, 2000). Temperatures currently typical of the northern tip of the GBR are very likely to extend to its southern end by 2040 to 2050 (SRES scenarios A1, A2) and 2070 to 2090 (SRES scenarios B1, B2) (Done et al., 2003). Temperatures only 1°C above the long-term summer maxima already cause mass coral bleaching (loss of symbiotic algae). Corals may recover but will die under high or prolonged temperatures (2 to 3°C above long-term maxima for at least 4 weeks). The GBR has experienced eight mass bleaching events since 1979 (1980, 1982, 1987, 1992, 1994, 1998, 2002 and 2006); there are no records of events prior to 1979 (Hoegh-Guldberg, 1999). The most widespread and intense events occurred in the summers of 1998 and 2002, with about 42% and 54% of reefs affected, respectively (Done et al., 2003; Berkelmans et al., 2004). Mortality was distributed patchily, with the greatest effects on near-shore reefs, possibly exacerbated by osmotic stress caused by floodwaters in some areas (Berkelmans and Oliver, 1999). The 2002 event was followed by localised outbreaks of coral disease, with incidence of some disease-like syndromes increasing by as much as 500% over the past decade at a few sites (Willis et al., 2004). While the impacts of coral disease on the GBR are currently minor, experiences in other parts of the world suggest that disease has the potential to be a threat to GBR reefs. Effects from thermal stress are likely to be exacerbated under future scenarios by the gradual acidification of the world's oceans, which have absorbed about 30% of the excess CO_2 released to the atmosphere (Orr et al., 2005; Raven et al., 2005). Calcification declines with decreasing carbonate ion concentrations, becoming zero at carbonate ion concentrations of approximately 200 μmol/kg (Langdon et al., 2000; Langdon, 2002). These occur at atmospheric CO_2 concentrations of approximately 500 ppm. Reduced growth due to acidic conditions is very likely to hinder reef recovery after bleaching events and will reduce the resilience of reefs to other stressors (e.g., sediment, eutrophication).

Even under a moderate warming scenario (A1T, 2°C by 2100), corals on the GBR are very likely to be exposed to regular summer temperatures that exceed the thermal thresholds observed over the past 20 years (Done et al., 2003). Annual bleaching is projected under the A1FI scenario by 2030, and under A1T by 2050 (Done et al., 2003; Wooldridge et al., 2005). Given that the recovery time from a severe bleaching-induced mortality event is at least 10 years (and may exceed 50 years for full recovery), these models suggest that reefs are likely to be dominated by non-coral organisms such as macroalgae by 2050 (Hoegh-Guldberg, 1999; Done et al., 2003). Substantial impacts on biodiversity, fishing and tourism are likely. Maintenance of hard coral cover on the GBR will require corals to increase their upper thermal tolerance limits at the same pace as the change in sea temperatures driven by climate change, i.e., about 0.1-0.5°C/decade (Donner et al., 2005). There is currently little evidence that corals have the capacity for such rapid genetic change; most of the evidence is to the contrary (Hoegh-Guldberg, 1999, 2004). Given that recovery from mortality can be potentially enhanced by reducing local stresses (water quality, fishing pressure), management initiatives such as the Reef Water Quality Protection Plan and the Representative Areas Programme (which expanded totally protected areas on the GBR from 4.6% to over 33%) represent planned adaptation options to enhance the ability of coral reefs to endure the rising pressure from rapid climate change.

C2.2.4 Impact of coral mortality on reef fisheries (Chapter 5, Box 5.4)

Coral reefs and their fisheries are subject to many stresses in addition to climate change (see Chapter 4). So far, events such as the 1998 mass coral bleaching in the Indian Ocean have not provided evidence of negative short-term bio-economic impacts for coastal reef fisheries (Spalding and Jarvis, 2002; Grandcourt and Cesar, 2003). In the longer term, there may be serious consequences for fisheries production that result from loss of coral communities and reduced structural complexity, which result in reduced fish species richness, local extinctions and loss of species within key functional groups of reef fish (Sano, 2004; Graham et al., 2006).

C2.3 Multiple stresses on coral reefs

C2.3.1 Non-climate-change threats to coral reefs of small islands (Chapter 16, Box 16.2)

A large number of non-climate-change stresses and disturbances, mainly driven by human activities, can impact coral reefs (Nyström et al., 2000; Hughes et al., 2003). It has been suggested that the 'coral reef crisis' is almost certainly the result of complex and synergistic interactions among global-scale climatic stresses and local-scale, human-imposed stresses (Buddemeier et al., 2004).

In a study by Bryant et al. (1998), four human-threat factors – coastal development, marine pollution, over-exploitation and destructive fishing, and sediment and nutrients from inland – provide a composite indicator of the potential risk to coral reefs associated with human activity for 800 reef sites. Their map (Figure C2.3) identifies low-risk (blue), medium-risk (yellow) and high-risk (red) sites, the first being common in the insular central Indian and Pacific Oceans, the last in maritime South-East Asia and the Caribbean archipelago. Details of reefs at risk in the two highest-risk areas have been documented by Burke et al. (2002) and Burke and Maidens (2004), who indicate that about 50% of the reefs in South-East Asia and 45% in the Caribbean are classed in the high- to very-high-risk category. There are, however, significant local and regional differences in

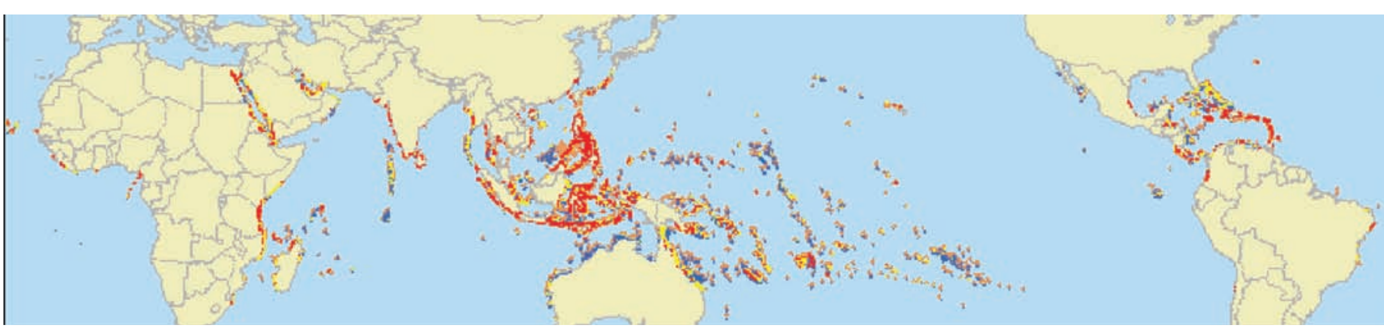

Figure C2.3. *The potential risk to coral reefs from human-threat factors. Low risk (blue), medium risk (yellow) and high risk (red). Source: Bryant et al. (1998)*

the scale and type of threats to coral reefs in both continental and small-island situations.

Recognising that coral reefs are especially important for many Small Island states, Wilkinson (2004) notes that reefs on small islands are often subject to a range of non-climate impacts. Some common types of reef disturbance are listed below, with examples from several island regions and specific islands.

1. Impact of coastal developments and modification of shorelines:
   - coastal development on fringing reefs, Langawi Island, Malaysia (Abdullah et al., 2002);
   - coastal resort development and tourism impacts in Mauritius (Ramessur, 2002).
2. Mining and harvesting of corals and reef organisms:
   - coral harvesting in Fiji for the aquarium trade (Vunisea, 2003).
3. Sedimentation and nutrient pollution from the land:
   - sediment smothering reefs in Aria Bay, Palau (Golbuua et al., 2003) and southern islands of Singapore (Dikou and van Woesik, 2006);
   - non-point source pollution, Tutuila Island, American Samoa (Houk et al., 2005);
   - nutrient pollution and eutrophication, fringing reef, Réunion (Chazottes et al., 2002) and Cocos Lagoon, Guam (Kuffner and Paul, 2001).
4. Over-exploitation and damaging fishing practices:
   - blast fishing in the islands of Indonesia (Fox and Caldwell, 2006);
   - intensive fish-farming effluent in Philippines (Villanueva et al., 2006);
   - subsistence exploitation of reef fish in Fiji (Dulvy et al., 2004);
   - giant clam harvesting on reefs, Milne Bay, Papua New Guinea (Kinch, 2002).
5. Introduced and invasive species:
   - non-indigenous species invasion of coral habitats in Guam (Paulay et al., 2002).

There is another category of 'stress' that may inadvertently result in damage to coral reefs – the human component of poor governance (Goldberg and Wilkinson, 2004). This can accompany political instability; one example being problems with contemporary coastal management in the Solomon Islands (Lane, 2006).

References

Abdullah, A., Z. Yasin, W. Ismail, B. Shutes and M. Fitzsimons, 2002: The effect of early coastal development on the fringing coral reefs of Langkawi: a study in small-scale changes. *Malaysian Journal of Remote Sensing and GIS*, **3**, 1-10.

Access Economics, 2005: *Measuring the Economic and Financial Value of the Great Barrier Reef Marine Park*. Report by Access Economics for Great Barrier Reef Marine Park Authority, June 2005, 61 pp. http://www.accesseconomics.com.au/publicationsreports/showreport.php?id=10&searchfor=Economic%20Consulting&searchby=area.

Arthur, R., T.J. Done and H. Marsh, 2005: Benthic recovery four years after an El Niño-induced coral mass mortality in the Lakshadweep atolls. *Curr. Sci. India*, **89**, 694-699.

Ayre, D.J. and T.P. Hughes, 2004: Climate change, genotypic diversity and gene flow in reef-building corals. *Ecol. Lett*., **7**, 273-278.

Barnett, J. and W.N. Adger, 2003: Climate dangers and atoll countries. *Climatic Change*, **61**, 321-337.

Barton, A.D. and K.S. Casey, 2005: Climatological context for large-scale coral bleaching. *Coral Reefs*, **24**, 536-554.

Bellwood, D.R., A.S. Hoey, J.L. Ackerman and M. Depczynski, 2006: Coral bleaching, reef fish community phase shifts and the resilience of coral reefs. *Glob. Change Biol*., **12**, 1587-1594.

Berkelmans, R. and J.K. Oliver, 1999: Large-scale bleaching of corals on the Great Barrier Reef. *Coral Reefs*, **18**, 55-60.

Berkelmans, R., G. De'ath, S. Kininmonth and W.J. Skirving, 2004: A comparison of the 1998 and 2002 coral bleaching events of the Great Barrier Reef: spatial correlation, patterns and predictions. *Coral Reefs*, **23**, 74-83.

Bindoff, N., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, C.K. Shum, L. Talley and A. Unnikrishnan, 2007: Observations: oceanic climate change and sea level. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, Eds., Cambridge University Press, Cambridge, 385-432.

Bruno, J.F., C.E. Siddon, J.D. Witman, P.L. Colin and M.A. Toscano, 2001: El Niño related coral bleaching in Palau, Western Caroline Islands. *Coral Reefs*, **20**, 127-136.

Bryant, D., L. Burke, J. McManus and M. Spalding, 1998: *Reefs at Risk: A Map-Based Indicator of Threats to the World's Coral Reefs*. World Resources Institute, Washington, DC, 56 pp.

Buddemeier, R.W., J.A. Kleypas and B. Aronson, 2004: *Coral Reefs and Global Climate Change: Potential Contributions of Climate Change to Stresses on Coral Reef Ecosystems*. Report prepared for the Pew Centre on Global Climate Change, Arlington, Virginia, 56 pp.

