NATIONAL AFFAIRS

Australia

Legal and Political Aspects of Iron Fertilisation in the Southern Ocean: Implications of Australian Involvement[1]

by Julia Jabour Green*

Introduction

CO_2 sequestration in the deep oceans is a natural process and the Southern Ocean is the world's major atmospheric CO_2 reservoir. Recently, small-scale open-ocean iron fertilisation experiments were conducted in selected high nutrient low chlorophyll-a (HNLC) areas to verify the 'iron hypothesis'.[2] In the process, it was discovered that there might be a potentially beneficial dual application for iron fertilisation. The research found that fertilisation enhanced the natural sequestration process by promoting phytoplankton biomass – one critical component of the biological pump which intrinsically draws down atmospheric CO_2 to the deep ocean during the photosynthetic process. In addition, it was thought that the resulting phytoplankton bloom might, under optimum circumstances, increase oceanic biological productivity by proving a richer food source throughout all trophic levels. However, the science should be treated with caution because it is new, complex and also to a certain degree contentious.[3] Neither its efficacy nor its consequences regarding CO_2 sequestration or enhanced productivity are well understood.

This article reviews what little is known about the process so far and makes some observations about the likely legal and political aspects that would need to be addressed should the science evolve into commercial activity.

The carbon problem

The global community has reacted strongly to the steadily rising level of atmospheric CO_2 and, despite scientific uncertainty, a framework law was drafted in 1992 – the United Nations Framework Convention on Climate Change (FCCC).[4] The FCCC, to which Australia is a signatory, encourages all governments to achieve *stabilisation of greenhouse gas emissions* at acceptable levels,[5] specifically those of the base year 1990. Individual state sovereignty, economic but sustainable development and reduction of emissions are guiding principles within FCCC.[6] It asks Parties to promote, *inter alia*, enhancement of *natural* sinks and reservoirs, including the oceans and marine ecosystems, where appropriate.[7] It is egalitarian in its approach to what is clearly a global problem and it is the primary source of Australia's international legal obligations in this respect.

The FCCC provides for annexes and protocols to be attached to the parent document that supply further details as information becomes available.[8] The 1997 Kyoto Protocol[9] to the FCCC, while not specifically mentioning oceans, asks the Parties to protect and enhance carbon sinks and reservoirs, and to research, promote, develop and increase the use of sequestration technologies.[10]

Australia signed the Kyoto Protocol in 1998 but remains undecided about ratification, primarily because of economic concerns in view of the fact that developing countries are not included in Annex I of the FCCC.[11] Annex I, together with Article 25 of the Protocol, prescribes whose ratification is essential for the Protocol to enter into force.[12] Australia has also argued that without ratification by the United States, there is no point; consequently, despite a total of 74 ratifications to date, the Protocol is not yet in force.

However, should Australia decide to ratify, as a Party listed in Annexes I and II it could participate in international carbon trading on the basis of its CO_2 emission reduction or sequestration activities carried out during the fulfilment of its commitments under FCCC and subsequent protocols. These so-called *carbon credits* are defined as 'emission reduction units' in the Kyoto Protocol.[13] A Party (Australia, for example) may authorise a legal entity (an Australian company, for example) to participate, under its responsibility, in emission reduction units trading and – providing other obligations are also met – credits may be obtained by either reducing emissions or enhancing removal by sinks.[14]

The Kyoto Protocol deals only with land use practices, but this does not undermine the importance of primary obligations regarding oceans contained in Article 4 of the FCCC. Ocean use governance, however, is complex and includes a number of international instruments that directly affect regulation of Southern Ocean iron fertilisation.

The marine resources problem

The world's oceans are a rich source of living and non-living resources, a major trading and transport route, a fundamental scientific laboratory, places of great beauty and leisure, and one of the key drivers of global climate. There are substantial legal frameworks in place that deal

* Post-doctoral Fellow, Institute of Antarctic & Southern Ocean Studies, University of Tasmania. e.mail: julia.green@utas.edu.au.

0378-777X/01/$12.00 © 2002 IOS Press

with all of these aspects broadly (e.g. the UN Convention on the Law of the Sea) and more specifically (e.g. the Convention on the Conservation of Antarctic Marine Living Resources).

The sustainability of marine living resources, for example, is a significant concern to governments worldwide as they strive at international, regional, national and local levels to construct effective ocean use management strategies. However their record to date is not impressive. The UN FAO reports that:

> *Among the major marine fish stocks or groups of stocks for which information is available … About 47 to 50 per cent of stocks are fully exploited and are, therefore, producing catches that have either reached or are very close to their maximum limits, with no room expected for further expansion. Another 15 to 18 per cent are over-exploited and have no potential for further increase.*[15]

In terms of fisheries alone, any process that results in enhancing biological productivity and enriching the oceans with one of the world's favourite food resources would be warmly welcomed.