Burke, L. and J. Maidens, 2004: *Reefs at Risk in the Caribbean*. World Resources Institute, Washington, District of Columbia, 81 pp.

Burke, L., E. Selig and M. Spalding, 2002: *Reefs at Risk in Southeast Asia*. World Resources Institute, Washington, District of Columbia, 72 pp.

Caldeira, K. and M.E. Wickett, 2003: Anthropogenic carbon and ocean pH. *Nature*, **425**, 365-365.

Cesar, H., L. Burke and L. Pet-Soede, 2003: *The Economics of Worldwide Coral Reef Degradation*. Cesar Environmental Economics Consulting (CEEC), Arnhem, 23 pp.

Chazottes, V., T. Le Campion-Alsumard, M. Peyrot-Clausade and P. Cuet, 2002: The effects of eutrophication-related alterations to coral reef communities on agents and rates of bioerosion (Reunion Island, Indian Ocean). *Coral Reefs*, **21**, 375-390.

Cole, J., 2003: Global change: dishing the dirt on coral reefs. *Nature*, **421**, 705-706.

Coles, S.L.and B.E. Brown, 2003: Coral bleaching: capacity for acclimatization and adaptation. *Adv. Mar. Biol*., **46**, 183-224.

Denman, K.L., G. Brasseur, A. Chidthaisong, P. Ciais, P. Cox, R.E. Dickinson, D. Hauglustaine, C. Heinze, E. Holland, D. Jacob, U. Lohmann, S. Ramachandran, P.L. da Silva Dias, S.C. Wofsy and X. Zhang, 2007: Couplings between changes in the climate system and biogeochemistry. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, Eds., Cambridge University Press, Cambridge, 499-587.

Dickinson, W.R., 2004: Impacts of eustasy and hydro-isostasy on the evolution and landforms of Pacific atolls. *Palaeogeogr. Palaeoclimatol. Palaeoecol*., **213**, 251-269.

Dikou, A. and R. van Woesik, 2006: Survival under chronic stress from sediment load: spatial patterns of hard coral communities in the southern islands of Singapore. *Mar. Pollut. Bull*., **52**, 7-21.

Done, T., P. Whetton, R. Jones, R. Berkelmans, J. Lough, W. Skirving and S. Wooldridge, 2003: Global climate change and coral bleaching on the Great Barrier Reef. Final Report to the State of Queensland Greenhouse Taskforce through the Department of Natural Resources and Mining, Townsville, 49 pp. http://www.longpaddock.qld.gov.au/ClimateChanges/pub/CoralBleaching.pdf.

Donner, S.D., W.J. Skirving, C.M. Little, M. Oppenheimer and O. Hoegh-Guldberg, 2005: Global assessment of coral bleaching and required rates of adaptation under climate change. *Glob. Change Biol*., **11**, 2251-2265.

Douglas, A.E., 2003: Coral bleaching: how and why? *Mar. Pollut. Bull*., **46**, 385-392.

Dulvy, N., R. Freckleton and N. Polunin, 2004: Coral reef cascades and the indirect effects of predator removal by exploitation. *Ecol. Lett.*, **7**, 410-416.

Feely, R.A., C.L. Sabine, K. Lee, W. Berelson, J. Kleypas, V.J. Fabry and F.J. Millero, 2004: Impact of anthropogenic CO_2 on the $CaCO_3$ system in the oceans. *Science*, **305**, 362-366.

Fox, H. and R. Caldwell, 2006: Recovery from blast fishing on coral reefs: a tale of two scales. *Ecol. Appl.*, **16**, 1631-1635.

Gardner, T.A., I.M. Cote, J.A. Gill, A. Grant and A.R. Watkinson, 2003: Long-term region-wide declines in Caribbean corals. *Science*, **301**, 958-960.

Gardner, T.A., I.M. Côté, J.A. Gill, A. Grant and A.R. Watkinson, 2005: Hurricanes and Caribbean coral reefs: impacts, recovery patterns and role in long-term decline. *Ecology*, **86**, 174-184.

Garpe, K.C., S.A.S. Yahya, U. Lindahl and M.C. Ohman, 2006: Long-term effects of the 1998 coral bleaching event on reef fish assemblages. *Mar. Ecol.–Prog. Ser.*, **315**, 237-247.

Gill, J.A., J.P. McWilliams, A.R. Watkinson and I.M. Côté, 2006: Opposing forces of aerosol cooling and El Niño drive coral bleaching on Caribbean reefs. *P. Natl. Acad. Sci. USA*, **103**, 18870-18873.

Golbuua, Y., S. Victora, E. Wolanski and R.H. Richmond, 2003: Trapping of fine sediment in a semi-enclosed bay, Palau, Micronesia. *Estuar. Coast. Shelf S.*, **57**, 1-9.

Goldberg, J. and C. Wilkinson, 2004: Global threats to coral reefs: coral bleaching, global climate change, disease, predator plagues, and invasive species. *Status of Coral Reefs of the World: 2004*, C. Wilkinson, Ed., Australian Institute of Marine Science, Townsville, 67-92.

Goldenberg, S.B., C.W. Landsea, A.M. Mestas-Nunez and W.M. Gray, 2001: The recent increase in Atlantic hurricane activity: causes and implications. *Science*, **293**, 474-479.

Grandcourt, E.M. and H.S.J. Cesar, 2003: The bio-economic impact of mass coral mortality on the coastal reef fisheries of the Seychelles. *Fish. Res.*, **60**, 539-550.

Graham, N.A.J., S.K. Wilson, S. Jennings, N.V.C. Polunin, J.P. Bijoux and J. Robinson, 2006: Dynamic fragility of oceanic coral reef ecosystems. *P. Natl. Acad. Sci. USA*, **103**, 8425-8429.

Guinotte, J.M., R.W. Buddemeier and J.A. Kleypas, 2003: Future coral reef habitat marginality: temporal and spatial effects of climate change in the Pacific basin. *Coral Reefs*, **22**, 551-558.

Hallock, P., 2005: Global change and modern coral reefs: new opportunities to understand shallow-water carbonate depositional processes. *Sediment. Geol.*, **175**, 19-33.

Harvell, C.D., C.E. Mitchell, J.R. Ward, S. Altizer, A.P. Dobson, R.S. Ostfeld and M.D. Samuel, 2002: Climate warming and disease risks for terrestrial and marine biota. *Science*, **296**, 2158-2162.

Hayne, M. and J. Chappell, 2001: Cyclone frequency during the last 5000 years at Curacao Island, north Queensland, Australia. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **168**, 207-219.

Hoegh-Guldberg, O., 1999: Climate change, coral bleaching and the future of the world's coral reefs. *Mar. Freshwater Res.*, **50**, 839-866.

Hoegh-Guldberg, O., 2004: Coral reefs in a century of rapid environmental change. *Symbiosis*, **37**, 1-31.

Hoegh-Guldberg, O., 2005: Low coral cover in a high-CO_2 world. *J. Geophys. Res. C*, **110**, C09S06, doi:10.1029/2004JC002528.

Hoegh-Guldberg, O., H. Hoegh-Guldberg, D.K. Stout, H. Cesar and A. Timmerman, 2000: *Pacific in Peril: Biological, Economic and Social Impacts of Climate Change on Pacific Coral Reefs*. Greenpeace, Sidney, 72 pp.

Houk, P., G. Didonato, J. Iguel and R. van Woesik, 2005: Assessing the effects of non-point source pollution on American Samoa's coral reef communities. *Environ. Monit. Assess.*, **107**, 11-27.

Hughes, T.P., 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 and J. Roughgarden, 2003: Climate change, human impacts, and the resilience of coral reefs. *Science*, **301**, 929-933.

Jompa, J. and L.J. McCook, 2003: Coral-algal competition: macroalgae with different properties have different effects on corals. *Mar. Ecol.–Prog. Ser.*, **258**, 87-95.

Kinch, J., 2002: Giant clams: their status and trade in Milne Bay Province, Papua New Guinea. *TRAFFIC Bulletin*, **19**, 1-9.

Kleypas, J.A. and C. Langdon, 2002: Overview of CO_2-induced changes in seawater chemistry. *World Coral Reefs in the New Millenium: Bridging Research and Management for Sustainable Development*, M.K. Moosa, S. Soemodihardjo, A. Soegiarto, K. Romimohtarto, A. Nontji and S. Suharsono, Eds., Proceedings of the 9th International Coral Reef Symposium, 2, Bali, Indonesia. Ministry of Environment, Indonesian Institute of Sciences, International Society for Reef Studies, 1085-1089.

Kleypas, J.A., R.W. Buddemeier, D. Archer, J.P. Gattuso, C. Langdon and B.N. Opdyke, 1999: Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. *Science*, **284**, 118-120.

Kleypas, J.A., R.W. Buddemeier and J.P. Gattuso, 2001: The future of coral reefs in an age of global change. *Int. J. Earth Sci.*, **90**, 426-437.

Kleypas, J.A., R.W. Buddemeier, C.M. Eakin, J.P. Gattuso, J. Guinotte, O. Hoegh-Guldberg, R. Iglesias-Prieto, P.L. Jokiel, C. Langdon, W. Skirving and A.E. Strong, 2005: Comment on "Coral reef calcification and climate change: the effect of ocean warming". *Geophys. Res. Lett.*, **32**, L08601, doi:10.1029/2004 GL022329.

Koop, K., D. Booth, A. Broadbent, J. Brodie, D. Bucher, D. Capone, J. Coll, W. Dennison, M. Erdmann, P. Harrison, O. Hoegh-Guldberg, P. Hutchings, G.B. Jones, A.W.D. Larkum, J. O'Neil, A. Steven, E. Tentori, S. Ward, J. Williamson and D. Yellowlees, 2001: ENCORE: The effect of nutrient enrichment on coral reefs: synthesis of results and conclusions. *Mar. Pollut. Bull.*, **42**, 91-120.

Kuffner, I. and V. Paul, 2001: Effects of nitrate, phosphate and iron on the growth of macroalgae and benthic cyanobacteria from Cocos Lagoon, Guam. *Mar. Ecol.–Prog. Ser.*, **222**, 63-72.

Lane, M., 2006: Towards integrated coastal management in the Solomon Islands: identifying strategic issues for governance reform. *Ocean Coast. Manage.*, **49**, 421-441.

Langdon, C., 2002: Review of experimental evidence for effects of CO_2 on calcification of reef builders. *Proc. of the 9th International Coral Reef Symposium*, Ministry of Environment, Indonesian Institute of Science, International Society for Reef Studies, Bali 23–27 October, 1091-1098.

Langdon, C., T. Takahashi, C. Sweeney, D. Chipman, J. Goddard, F. Marubini, H. Aceves, H. Barnett and M.J. Atkinson, 2000: Effect of calcium carbonate saturation state on the calcification rate of an experimental coral reef. *Global Biogeochem. Cy.*, **14**, 639-654.

Langdon, C., W.S. Broecker, D.E. Hammond, E. Glenn, K. Fitzsimmons, S.G. Nelson, T.H. Peng, I. Hajdas and G. Bonani, 2003: Effect of elevated CO_2 on the community metabolism of an experimental coral reef. *Global Biogeochem. Cy.*, **17**, 1011, doi:10.1029/2002GB001941.

LeClerq, N., J.-P. Gattuso and J. Jaubert, 2002: Primary production, respiration, and calcification of a coral reef mesocosm under increased CO_2 pressure. *Limnol. Oceanogr.*, **47**, 558-564.

Lesser, M.P., 2004: Experimental biology of coral reef ecosystems. *J. Exp. Mar. Biol. Ecol.*, **300**, 217-252.

Little, A.F., M.J.H. van Oppen and B.L. Willis, 2004: Flexibility in algal endosymbioses shapes growth in reef corals. *Science*, **304**, 1492-1494.

Lough, J.M., 2000: 1997-98: unprecedented thermal stress to coral reefs? *Geophys. Res. Lett.*, **27**, 3901-3904.

Lough, J.M. and D.J. Barnes, 2000: Environmental controls on growth of the massive coral *Porites*. *J. Exp. Mar. Biol. Ecol.*, **245**, 225-243.

Marubini, F., H. Barnett, C. Langdon and M.J. Atkinson, 2001: Dependence of calcification on light and carbonate ion concentration for the hermatypic coral *Porites compressa*. *Mar. Ecol.–Prog. Ser.*, **220**, 153-162.

Marubini, F., C. Ferrier-Pages and J.P. Cuif, 2003: Suppression of skeletal growth in scleractinian corals by decreasing ambient carbonate-ion concentration: a cross-family comparison. *P. Roy. Soc. Lond. B*, **270**, 179-184.

McClanahan, T.R., N.A. Muthiga and S. Mangi, 2001: Coral and algal changes after the 1998 coral bleaching: interaction with reef management and herbivores on Kenyan reefs. *Coral Reefs*, **19**, 380-391.

McNeil, B.I., R.J. Matear and D.J. Barnes, 2004: Coral reef calcification and climate change: the effect of ocean warming. *Geophys. Res. Lett.*, **31**, L22309, doi:10.1029/2004GL021541.

McWilliams, J.P., I.M. Côté, J.A. Gill, W.J. Sutherland and A.R. Watkinson, 2005: Accelerating impacts of temperature-induced coral bleaching in the Caribbean. *Ecology*, **86**, 2055-2060.

Meehl, G.A., T.F. Stocker, W. Collins, P. Friedlingstein, A. Gaye, J. Gregory, A. Kitoh, R. Knutti and co-authors, 2007: Global climate projections. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt,

M. Tignor and H.L. Miller, Eds., Cambridge University Press, Cambridge, 747-846.

Mendes, J.M. and J.D. Woodley, 2002: Effect of the 1995-1996 bleaching event on polyp tissue depth, growth, reproduction and skeletal band formation in *Montastraea annularis*. *Mar. Ecol.–Prog. Ser.*, **235**, 93-102.

Mestas-Nunez, A.M. and A.J. Miller, 2006: Interdecadal variability and climate change in the eastern tropical Pacific: a review. *Prog. Oceanogr.*, **69**, 267-284.

Nott, J. and M. Hayne, 2001: High frequency of 'super-cyclones' along the Great Barrier Reef over the past 5,000 years. *Nature*, **413**, 508-512.

Nyström, M., C. Folke and F. Moberg, 2000: Coral reef disturbance and resilience in a human-dominated environment. *Trends Ecol. Evol.*, **15**, 413-417.

Obura, D.O., 2005: Resilience and climate change: lessons from coral reefs and bleaching in the western Indian Ocean. *Estuar. Coast. Shelf Sci.*, **63**, 353-372.

Ohde, S. and M.M.M. Hossain, 2004: Effect of $CaCO_3$ (aragonite) saturation state of seawater on calcification of *Porites* coral. *Geochem. J.*, **38**, 613-621.

Orr, J.C., V.J. Fabry, O. Aumont, L. Bopp, S.C. Doney, R.A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, R.M. Key, K. Lindsay, E. Maier-Reimer, R. Matear, P. Monfray, A. Mouchet, R.G. Najjar, G.K. Plattner, K.B. Rodgers, C.L. Sabine, J.L. Sarmiento, R. Schlitzer, R.D. Slater, I.J. Totterdell, M.F. Weirig, Y. Yamanaka and A. Yool, 2005: Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, **437**, 681-686.

Pandolfi, J.M., R.H. Bradbury, E. Sala, T.P. Hughes, K.A. Bjorndal, R.G. Cooke, D. McArdle, L. McClenachan and co-authors, 2003: Global trajectories of the long-term decline of coral reef ecosystems. *Science*, **301**, 955-958.

Pauly, D., J. Alder, A. Bakun, S. Heileman, K.H. Kock, P. Mace, W. Perrin, K. Stergiou, U.R. Sumaila, M. Vierros, K. Freire and Y. Sadovy, 2005: Marine fisheries systems. *Ecosystems and Human Well-being. Volume 1: Current State and Trends*, R. Hassan, R. Scholes and N. Ash, Eds., Island Press, Washington, District of Columbia, 477-511.

Paulay, G., L. Kirkendale, G. Lambert and C. Meyer, 2002: Anthropogenic biotic interchange in a coral reef ecosystem: a case study from Guam. *Pac. Sci.*, **56**, 403-422.

Pelejero, C., E. Calvo, M.T. McCulloch, J.F. Marshall, M.K. Gagan, J.M. Lough and B.N. Opdyke, 2005: Preindustrial to modern interdecadal variability in coral reef pH. *Science*, **309**, 2204-2207.

Puotinen, M.L., 2006: Modelling the risk of cyclone wave damage to coral reefs using GIS: a case study of the Great Barrier Reef, 1969-2003. *Int. J. Geogr. Inf. Sci.*, **21**, 97-120.

Precht, W.F. and R.B. Aronson, 2004: Climate flickers and range shifts of coral reefs. *Front. Ecol. Environ.*, **2**, 307-314.

Ramessur, R., 2002: Anthropogenic-driven changes with focus on the coastal zone of Mauritius, south-western Indian Ocean. *Reg. Environ. Change*, **3**, 99-106.

Raven, J., K. Caldeira, H. Elderfield, O. Hoegh-Guldberg, P. Liss, U. Riebesell, J. Shepherd, C. Turley and A. Watson, 2005: Ocean acidification due to increasing atmospheric carbon dioxide. Policy Document 12/05, The Royal Society, The Clyvedon Press Ltd, Cardiff, 68 pp.

Riegl, B., 2003: Climate change and coral reefs: different effects in two high-latitude areas (Arabian Gulf, South Africa). *Coral Reefs*, **22**, 433-446.

Reynaud, S., N. Leclercq, S. Romaine-Lioud, C. Ferrier-Pages, J. Jaubert and J.P. Gattuso, 2003: Interacting effects of CO_2 partial pressure and temperature on photosynthesis and calcification in a scleractinian coral. *Global Change Biol.*, **9**, 1660-1668.

Roberts, C.M., 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 and T.B. Werner, 2002: Marine biodiversity hotspots and conservation priorities for tropical reefs. *Science*, **295**, 1280-1284.

Rowan, R., 2004: Coral bleaching: thermal adaptation in reef coral symbionts. *Nature*, **430**, 742.

Sadovy, Y., 2005: Trouble on the reef: the imperative for managing vulnerable and valuable fisheries. *Fish Fish.*, **6**, 167-185.

Sano, M., 2004: Short-term effects of a mass coral bleaching event on a reef fish assemblage at Iriomote Island, Japan. *Fish. Sci.*, **70**, 41-46.

Sheppard, C.R.C., 2003: Predicted recurrences of mass coral mortality in the Indian Ocean. *Nature*, **425**, 294-297.

Sheppard, C.R.C., D.J. Dixon, M. Gourlay, A. Sheppard and R. Payet, 2005: Coral mortality increases wave energy reaching shores protected by reef flats: examples from the Seychelles. *Estuar. Coast. Shelf S.*, **64**, 223-234.

Spalding, M.D. and G.E. Jarvis, 2002: The impact of the 1998 coral mortality on reef fish communities in the Seychelles. *Mar. Pollut. Bull.*, **44**, 309-321.

Szmant, A.M., 2001: Why are coral reefs world-wide becoming overgrown by algae? 'Algae, algae everywhere, and nowhere a bite to eat!' *Coral Reefs*, **19**, 299-302.

Trenberth, K.E., P.D. Jones, P.G. Ambenje, R. Bojariu, D.R. Easterling, A.M.G. Klein Tank, D.E. Parker, J.A. Renwick, F. Rahimzadeh, M.M. Rusticucci, B.J. Soden and P.-M. Zhai, 2007: Observations: surface and atmospheric climate change. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, Eds., Cambridge University Press, Cambridge, 235-336.

Turley, C., J. Blackford, S. Widdicombe, D. Lowe and P. Nightingale, 2006: Reviewing the impact of increased atmospheric CO_2 on oceanic pH and the marine ecosystem. *Avoiding Dangerous Climate Change*, H.J. Schellnhuber, W. Cramer, N. Nakićenović, T.M.L. Wigley and G. Yohe, Eds., Cambridge University Press, Cambridge, 65-70.

Villanueva, R., H. Yap and N. Montaño, 2006: Intensive fish farming in the Philippines is detrimental to the reef-building coral *Pocillopora damicornis*. *Mar. Ecol.–Prog. Ser.*, **316**, 165-174.

Vunisea, A., 2003: Coral harvesting and its impact on local fisheries in Fiji. *SPC Women in Fisheries Information Bulletin*, **12**, 17-20.

Webster, P.J., A.M. Moore, J.P. Loschnigg and R.R. Leben, 1999: Coupled ocean–temperature dynamics in the Indian Ocean during 1997-98. *Nature*, **401**, 356-360.

Whittingham, E., J. Campbell and P. Townsley, 2003: *Poverty and Reefs*. DFID-IMM-IOC/UNESCO, Exeter, 260 pp.

Wilkinson, C.R., 2002: *Status of Coral Reefs of the World*. Australian Institute of Marine Science, Townsville, 388 pp.

Wilkinson, J.W., 2004. *Status of Coral Reefs of the World*. Australian Institute of Marine Science, Townsville, 580 pp.

Willig, M.R., D.M. Kaufman and R.D. Stevens, 2003: Latitudinal gradients of biodiversity: pattern, process, scale, and synthesis. *Annu. Rev. Ecol. Evol. Syst.*, **34**, 273-309.

Willis, B.L., C.A. Page and E.A. Dinsdale, 2004: Coral disease on the Great Barrier Reef. *Coral Health and Disease*, E. Rosenberg and Y. Loya, Eds., Springer, Berlin, 69-104.

Woodroffe, C.D. and R.J. Morrison, 2001: Reef-island accretion and soil development, Makin Island, Kiribati, central Pacific. *Catena*, **44**, 245-261.

Woodroffe, C.D., M. Dickson, B.P. Brooke and D.M. Kennedy, 2005: Episodes of reef growth at Lord Howe Island, the southernmost reef in the southwest Pacific. *Global Planet. Change*, **49**, 222-237.

Wooldridge, S., T. Done, R. Berkelmans, R. Jones and P. Marshall, 2005: Precursors for resilience in coral communities in a warming climate: a belief network approach. *Mar. Ecol.–Prog. Ser.*, **295**, 157-169.

C3. Megadeltas: their vulnerabilities to climate change

C3.1 Introduction

C3.1.1 Deltas and megadeltas: hotspots for vulnerability (Chapter 6, Box 6.3)

Deltas, some of the largest sedimentary deposits in the world, are widely recognised as being highly vulnerable to the impacts of climate change, particularly sea-level rise and changes in runoff, as well as being subject to stresses imposed by human modification of catchment and delta plain land use. Most deltas are already undergoing natural subsidence that results in accelerated rates of relative sea-level rise above the global average. Many are impacted by the effects of water extraction and diversion, as well as declining sediment input as a consequence of entrapment in dams. Delta plains, particularly those in Asia (see C3.2.1), are densely populated, and large numbers of people are often impacted as a result of external terrestrial influences (river floods, sediment starvation) and/or external marine influences (storm surges, erosion) (see Figure 6.1).