The right to use the world's oceans is a fundamental freedom enshrined in the UN Convention on the Law of the Sea (LOSC[16]). However, rights have concomitant duties and environmental protection is one such fundamental obligation. Activities (intentional or accidental) that are not environmentally benign risk unacceptable consequences ranging from the transient, through cumulative to the catastrophic (e.g. pollution from land-based sources, ecosystem alterations through over-fishing, illegal activity such as deliberate dumping of toxic substances).

The Southern Ocean iron fertilisation experiments are currently considered data-collecting scientific activities – sanctioned through Part XIII of LOSC. But *where* these activities take place, *how, using what substance, for what reason* and *by whom* will matter in the future if, for example, carbon credits are to be sought or fishing rights claimed under commercial arrangements.

Southern Ocean iron fertilisation – key issues

There are six key issues to be addressed with regard to the political and legal aspects of open-ocean iron fertilisation in the Southern Ocean:

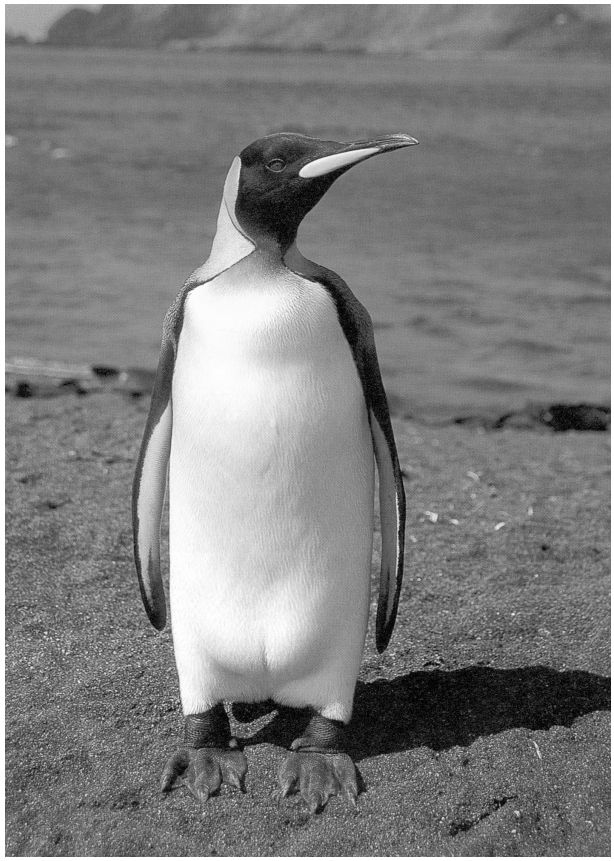
1. substance
2. action
3. intention
4. consequences
5. location
6. jurisdiction

These variables are critically interdependent and the legal and political scenario may at times be contingent upon the intercourse between all six.

1. Substance

The composition of the substance used in the open-ocean iron fertilisation experiments is important because it will have a bearing on legal rights and obligations. There are international legal restrictions on what can be put into the ocean. Substances which may be permitted under the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (LC72) and its 1996 Protocol,[17] for example, and to which Australia is a signatory, include the categories described as:

1 dredged material;
2 sewage sludge;
3 fish waste, or material resulting from industrial fish processing operations;
4 vessels and platforms or other man-made structures at sea;
5 inert, inorganic geological material;



King penguin, Australia — Courtesy: Heide Schlicht for EH Foundation

6 organic material of natural origin; and
7 bulky items primarily comprising iron, steel, concrete and similarly unharmful materials for which the concern is physical impact, and limited to those circumstances where such wastes are generated at locations, such as small islands with isolated communities, having no practicable access to disposal options other.[18]

The placement of all other substances into the ocean is prohibited. The substances used in the experiments mentioned earlier have been mixtures of iron or ferrous sulphate and seawater. These compounds have not differed

0378-777X/01/$12.00 © 2002 IOS Press

significantly in any of the four individual research projects. Initial assessment suggests that they would not accord with the categories permitted under LC72/Protocol, shown above. The open-ocean fertilisation substances may, therefore, contravene LC72/Protocol (when the Protocol enters into force).

Two mitigating factors could, however, be the nature of the action being undertaken and the intention of this action.