Ericson et al. (2006) estimated that nearly 300 million people inhabit a sample of 40 deltas globally, including all the large megadeltas. Average population density is 500 people/km^2, with the largest population in the Ganges-Brahmaputra delta, and the highest density in the Nile delta. Many of these deltas and megadeltas are associated with significant and expanding urban areas. Ericson et al. (2006) used a generalised modelling approach to approximate the effective rate of sea-level rise under present conditions, basing estimates of sediment trapping and flow diversion on a global dam database, and modifying estimates of natural subsidence to incorporate accelerated human-induced subsidence. This analysis showed that much of the population of these 40 deltas is at risk through coastal erosion and land loss, primarily as a result of decreased sediment delivery by the rivers, but also through accentuated rates of sea-level rise. They estimate, using a coarse digital terrain model and global population distribution data, that more than 1 million people will be directly affected by 2050 in three megadeltas: the Ganges-Brahmaputra delta in Bangladesh, the Mekong delta in Vietnam and the Nile delta in Egypt. More than 50,000 people are likely to be directly impacted in each of a further nine deltas, and more than 5,000 in each of a further twelve deltas (Figure C3.1). This generalised modelling approach indicates that 75% of the population affected live on Asian megadeltas and deltas, and a large proportion of the remainder are on deltas in Africa. These impacts would be exacerbated by accelerated sea-level rise and enhanced human pressures (see, e.g., C3.2.1). Within the Asian megadeltas, the surface topography is complex as a result of the geomorphological development of the deltas, and the population distribution shows considerable spatial variability, reflecting the intensive land use and the growth of some of the world's largest megacities (Woodroffe et al., 2006). Many people in these and other deltas worldwide are already subject to flooding from both storm surges and seasonal river floods, and therefore it is necessary to develop further methods to assess individual delta vulnerability (e.g., Sánchez-Arcilla et al., 2007).

Figure C3.1. *Relative vulnerability of coastal deltas as shown by the indicative population potentially displaced by current sea-level trends to 2050 (Extreme = >1 million; High = 1 million to 50,000; Medium = 50,000 to 5,000; following Ericson et al., 2006).*

C3.2 Megadeltas in Asia

C3.2.1 Megadeltas in Asia (Chapter 10, Section 10.6.1, Table 10.10)

There are eleven megadeltas with an area greater than 10,000 km^2 (Table C3.1) in the coastal zone of Asia that are continuously being formed by rivers originating from the Tibetan Plateau (Milliman and Meade, 1983; Penland and Kulp, 2005) These megadeltas are vital to Asia because they are home to millions of people, especially in the seven megacities that are located in these deltas (Nicholls, 1995; Woodroffe et al., 2006). The megadeltas, particularly the Zhujiang delta, Changjiang delta and Huanghe delta, are also economically important, accounting for a substantial proportion of China's total GDP (Niou, 2002; She, 2004). Ecologically, the Asian megadeltas are critical diverse ecosystems of unique assemblages of plants and animals located in different climatic regions (IUCN, 2003b; ACIA, 2005; Macintosh, 2005; Sanlaville and Prieur, 2005). However, the megadeltas of Asia are vulnerable to climate change and sea-level rise that could increase the frequency and level of inundation of megadeltas due to storm surges and floods from river drainage (Nicholls, 2004; Woodroffe et al., 2006) putting communities, biodiversity and infrastructure at risk of being damaged. This impact could be more pronounced in megacities located in megadeltas, where natural ground subsidence is enhanced by human activities, such as in Bangkok in the Chao Phraya delta, Shanghai in the Changjiang delta, Tianjin in the old Huanghe delta (Nguyen et al., 2000; Li et al., 2004a, 2005; Jiang, 2005; Woodroffe et al., 2006). Climate change together with human activities could also enhance erosion that has, for example, caused the Lena delta to retreat at a rate of 3.6 to 4.5 m/yr (Leont'yev, 2004) and has affected the progradation and retreat of megadeltas fed by rivers originating from the Tibetan Plateau (Li et al., 2004b; Thanh et al., 2004; Shi et al., 2005; Woodroffe et al., 2006). The adverse impacts of salt-water intrusion on water supply in the Changjiang delta and Zhujiang delta, mangrove forests, agriculture production and freshwater fish catch, resulting in a loss of US$125×$10^6$ per annum in the Indus delta, could also be aggravated by climate change (IUCN, 2003a, b; Shen et al., 2003; Huang and Zhang, 2004).

Externally, the sediment supplies to many megadeltas have been reduced by the construction of dams, and there are plans for many more dams in the 21st century (see C3.1.1; Woodroffe et al., 2006). The reduction of sediment supplies makes these systems much more vulnerable to climate change and sea-level rise. When considering all the non-climate pressures, there is very high confidence that the group of populated Asian megadeltas is highly threatened by climate change and responding to this threat will present important challenges (see also C3.1.1). The sustainability of megadeltas in Asia in a warmer climate will rest heavily on policies and programmes that promote integrated and co-ordinated development of the megadeltas and upstream areas, balanced use and development of megadeltas for conservation and production goals, and comprehensive protection against erosion from river-flow anomalies and sea-water actions that combines structural with human and institutional capability-building measures (Du and Zhang, 2000; Inam et al., 2003; Li et al., 2004b; Thanh et al., 2004; Saito, 2005; Woodroffe et al., 2006; Wolanski, 2007).

C3.2.2 Climate change and the fisheries of the lower Mekong: an example of multiple stresses on a megadelta fisheries system due to human activity (Chapter 5, Box 5.3)

Fisheries are central to the lives of the people, particularly the rural poor, who live in the lower Mekong countries. Two-thirds of the basin's 60 million people are in some way active in fisheries, which represent about 10% of the GDP of Cambodia and Lao People's Democratic Republic (PDR). There are approximately 1,000 species of fish commonly found in the river, with many more marine vagrants, making it one of the most prolific and diverse faunas in the world (MRC, 2003). Recent estimates of the annual catch from capture fisheries alone exceed 2.5 Mtonnes (Hortle and Bush, 2003), with the delta contributing over 30% of this.

Direct effects of climate will occur due to changing patterns of precipitation, snow melt and rising sea level, which will affect hydrology and water quality. Indirect effects will result from changing vegetation patterns that may alter the food chain and increase soil erosion. It is likely that human impacts on the fisheries (caused by population growth, flood mitigation, increased water abstractions, changes in land use and over-fishing) will be greater than the effects of climate, but the pressures are strongly interrelated.

An analysis of the impact of climate-change scenarios on the flow of the Mekong (Hoanh et al., 2004) estimated increased maximum monthly flows of 35 to 41% in the basin and 16 to 19% in the delta (lower value is for years 2010 to 2138 and higher value for years 2070 to 2099, compared with 1961 to 1990 levels). Minimum monthly flows were estimated to decrease by 17 to 24% in the basin and 26 to 29% in the delta. Increased flooding would positively affect fisheries yields, but a reduction in dry season habitat may reduce recruitment of some species. However, planned water-management interventions, primarily dams, are expected to have the opposite effects on hydrology, namely marginally decreasing wet-season flows and considerably increasing dry-season flows (World Bank, 2004).

Models indicate that even a modest sea level rise of 20 cm would cause contour lines of water levels in the Mekong delta to shift 25 km towards the sea during the flood season and salt water to move further upstream (although confined within canals) during the dry season (Wassmann et al., 2004). Inland movement of salt water would significantly alter the species composition of fisheries, but may not be detrimental for overall fisheries yields.

C3.3 Megadeltas in the Arctic

C3.3.1 Arctic megadeltas (Chapter 15, Section 15.6.2)

Numerous river deltas are located along the Arctic coast and the rivers that flow to it. Of particular importance are the megadeltas of the Lena (44,000 km^2) and Mackenzie (9,000 km^2) rivers, which are fed by the largest Arctic rivers of

Table C3.1. *Megadeltas of Asia.*

Features	Lena	Huanghe-Huaihe	Changjiang	Zhujiang	Red River	Mekong	Chao Phraya	Irrawaddy	Ganges-Brahmaputra	Indus	Shatt-el-Arab (Arvand Rud)
Area (10^3 km^2)	43.6	36.3	66.9	10	16	62.5	18	20.6	100	29.5	18.5
Water discharge (10^9 m^3/yr)	520	33.3	905	326	120	470	30	430	1330	185	46
Sediment load (10^6 t/yr)	18	849	433	76	130	160	11	260	1969	400	100
Delta growth (km^2/yr)	--	21.0	16.0	11.0	3.6	1.2		10.0	5.5 to 16.0	PD30	
Climate zone	Boreal	Temperate	Sub-tropical	Sub-tropical	Tropical	Tropical	Tropical	Tropical	Tropical	Semi-arid	Arid
Mangroves (10^3 km^2)	None	None	None	None		5.2	2.4	4.2	10	1.6	None
Population (10^6) in 2000	0.000079	24.9 (00)	76 (03)	42.3 (03)	13.3	15.6	11.5	10.6	130	3.0	0.4
Population increase by 2015	None	18	-	176	21	21	44	15	28	45	--
GDP (US$$10^9$)		58.8 (00)	274.4 (03)	240.8 (03)	9.2 (04)	7.8 (04)	--	--	--	--	--
Megacity	None	Tianjin	Shanghai	Guangzhou	--	--	Bangkok	--	Dhaka	Karachi	--
Ground subsidence (m)	None	2.6 to 2.8	2.0 to 2.6	X	XX	--	0.2 to 1.6	--	0.6 to 1.9 mm/a		--
SLR (cm) in 2050	10 to 90 (2100)	70 to 90	50 to 70	40 to 60	--	--	--	--	--	20 to 50	--
Salt-water intrusion (km)	--	--	100	--	30 to 50	60 to 70	--	--	100	80	--
Natural hazards	--	FD	CS, SWI, FD	CS, FD, SWI	CS, FD, SWI	SWI	--	--	CS, FD, SWI	CS, SWI	--
Area inundated by SLR (10^3 km^2). Figure in brackets indicates amount SLR.	--	21.3 (0.3m)	54.5 (0.3m)	5.5 (0.3m)	5 (1m)	20 (1m)	--	--	--	--	--
Coastal protection	No protection	Protected	Protected	Protected	Protected	Protected	Protected	Protected	Protected	Partial Protection	Partial protection

PD: Progradation of coast; CS: Tropical cyclone and storm surge; FD: Flooding; SLR: Sea-level rise; SWI: Salt water intrusion; DG: Delta growth in area; XX: Strong ground subsidence; X: Slight ground subsidence; --: No data available

Eurasia and North America, respectively. In contrast to non-polar megadeltas, the physical development and ecosystem health of these systems are strongly controlled by cryospheric processes and are thus highly susceptible to the effects of climate change.

Currently, advance/retreat of Arctic marine deltas is highly dependent on the protection afforded by near-shore and land-fast sea ice (Solomon, 2005; Walsh et al., 2005). The loss of such protection with warming will lead to increased erosion by waves and storm surges. The problems will be exacerbated by rising sea levels, greater wind fetch produced by shrinking sea-ice coverage, and potentially by increasing storm frequency. Similarly, thawing of the permafrost and ground-ice that currently consolidates deltaic material will induce hydrodynamic erosion on the delta front and along riverbanks. Thawing of permafrost on the delta plain itself will lead to similar changes; for example, the initial development of more ponded water, as thermokarst activity increases, will eventually be followed by drainage as surface and groundwater systems become linked. Climate warming may have already caused the loss of wetland area as lakes expanded on the Yukon River delta in the late 20th century (Coleman and Huh, 2004). Thaw subsidence may also affect the magnitude and frequency of delta flooding from spring flows and storm surges (Kokelj and Burn, 2005).

The current water budget and sediment-nutrient supply for the multitude of lakes and ponds that populate much of the tundra plains of Arctic deltas depends strongly on the supply of floodwaters produced by river-ice jams during the spring freshet. Studies of future climate conditions on a major river delta of the Mackenzie River watershed (Peace-Athabasca Delta) indicate that a combination of thinner river ice and reduced spring runoff will lead to decreased ice-jam flooding (Beltaos et al., 2006). This change, combined with greater summer evaporation due to warmer temperatures, will cause a decline in delta-pond water levels (Marsh and Lesack, 1996). For many Arctic regions, summer evaporation already exceeds precipitation and therefore the loss of ice-jam flooding could lead to a drying of delta ponds and a loss of sediment and nutrients known to be critical to their ecosystem health (Lesack et al., 1998; Marsh et al., 1999). A successful adaptation strategy that has already been used to counteract the effects of drying of delta ponds involves managing water release from reservoirs to increase the probability of ice-jam formation and related flooding (Prowse et al., 2002).

C3.4 Case study of Hurricane Katrina

C3.4.1 Hurricane Katrina and coastal ecosystem services in the Mississippi delta (Chapter 6, Box 6.4)

Whereas an individual hurricane event cannot be attributed to climate change, it can serve to illustrate the consequences for ecosystem services if the intensity and/or frequency of such events were to increase in the future. One result of Hurricane Katrina, which made landfall in coastal Louisiana on 29 August 2005, was the loss of 388 km^2 of coastal wetlands, levees and islands that flank New Orleans in the Mississippi River deltaic plain (Barras, 2006) (Figure C3.2). (Hurricane Rita, which struck in September 2005, had relatively minor effects on this part of the Louisiana coast which are included in this estimate.) The Chandeleur Islands, which lie south-east of the city, were reduced to roughly half of their former extent as a direct result of Hurricane Katrina. Collectively, these natural systems serve as the first line of defence against storm surge in this highly populated region. While some habitat recovery is expected, it is likely to be minimal compared to the scale of the losses. The Chandeleur Islands serve as an important wintering ground for migratory waterfowl and neo-tropical birds; a large population of North American redhead ducks, for example, feed on the rhizomes of sheltered sea grasses leeward of the Chandeleur Islands (Michot, 2000). Historically the region has ranked second only to Alaska in U.S. commercial fisheries production, and this high productivity has been attributed to the extent of coastal marshes and sheltered estuaries of the Mississippi River delta. Over 1,800 people lost their lives (Graumann et al., 2005) during Hurricane Katrina and the economic losses totalled more than US$100 billion (NOAA, 2007). Roughly 300,000 homes and over 1,000 historical and cultural sites were destroyed along the Louisiana and Mississippi coasts (the loss of oil production and refinery capacity helped to raise global oil prices in the short term). Post-Katrina, some major changes to the delta's management are being advocated, most notably abandonment of the 'bird-foot delta', where artificial levees channel valuable sediments into deep water (EFGC, 2006; NRC, 2006). The aim is to restore large-scale delta building processes and hence sustain the ecosystem services in the long term. Hurricane Katrina is further discussed in C3.4.2 and Chapter 14.

C3.4.2 Vulnerabilities to extreme weather events in megadeltas in the context of multiple stresses: the case of Hurricane Katrina (Chapter 7, Box 7.4)

It is possible to say with a high level of confidence that sustainable development in some densely populated megadeltas of the world will be challenged by climate change, not only in developing countries but in developed countries also. The experience of the U.S. Gulf Coast with Hurricane Katrina in 2005 is a dramatic example of the impact of a tropical cyclone – of an intensity expected to become more common with climate change – on the demographic, social and economic processes and stresses of a major city located in a megadelta.

In 2005, the city of New Orleans had a population of about half a million, located on the delta of the Mississippi River along the U.S. Gulf Coast. The city is subject not only to seasonal storms (Emanuel, 2005) but also to land subsidence at an average rate of 6 mm/yr, rising to 10-15 mm/year or more (Dixon et al., 2006). Embanking the main river channel has led to a reduction in sedimentation, leading to the loss of coastal wetlands that tend to reduce storm surge flood heights, while urban development throughout the 20th century has significantly increased land use and settlement in areas vulnerable to flooding. A number of studies of the protective levee system had indicated growing vulnerabilities to flooding, but actions were not taken to improve protection.

In late August 2005, Hurricane Katrina – which had been a Category 5 storm but weakened to Category 3 before landfall – moved onto the Louisiana and Mississippi coast with a storm surge, supplemented by waves, reaching up to 8.5 m above sea level along the southerly-facing shallow Mississippi coast (see also C3.4.1). In New Orleans, the surge reached around 5 m, overtopping and breaching sections of the city's 4.5 m defences, flooding 70 to 80% of New Orleans, with 55% of the city's properties inundated by more than 1.2 m of water and maximum flood depths up to 6 m. In Louisiana 1,101 people died, nearly all related to flooding, concentrated among the poor and elderly.

Across the whole region, there were 1.75 million private insurance claims, costing in excess of US$40 billion (Hartwig, 2006), while total economic costs are projected to be significantly in excess of US$100 billion. Katrina also exhausted the federally-backed National Flood Insurance Program (Hunter,

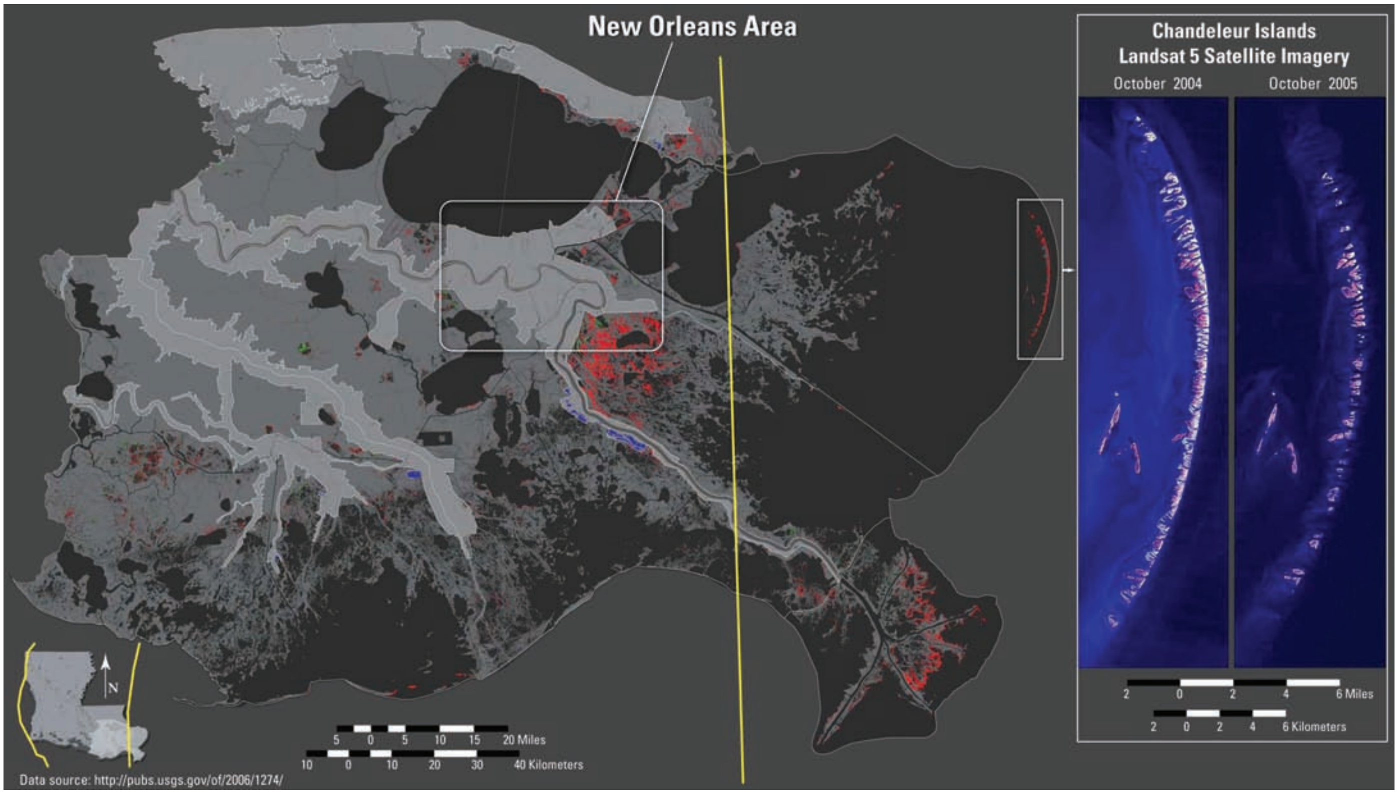

Figure C3.2. *The Mississippi delta, including the Chandeleur Islands. Areas in red were converted to open water during the hurricane. Yellow lines on index map of Louisiana show tracks of Hurricane Katrina on the right and Hurricane Rita on the left. (Figure source: U.S. Geological Survey, modified from Barras, 2006.)*

2006), which had to borrow US$20.8 billion from the Government to fund the Katrina residential flood claims. In New Orleans alone, while flooding of residential structures caused US$8 to 10 billion in losses, US$3 to 6 billion was uninsured. Of the flooded homes, 34,000 to 35,000 carried no flood insurance, including many that were not in a designated flood risk zone (Hartwig, 2006).

Beyond the locations directly affected by the storm, areas that hosted tens of thousands of evacuees had to provide shelter and schooling, while storm damage to the oil refineries and production facilities in the Gulf region raised highway vehicle fuel prices nationwide. Reconstruction costs have driven up the costs of building construction across the southern USA, and federal government funding for many programmes was reduced because of commitments to provide financial support for hurricane damage recovery. Six months after Katrina, it was estimated that the population of New Orleans was 155,000, with this number projected to rise to 272,000 by September 2008; 56% of its pre-Katrina level (McCarthy et al., 2006).

References

ACIA (Arctic Climate Impact Assessment), 2005: *Impacts of a Warming Arctic: Arctic Climate Impact Assessment*. Cambridge University Press, Cambridge, 140 pp.

Barras, J.A., 2006: Land area change in coastal Louisiana after the 2005 hurricanes: a series of three maps. U.S. Geological Survey Open-File Report 2006-1274. http://pubs.usgs.gov/of/2006/1274/.

Beltaos, S., T. Prowse, B. Bonsal, R. MacKay, L. Romolo, A. Pietroniro and B. Toth, 2006: Climatic effects on ice-jam flooding of the Peace–Athabasca Delta. *Hydrol. Process*., **20**, 4013-4050.

Coleman, J.M. and O.K. Huh, 2004: *Major World Deltas: A Perspective from Space*. Coastal Studies Institute, Louisiana State University, Baton Rouge, Louisiana. http://www.geol.lsu.edu/WDD/PUBLICATIONS/introduction.htm.

Dixon, T.H., F. Amelung, A. Ferretti, F. Novali, F. Rocca, R. Dokka, G. Sellall, S.-W. Kim, S. Wdowinski and D. Whitman, 2006: Subsidence and flooding in New Orleans. *Nature*, **441**, 587-588.

Du, B.L. and J.W. Zhang, 2000: Adaptation strategy for sea-level rise in vulnerable areas along China's coast. *Acta Oceanologica Sinica*, **19**, 1-16.

EFGC, 2006: *Envisioning the Future of the Gulf Coast: Final Report and Findings*. D. Reed, Ed., America's Wetland: Campaign to Save Coastal Louisiana, 11 pp.

Emanuel, K., 2005: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, **434**, 686-688.

Ericson, J.P., C.J. Vorosmarty, S.L. Dingman, L.G. Ward and M. Meybeck, 2006: Effective sea-level rise and deltas: causes of change and human dimension implications. *Global Planet. Change*, **50**, 63-82.

Graumann, A., T. Houston, J. Lawrimore, D. Levinson, N. Lott, S. McCown, S. Stephens and D. Wuertz, 2005: Hurricane Katrina: a climatological perpective. October 2005, updated August 2006. Technical Report 2005-01, NOAA National Climate Data Center, 28 pp. http://www.ncdc.noaa.gov/oa/reports/tech-report-200501z.pdf.

Hartwig, R., 2006: *Hurricane Season of 2005: Impacts on U.S. P/C Insurance Markets in 2006 and Beyond*. Presentation to the Insurance Information Institute, New York, 239 pp. http://www.iii.org/media/presentations/katrina/.

Hoanh, C.T., H. Guttman, P. Droogers and J. Aerts, 2004: Will we produce sufficient food under climate change? Mekong Basin (South-east Asia). *Climate Change in Contrasting River Basins: Adaptation Strategies for Water, Food, and Environment*, J.C.J.H. Aerts and P. Droogers, Eds., CABI Publishing, Wallingford, 157-180.

Hortle, K. and S. Bush, 2003: Consumption in the lower Mekong basin as a measure of fish yield. *New Approaches for the Improvement of Inland Capture Fish-*

ery Statistics in the Mekong Basin, T. Clayton, Ed., FAO RAP Publication 2003/01, Bangkok, 76-88.

Huang, Z.G. and W.Q. Zhang, 2004: Impacts of artificial factors on the evolution of geomorphology during recent 30 years in the Zhujiang Delta. *Quaternary Res.*, **24**, 394-401.

Hunter, J.R., 2006: *Testimony before the Committee on Banking, Housing and Urban Affairs of the United States Senate Regarding Proposals to Reform the National Flood Insurance Program*. Consumer Federation of America, 7 pp.

Inam, A., T.M. Ali Khan, A.R. Tabrez, S. Amjad, M. Danishb and S.M. Tabrez, 2003: Natural and man-made stresses on the stability of Indus deltaic Eco region. *Extended Abstract, 5th International Conference on Asian Marine Geology*, Bangkok, Thailand (IGCP475/APN).

IUCN (The World Conservation Union), 2003a: *Indus Delta, Pakistan: Economic Costs of Reduction in Freshwater Flows*. Case Studies in Wetland Valuation No. 5. Pakistan Country Office, Karachi, 6 pp. http://www.waterandnature.org/econ/CaseStudy05Indus.pdf.

IUCN (The World Conservation Union), 2003b: *The Lower Indus River: Balancing Development and Maintenance of Wetland Ecosystems and Dependent Livelihoods*. Water and Nature Initiative, 5 pp. http://www.iucn.org/themes/wani/flow/cases/Indus.pdf.

Jiang, H.T., 2005, Problems and discussion in the study of land subsidence in the Suzhou-Wuxi-Changzhou Area. *Quaternary Res.*, **25**, 29-33.

Kokelj, S.V. and C.R. Burn, 2005: Near-surface ground ice in sediments of the Mackenzie Delta, Northwest Territories, Canada. *Permafrost Periglac.*, **16**, 291-303.

Leont'yev, I.O., 2004: Coastal profile modelling along the Russian Arctic coast. *Coast. Eng.*, **51**, 779–794.

Lesack, L.F.W., P. Marsh and R.E. Hecky, 1998: Spatial and temporal dynamics of major solute chemistry along Mackenzie Delta lakes. *Limnol. Oceanogr.*, **43**, 1530-1543.

Li, C.X, D.D. Fan, B. Deng and V. Korotaev, 2004a: The coasts of China and issues of sea level rise. *J. Coastal Res.*, **43**, 36-47.

Li, C.X., S.Y. Yang, D.D. Fan and J. Zhao, 2004b: The change in Changjiang suspended load and its impact on the delta after completion of Three-Gorges Dam (in Chinese with English abstract). *Quaternary Sci.*, **24**, 495-500.

Li, J., J.Y. Zang, Y. Saito, X.W. Xu, Y.J. Wang, E. Matsumato and Z.Y. Zhang, 2005: Several cooling events over the Hong River Delta, Vietnam during the past 5000 years (in Chinese with English abstract). *Advances in Marine Science*, **23**, 43-53.

Macintosh, D., 2005: Asia, eastern, coastal ecology. *Encyclopedia of Coastal Science*, M. Schwartz, Ed., Springer, Dordrecht, 56-67.

Marsh, P. and L.F.W. Lesack, 1996: The hydrologic regime of perched lakes in the Mackenzie Delta: potential responses to climate change. *Limnol. Oceanogr.*, **41**, 849-856.

Marsh, P., L.F.W. Lesack and A. Roberts, 1999: Lake sedimentation in the Mackenzie Delta, NWT. *Hydrol. Process.*, **13**, 2519-2536.

McCarthy, K., D.J. Peterson, N. Sastry and M. Pollard, 2006: The repopulation of New Orleans after Hurricane Katrina. Technical Report, Santa Monica, RAND Gulf States Policy Institute, 59 pp.

Milliman, J.D. and R.H. Meade, 1983: World-wide delivery of river sediment to the oceans. *J. Geol.*, **90**, 1-21.

MRC, 2003: *State of the Basin Report: 2003*. Mekong River Commission, Phnom Penh, 300 pp.

Nguyen V.L., T.K.O. Ta and M. Tateishib, 2000: Late Holocene depositional environments and coastal evolution of the Mekong River Delta, Southern Vietnam. *J. Asian Earth Sci.*, **18**, 427-439.

Nicholls, R.J., 1995: Coastal mega-cities and climate change. *GeoJournal*, **37**, 369-379.

Nicholls, R.J., 2004: Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios. *Global Environ. Chang.*, **14**, 69-86.

Niou, Q.Y., 2002: *2001-2002 Report on Chinese Metropolitan Development* (in Chinese). Xiyuan Press, Beijing, 354 pp.

NOAA, 2007: *Billion Dollar U.S. Weather Disasters, 1980-2006*. http://www.ncdc.noaa.gov/oa/reports/billionz.html.

NRC, 2006: *Drawing Louisiana's New Map: Addressing Land Loss in Coastal Louisiana*. National Research Council, National Academy Press, Washington, District of Columbia, 204 pp.

Penland, S. and M.A. Kulp, 2005: Deltas. *Encyclopedia of Coastal Science*, M.L. Schwartz, Ed., Springer, Dordrecht, 362-368.

Prowse, T.D., D.L. Peters, S. Beltaos, A. Pietroniro, L. Romolo, J. Töyrä and R. Leconte, 2002: Restoring ice-jam floodwater to a drying delta ecosystem. *Water Int.*, **27**, 58-69.

Saito, Y., 2005: Mega-deltas in Asia: characteristics and human influences. *Mega-Deltas of Asia: Geological Evolution and Human Impact*, Z.Y. Chen, Y. Saito, S.L. Goodbred, Jr., Eds., China Ocean Press, Beijing, 1-8.

Sánchez-Arcilla, A., J.A. Jiménez and H.I. Valdemoro, 2007: A note on the vulnerability of deltaic coasts: application to the Ebro delta. *Managing Coastal Vulnerability: An Integrated Approach*, L. McFadden, R.J. Nicholls and E. Penning-Rowsell, Eds., Elsevier Science, Amsterdam, in press.

Sanlaville P. and A. Prieur, 2005: Asia, Middle East, coastal ecology and geomorphology. *Encyclopedia of Coastal Science*, M.L. Schwartz, Ed., Springer, Dordrecht, 71-83.

She, Z.X., 2004: Human–land interaction and socio-economic development, with special reference to the Changjiang Delta (in Chinese). *Proc. of the Xiangshan Symposium on Human–Land Coupling System of River Delta Regions: Past, Present and Future*, Beijing.

Shen, X.T., Z.C. Mao and J.R. Zhu, 2003: *Saltwater Intrusion in the Changjiang Estuary* (in Chinese). China Ocean Press, Beijing, 175 pp.

Shi, L.Q., J.F. Li, M. Ying, W.H. Li, S.L. Chen and G.A. Zhang, 2005: Advances in researches on the modern Huanghe Delta development and evolution. *Adv. Mar. Sci.*, **23**, 96-104.

Solomon, S.M., 2005: Spatial and temporal variability of shoreline change in the Beaufort-Mackenzie region, Northwest Territories, Canada. *Geo-Mar. Lett.*, **25**, 127-137.

Thanh, T.D., Y. Saito, D.V. Huy, V.L. Nguyen, T.K.O. Ta and M. Tateish, 2004: Regimes of human and climate impacts on coastal changes in Vietnam. *Reg. Environ. Change*, **4**, 49-62.

Walsh, J.E., O. Anisimov, J.O.M. Hagen, T. Jakobsson, J. Oerlemans, T.D. Prowse, V. Romanovsky, N. Savelieva, M. Serreze, I. Shiklomanov and S. Solomon, 2005: Cryosphere and hydrology. *Arctic Climate Impacts Assessment, ACIA*, C. Symon, L. Arris and B. Heal, Eds., Cambridge University Press, Cambridge, 183-242.

Wassmann, R., N.X. Hein, C.T. Hoanh and T.P. Tuong, 2004: Sea level rise affecting the Vietnamese Mekong Delta: water elevation in the flood season and implications for rice production. *Climatic Change*, **66**, 89-107.

Wolanski, E., 2007: Protective functions of coastal forests and trees against natural hazards: coastal protection in the aftermath of the Indian Ocean tsunami – what role for forests and trees? *Proc. of theFAO Regional Technical Workshop, Khao Lak, Thailand*, 28-31 August 2006. FAO, Bangkok.

Woodroffe, C.D., R.J. Nicholls, Y. Saito, Z. Chen and S.L. Goodbred, 2006: Landscape variability and the response of Asian megadeltas to environmental change. *Global Change and Integrated Coastal Management: The Asia-Pacific Region*, N. Harvey, Ed., Springer, New York, 277-314.

World Bank, 2004: *Modelled observations on development scenarios in the Lower Mekong Basin: Mekong Regional Water Resources Assistance Strategy*. Prepared for the World Bank with Mekong River Commission cooperation, Washington, District of Columbia and Vientiane, 142 pp. http://www.mrcmekong.org/free_download/report.htm.

C4. Indigenous knowledge for adaptation to climate change

C4.1 Overview

C4.1.1 Role of local and indigenous knowledge in adaptation and sustainability research (Chapter 20, Box 20.1)

Research on indigenous environmental knowledge has been undertaken in many countries, often in the context of understanding local oral histories and cultural attachment to place. A survey of research during the 1980s and early 1990s was produced by Johnson (1992). Reid et al. (2006) outline the many technical and social issues related to the intersection of different knowledge systems, and the challenge of linking the scales and contexts associated with these forms of knowledge. With the increased interest in climate change and global environmental change, recent studies have emerged that explore how indigenous knowledge can become part of a shared learning effort to address climate-change impacts and adaptation, and its links with sustainability. Some examples are indicated here.

Sutherland et al. (2005) describe a community-based vulnerability assessment in Samoa, addressing both future changes in climate-related exposure and future challenges for improving adaptive capacity. Twinomugisha (2005) describes the dangers of not considering local knowledge in dialogues on food security in Uganda.

A scenario-building exercise in Costa Rica has been undertaken as part of the Millennium Ecosystem Assessment (MA, 2005). This was a collaborative study in which indigenous communities and scientists developed common visions of future development. Two pilot 5-year storylines were constructed, incorporating aspects of coping with external drivers of development (Bennett and Zurek, 2006). Although this was not directly addressing climate change, it demonstrates the potential for joint scenario-building incorporating different forms of knowledge.

In Arctic Canada, traditional knowledge was used as part of an assessment which recognised the implications of climate change for the ecological integrity of a large freshwater delta (NRBS, 1996). In another case, an environmental assessment of a proposed mine was produced through a partnership with governments and indigenous peoples. Knowledge to facilitate sustainable development was identified as an explicit goal of the assessment, and climate-change impacts were listed as one of the long-term concerns for the region (WKSS, 2001).

Vlassova (2006) describes results of interviews with indigenous peoples of the Russian North on climate and environmental trends within the Russian boreal forest. Additional examples from the Arctic are described in ACIA (2005), Riedlinger and Berkes (2001), Krupnik and Jolly (2002), Furgal et al. (2006) and Chapter 15.

C4.2 Case studies

C4.2.1 Adaptation capacity of the South American highlands' pre-Colombian communities (Chapter 13, Box 13.2)

The subsistence of indigenous civilisations in the Americas relied on the resources cropped under the prevailing climate conditions around their settlements. In the highlands of today's Latin America, one of the most critical limitations affecting development was, and currently is, the irregular distribution of water. This situation is the result of the particularities of the atmospheric processes and extremes, the rapid runoff in the deep valleys, and the changing soil conditions. The tropical Andes' snowmelt was, and still is, a reliable source of water. However, the streams run into the valleys within bounded water courses, bringing water only to certain locations. Moreover, valleys and foothills outside of the Cordillera Blanca glaciers and extent of the snow cover, as well as the Altiplano, receive little or no melt-water at all. Therefore, in large areas, human activities depended on seasonal rainfall. Consequently, the pre-Colombian communities developed different adaptive actions to satisfy their requirements. Today, the problem of achieving the necessary balance between water availability and demand is practically the same, although the scale might be different.

Under such limitations, from today's Mexico to northern Chile and Argentina, the pre-Colombian civilisations developed the necessary capacity to adapt to the local environmental conditions. Such capacity involved their ability to solve some hydraulic problems and foresee climate variations and seasonal rain periods. On the engineering side, their developments included rainwater cropping, filtration and storage; the construction of surface and underground irrigation channels, including devices to measure the quantity of water stored (Figure C4.1) (Treacy, 1994; Wright and Valencia Zegarra, 2000; Caran and Nelly, 2006). They also were able to interconnect river basins from the Pacific and Atlantic watersheds, in the Cumbe valley and in Cajamarca (Burger, 1992).

Other capacities were developed to foresee climate variations and seasonal rain periods, to organise their sowing schedules and to programme their yields (Orlove et al., 2000). These efforts enabled the subsistence of communities which, at the peak of the Inca civilisation, included some 10 million people in what is today Peru and Ecuador.

Their engineering capacities also enabled the rectification of river courses, as in the case of the Urubamba River, and the building of bridges, either hanging ones or with pillars cast in the river bed. They also used running water for leisure and worship purposes, as seen today in the 'Baño del Inca' (the spa of the Incas), fed from geothermal sources, and the ruins of a musical garden at Tampumacchay in the vicinity of Cusco (Cortazar, 1968). The priests of the Chavin culture used running water

Figure C4.1. *Nasca (southern coast of Peru) system of water cropping for underground aqueducts and feeding the phreatic layers.*

flowing within tubes bored into the structure of the temples in order to produce a sound like the roar of a jaguar; the jaguar being one of their deities (Burger, 1992). Water was also used to cut stone blocks for construction. As seen in Ollantaytambo, on the way to Machu Picchu, these stones were cut in regular geometric shapes by leaking water into cleverly made interstices and freezing it during the Altiplano night, reaching below zero temperatures. They also acquired the capacity to forecast climate variations, such as those from El Niño (Canziani and Mata, 2004), enabling the most convenient and opportune organisation of their foodstuff production. In short, they developed pioneering efforts to adapt to adverse local conditions and define sustainable development paths.

Today, under the vagaries of weather and climate, exacerbated by the increasing greenhouse effect and the rapid retreat of the glaciers (Carey, 2005; Bradley et al., 2006), it would be extremely useful to revisit and update such adaptation measures. Education and training of present community members on the knowledge and technical abilities of their ancestors would be the way forward. ECLAC's procedures for the management of sustainable development (Dourojeanni, 2000), when considering the need to manage the extreme climate conditions in the highlands, refer back to the pre-Colombian irrigation strategies.

C4.2.2 African indigenous knowledge systems (Chapter 9, Section 9.6.2)

The term 'indigenous knowledge' is used to describe the knowledge systems developed by a community as opposed to the scientific knowledge that is generally referred to as 'modern' knowledge (Ajibade, 2003). Indigenous knowledge is the basis for local-level decision-making in many rural communities. It has value not only for the culture in which it evolves, but also for scientists and planners striving to improve conditions in rural localities. Incorporating indigenous knowledge into climate-change policies can lead to the development of effective adaptation strategies that are cost-effective, participatory and sustainable (Robinson and Herbert, 2001).

C4.2.2.1 Indigenous knowledge in weather forecasting

Local communities and farmers in Africa have developed intricate systems of gathering, predicting, interpreting and decision-making in relation to weather. A study in Nigeria, for example, shows that farmers are able to use knowledge of weather systems such as rainfall, thunderstorms, windstorms, harmattan (a dry dusty wind that blows along the north-west coast of Africa) and sunshine to prepare for future weather (Ajibade and Shokemi, 2003). Indigenous methods of weather forecasting are known to complement farmers' planning activities in Nigeria. A similar study in Burkina Faso showed that farmers' forecasting knowledge encompasses shared and selective experiences. Elderly male farmers formulate hypotheses about seasonal rainfall by observing natural phenomena, while cultural and ritual specialists draw predictions from divination, visions or dreams (Roncoli et al., 2001). The most widely relied-upon indicators are the timing, intensity and duration of cold temperatures during the early part of the dry season (November to January). Other forecasting indicators include the timing of fruiting by certain local trees, the water level in streams and ponds, the nesting behaviour of small quail-like birds, and insect behaviour in rubbish heaps outside compound walls (Roncoli et al., 2001).

C4.2.2.2 Indigenous knowledge in mitigation and adaptation

African communities and farmers have always coped with changing environments. They have the knowledge and practices to cope with adverse environments and shocks. The enhancement of indigenous capacity is a key to the empowerment of local communities and their effective participation in the development process (Leautier, 2004). People are better able to adopt new ideas when these can be seen in the context of existing practices. A study in Zimbabwe observed that farmers' willingness to use seasonal climate forecasts increased when the forecasts were presented in conjunction with and compared with the local indigenous climate forecasts (Patt and Gwata, 2002).

Local farmers in several parts of Africa have been known to conserve carbon in soils through the use of zero-tilling practices in cultivation, mulching, and other soil-management techniques (Dea and Scoones, 2003). Natural mulches moderate soil temperatures and extremes, suppress diseases and harmful pests, and conserve soil moisture. The widespread use of indigenous plant materials, such as agrochemicals to combat pests that normally attack food crops, has also been reported among small-scale farmers (Gana, 2003). It is likely that climate change will alter the ecology of disease vectors, and such indigenous practices of pest management would be useful adaptation strategies. Other indigenous strategies that are adopted by local farmers include: controlled bush clearing; using tall grasses such as *Andropogon gayanus* for fixing soil-surface nutrients washed away by runoff; erosion-control bunding to significantly reduce the effects of runoff; restoring lands by using green manure; constructing stone dykes; managing low-lying lands and protecting river banks (AGRHYMET, 2004).

Adaptation strategies that are applied by pastoralists in times of drought include the use of emergency fodder, culling of weak livestock for food, and multi-species composition of herds to survive climate extremes. During drought periods, pastoralists and agro-pastoralists change from cattle to sheep and goat husbandry, as the feed requirements of the latter are lower (Seo and Mendelsohn, 2006). The pastoralists' nomadic mobility reduces the pressure on low-capacity grazing areas through their cyclic movements from the dry northern areas to the wetter southern areas of the Sahel.

African women are particularly known to possess indigenous knowledge which helps to maintain household food security, particularly in times of drought and famine. They often rely on indigenous plants that are more tolerant to droughts and pests, providing a reserve for extended periods of economic hardship (Ramphele, 2004; Eriksen, 2005). In southern Sudan, for example, women are directly responsible for the selection of all sorghum seeds saved for planting each year. They preserve a spread of varieties of seeds that will ensure resistance to the range of conditions that may arise in any given growing season (Easton and Roland, 2000).

C4.2.3 Traditional knowledge for adaptation among Arctic peoples (Chapter 15, Section 15.6.1)

Among Arctic peoples, the selection pressures for the evolution of an effective knowledge base have been exceptionally strong, driven by the need to survive off highly variable natural resources in the remote, harsh Arctic environment. In response, they have developed a strong knowledge base concerning weather, snow and ice conditions as they relate to hunting and travel, and natural resource availability (Krupnik and Jolly, 2002). These systems of knowledge, belief and practice have been developed through experience and culturally transmitted among members and across generations (Huntington, 1998; Berkes, 1999). This Arctic indigenous knowledge offers detailed information that adds to conventional science and environmental observations, as well as to a holistic understanding of environment, natural resources and culture (Huntington et al., 2004). There is an increasing awareness of the value of Arctic indigenous knowledge and a growing collaborative effort to document it. In addition, this knowledge is an invaluable basis for developing adaptation and natural resource management strategies in response to environmental and other forms of change. Finally, local knowledge is essential for understanding the effects of climate change on indigenous communities (Riedlinger and Berkes, 2001; Krupnik and Jolly, 2002) and how, for example, some communities have absorbed change through flexibility in traditional hunting, fishing and gathering practices.

The generation and application of this knowledge is evidenced in the ability of Inuit hunters to navigate new travel and hunting routes despite decreasing ice stability and safety (e.g., Lafortune et al., 2004); in the ability of many indigenous groups to locate and hunt species such as geese and caribou that have shifted their migration times and routes and to begin to locate and hunt alternative species moving into the region (e.g., Krupnik and Jolly, 2002; Nickels et al., 2002; Huntington et al., 2005); the ability to detect safe sea ice and weather conditions in an environment with increasingly uncharacteristic weather (George et al., 2004); or the knowledge and skills required to hunt marine species in open water later in the year under different sea-ice conditions (Community of Arctic Bay, 2005).

Although Arctic peoples show great resilience and adaptability, some traditional responses to environmental change have already been compromised by recent socio-political changes. Their ability to cope with substantial climatic change in future, without a fundamental threat to their cultures and lifestyles, cannot be considered as unlimited. The generation and application of traditional knowledge requires active engagement with the environment, close social networks in communities, and respect for and recognition of the value of this form of knowledge and understanding. Current social, economic and cultural trends, in some communities and predominantly among younger generations, towards a more western lifestyle has the potential to erode the cycle of traditional knowledge generation and transfer, and hence its contribution to adaptive capacity.

C4.2.4 Adaptation to health impacts of climate change among indigenous populations (Chapter 8, Box 8.6)

A series of workshops organised by the national Inuit organisation in Canada, Inuit Tapiriit Kantami, documented climate-related changes and impacts, and identified and developed potential adaptation measures for local response (Furgal et al., 2002a, b; Nickels et al., 2003). The strong engagement of Inuit community residents will facilitate the successful adoption of the adaptation measures identified, such as using netting and screens on windows and house entrances to prevent bites from mosquitoes and other insects that have become more prevalent.

Another example is a study of the links between malaria and agriculture that included participation and input from a farming community in Mwea division, Kenya (Mutero et al., 2004). The approach facilitated identification of opportunities for long-term malaria control in irrigated rice-growing areas through the integration of agro-ecosystem practices aimed at sustaining livestock systems within a broader strategy for rural development.

References

ACIA (Arctic Climate Impact Assessment), 2005: *Arctic Climate Impact Assessment*. Cambridge University Press, Cambridge, 1042 pp.

AGRHYMET, 2004: Rapport synthèse de l'enquête générale sur les itinéraires d'adaptation des populations locales à la variabilité et aux changements climatiques conduite sur les projets pilotes par AGRHYMET et l'UQAM, par Hubert N'Djafa Ouaga, 13 pp.

Ajibade, L.T., 2003: A methodology for the collection and evaluation of farmers' indigenous environmental knowledge in developing countries. *Indilinga: African Journal of Indigenous Knowledge Systems*, **2**, 99-113.

Ajibade, L.T. and O. Shokemi, 2003: Indigenous approaches to weather forecasting in Asa L.G.A., Kwara State, Nigeria. *Indilinga: African Journal of Indigenous Knowledge Systems*, **2**, 37-44.

Bennett, E. and M. Zurek, 2006: Integrating epistemologies through scenarios. *Bridging Scales and Knowledge Systems*, W.V. Reid, F. Berkes, T. Wilbanks and D. Capistrano, Eds., Island Press, Washington, District of Columbia, 264-280.

Berkes, F., 1999: *Sacred Ecology: Traditional Ecological Knowledge and Resource Management*. Taylor and Francis, London, 232 pp.

Bradley, R.S., M. Vuille, H. Diaz and W. Vergara, 2006: Threats to water supplies in the tropical Andes. *Science*, **312**, 1755-1756.

Burger, R.L., 1992: *Chavin and the Origins of Andean Civilization*. Thames and Hudson, London, 240 pp.

Canziani, O.F. and L.J. Mata, 2004: The fate of indigenous communities under climate change. UNFCCC workshop on impacts of, and vulnerability and adaptation to, climate change. *Tenth Session of the Conference of Parties (COP-10)*, Buenos Aires, 3 pp.

Caran, S.C. and J.A. Nelly, 2006: Hydraulic engineering in prehistoric Mexico. *Sci. Am. Mag*., **October**, 8 pp.

Carey, M., 2005: Living and dying with glaciers: people's historical vulnerability to avalanches and outburst floods in Peru. *Global Planet. Change*, **47**, 122-134.

Community of Arctic Bay, 2005: *Inuit Observations on Climate and Environmental Change: Perspectives from Arctic Bay, Nunavut*. ITK, Nasivvik, NAHO, NTI, Ottawa, 57 pp.

Cortazar, P.F., 1968: Documental del Perú, Departamento del Cusco, IOPPE S.A. Eds., February 1968.

Dea, D. and I. Scoones, 2003: Networks of knowledge: how farmers and scientists understand soils and their fertility: a case study from Ethiopia. *Oxford Development Studies*, **31**, 461-478.

Dourojeanni, A., 2000: *Procedimientos de Gestión para el Desarrollo Sustentable*. ECLAC, Santiago, 376 pp.

Easton, P. and M. Roland, 2000: Seeds of life: women and agricultural biodiversity in Africa. IK Notes 23. World Bank, Washington, District of Columbia, 4 pp.

Eriksen, S., 2005: The role of indigenous plants in household adaptation to climate change: the Kenyan experience. *Climate Change and Africa*, P.S Low, Ed., Cambridge University Press, Cambridge, 248-259.

Furgal, C., D. Martin and P. Gosselin, 2002a: Climate change in Nunavik and Labrador: lessons from Inuit knowledge. *The Earth is Faster Now: Indigenous Observations on Arctic Environmental Change,* I. Krupnik and D. Jolly, Eds., ARCUS, Washington, District of Columbia, 266-300.

Furgal, C.M., D. Martin, P. Gosselin, A. Viau, Nunavik Regional Board of Health and Social Services (NRBHSS) and Labrador Inuit Association (LIA), 2002b: *Climate Change in Lunavik and Labrador: What we Know from Science and Inuit Ecological Knowledge*. Final report prepared for Climate Change Action Fund, WHO/PAHO Collaborating Center on Environmental and Occupational Health Impact Assessment and Surveillance, Centre Hospitalier Universitaire de Quebec (CHUQ), Beauport, Quebec, 141 pp.

Furgal, C.M., C. Fletcher and C. Dickson, 2006: Ways of knowing and understanding: towards the convergence of traditional and scientific understanding of climate change in the Canadian North. Environment Canada, No. KM467-05-6213, 96 pp.

Gana, F.S., 2003: The usage of indigenous plant materials among small-scale farmers in Niger state agricultural development project: Nigeria. *Indilinga: African Journal of Indigenous Knowledge Systems*, **2**, 53-60.

George, J.C., H.P. Huntington, K. Brewster, H. Eicken, D.W. Norton and R. Glenn, 2004: Observations on shorefast ice dynamics in arctic Alaska and the responses of the Inupiat hunting community. *Arctic*, **57**, 363-374.

Huntington, H., 1998: Observations on the utility of the semi-directive interview for documenting traditional ecological knowledge. *Arctic*, **51**, 237-242.

Huntington, H., T.V. Callaghan, S. Fox and I. Krupnik, 2004: Matching traditional and scientific observations to detect environmental change: a discussion on arctic terrestrial ecosystems. *Ambio*, **33**(S13), 18-23.

Huntington, H., S. Fox and Co-authors, 2005: The changing Arctic: indigenous perspectives. *Arctic Climate Impact Assessment*, C. Symon, L. Arris and B. Heal, Eds., Cambridge University Press, Cambridge, 61-98.

Johnson, M., Ed., 1992: *Lore: Capturing Traditional Environmental Knowledge*. Dene Cultural Institute, Hay River, and International Development Research Centre, Ottawa, 190 pp.

Krupnik, I. and D. Jolly, Eds., 2002: *The Earth is Faster Now: Indigenous Observations of Arctic Environmental Change*. Arctic Research Consortium of the United States, Fairbanks, 384 pp.

Lafortune, V., C. Furgal, J. Drouin, T. Annanack, N. Einish, B. Etidloie, M. Qiisiq, P. Tookalook and co-authors, 2004: Climate change in northern Québec: access to land and resource issues. Project report. Kativik Regional Government, Kuujjuaq, Québec.

Leautier, F., 2004: Indigenous capacity enhancement: developing community knowledge. *Indigenous Knowledge: Local Pathways to Global Development*. The World Bank, Washington, District of Columbia, 4-8.

MA (Millennium Ecosystem Assessment), 2005: *Ecosystems and Human Well-Being: Synthesis*. Island Press, Washington, District of Columbia, 155 pp.

Mutero, C.M., C. Kabutha, V. Kimani, L. Kabuage, G. Gitau, J. Ssennyonga, J. Githure, L. Muthami, A. Kaida, L. Musyoka, E. Kiarie and M. Oganda, 2004: A transdisciplinary perspective on the links between malaria and agroecosystems in Kenya. *Acta Trop*., **89**, 171-186.

Nickels, S., C. Furgal, J. Castelden, P. Moss-Davies, M. Buell, B. Armstrong, D. Dillon and R. Fonger, 2002: Putting the human face on climate change through community workshops. *The Earth is Faster Now: Indigenous Observations of Arctic Environmental Change*, I. Krupnik and D. Jolly, Eds., ARCUS, Washington, District of Columbia, 300-344.

Nickels, S., C. Furgal and J. Castleden, 2003: Putting the human face on climate change through community workshops: Inuit knowledge, partnerships and research. *The Earth is Faster Now: Indigenous Observations of Arctic Environmental Change*, I. Krupnik and D. Jolly, Eds., Arctic Studies Centre, Smithsonian Institution, Washington, District of Columbia, 300-344.

NRBS (Northern River Basins Study Board), 1996: *Northern River Basins Study*. Report to the Ministers 1996. Alberta Environmental Protection, Edmonton, Alberta, 287 pp. http://www3.gov.ab.ca/env/water/nrbs/index.html.

Orlove, B.S., J.C.H. Chiang and M.A. Cane, 2000: Forecasting Andean rainfall and crop yield from the influence of El Niño on Pleiades visibility. *Nature*, **403**, 68-71.

Patt, A. and C. Gwata, 2002: Effective seasonal climate forecast applications: examining constraints for subsistence farmers in Zimbabwe. *Global Environ. Chang.,* **12**, 185-195.

Ramphele, M., 2004: Women's indigenous knowledge: building bridges between the traditional and the modern. *Indigenous Knowledge: Local Pathways to Development*, The World Bank, Washington, District of Columbia, 13-17.

Reid, W.V., F. Berkes, T. Wilbanks and D. Capistrano, Eds., 2006: *Bridging Scales and Knowledge Systems*. Island Press, Washington, District of Columbia, 314 pp.

Riedlinger, D. and F. Berkes, 2001: Contributions of traditional knowledge to understanding climate change in the Canadian Arctic. *Polar Rec*., **37**, 315-328.

Robinson, J.B. and D. Herbert, 2001: Integrating climate change and sustainable

development. *Int. J. Global Environ.*, **1**, 130-149.
Roncoli, C., K. Ingram and P. Kirshen, 2001: The costs and risks of coping with drought: livelihood impacts and farmers' responses in Burkina Faso. *Climate Res.*, **19**, 119-132.
Seo, S.N. and R. Mendelsohn, 2006: Climate change adaptation in Africa: a microeconomic analysis of livestock choice. Centre for Environmental Economics and Policy in Africa (CEEPA) Discussion Paper No.19, University of Pretoria, Pretoria, 37 pp.
Sutherland, K., B. Smit, V. Wulf and T. Nakalevu, 2005: Vulnerability in Samoa. *Tiempo*, **54**, 11-15.
Treacy, J.M., 1994: *Las Chacras de Coparaque: Andenes y Riego en el Valle de Colca*. Instituto de Estudios Peruanos, Lima, 298 pp.
Twinomugisha, B., 2005: Indigenous adaptation. *Tiempo*, **57**, 6-8.
Vlassova, T.K., 2006: Arctic residents' observations and human impact assessments in understanding environmental changes in boreal forests: Russian experience and circumpolar perspectives. *Mitigation and Adaptation Strategies for Global Change*, **11**, 897-909.
WKSS (West Kitikmeot/Slave Study Society), 2001: West Kitikmeot/Slave Study Society Final Report. West Kitikmeot/Slave Study Society, Yellowknife, Canada, 87 pp. http://www.wkss.nt.ca/index.htm.
Wright, K.R. and A. Valencia Zegarra, 2000: *Machu Picchu: A Civil Engineering Marvel*. American Society of Civil Engineers Press, Virginia, 144 pp.