2. Action

The action of open-ocean iron fertilisation has differed in minor technical respects among the four individual research projects already undertaken. However, the significant point is whether the action would be considered 'dumping' or scientific research. According to LC72/Protocol, 'dumping' does *not* include:

> *… placement of matter for a purpose other than the mere disposal thereof, provided that such placement is not contrary to the aims of this Protocol.*[19]

The aims of the Protocol are stated to be that:

> *Contracting Parties shall individually and collectively protect and preserve the marine environment from all sources of pollution and take effective measures, according to their scientific, technical and economic capabilities, to prevent, reduce and where practicable eliminate pollution caused by dumping or incineration at sea of wastes or other matter. Where appropriate, they shall harmonise their policies in this regard.*[20]

In other words, if matter is placed in the ocean for reasons other than for disposal (say, for scientific research) and that placement did not constitute 'pollution' then the action may be permissible. Both the LOSC (Article 1) and LC72/Protocol define 'pollution' similarly:

> *… the introduction, directly or indirectly, by human activity, of wastes or other matter into the sea which results or is likely to result in such deleterious effects as harm to living resources and marine ecosystems, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of seawater and reduction of amenities*.[21]

Unfortunately there is no qualification of the terms 'other matter' or 'harm … to living resources and marine ecosystems' to assist here with interpretation. Clearly, unless the ecological consequences of open-ocean fertilisation are understood to be benign, it is difficult to be specific about whether or not the action could constitute pollution *per se*. It must be noted, however, that there are general obligations on all Parties to act in a precautionary manner in the absence of scientific 'certainty' and to do nothing which could cause transboundary environmental harm. Specifically, under LC72/Protocol, the Parties:

> *… shall apply a precautionary approach to environmental protection from dumping of wastes or other matter whereby appropriate preventative measures are taken when there is reason to believe that wastes or other matter introduced into the marine environment are likely to cause harm even when there is no conclusive evidence to prove a causal relation between inputs and their effects. In implementing the provisions of this Protocol, Contracting Parties shall act so as not to transfer, directly or indirectly, damage or likelihood of damage from one part of the environment to another or transform one type of pollution into another*.[22]

A strict application of these principles would seem to indicate that if there were any likelihood that the substance, in combination with the action, could cause environmental harm, the activity would not be permissible under the terms of the LC72/Protocol. This interpretation would be confirmed during the environmental evaluation process that occurs prior to a responsible state authority issuing a permit for the action.

A third possible mitigating factor linked to both the substance and the action may be the intention of the activity.

3. Intention

The intention of past open-ocean iron fertilisation experiments has been to gather scientific data to test the 'iron hypothesis'[23] and in fact the LOSC (to which Australia is a Party), expressly permits and encourages marine scientific research (Part XIII). Such activities, however, must comply with all relevant provisions and the spirit of the LOSC, including the protection and preservation of the marine environment.[24]

Furthermore, the LC72/Protocol does not make a distinction between scientific data-gathering and other intentions, except with regard to the definition of 'dumping' noted above. In all other respects there would appear to be little difference between a scientific experiment and any other intention carried out in the same manner using the same substance. It is likely that the commercialisation of this activity will make no difference in the context of its lawfulness under LC72/Protocol, for example. Even if the intention changes from pure scientific research to an action taken for the purposes of sequestering carbon to be traded as a commodity, neither the status of the substance nor the action will change significantly. Therefore, if the substance is prohibited, and/or the action is considered 'pollution' then the lawfulness of the activity is most likely to be judged on these variables alone.

Intention may not play a substantial part in the legal scenario but it will be of greater significance in social debate about potential commercial applications of ocean fertilisation – carbon sequestration or fish harvesting – especially when located in the 'pristine' Southern Ocean. Further insight might be gained by examining the action in combination with the substance to assess the possibilities of unacceptable outcomes. The consequences will help shape public opinion as well as invoke legal obligations. ➳

0378-777X/01/$12.00 © 2002 IOS Press

4. Consequences

Known

The known consequences of the scientific experiments conducted to date have been that:

- iron enrichment of some HNLC oceanic areas promotes phytoplankton growth through the provision of an additional nutrient (specifically iron) that was previously deficient in the natural environment (i.e. part of the iron hypothesis has been tested and proven); and that
- an amount of carbon is sequestered to the deep ocean as a result of increased photosynthesis by phytoplankton.[25]

Unknown

The unknown consequences of these experiments relate primarily to possible ecological/environmental effects of the artificially accelerated growth of phytoplankton. Such enhancement would clearly be the result of anthropogenic interference with a natural process, and how this interference might impact on the marine ecosystem is not yet clear. It is possible that long-term, cumulative or transboundary effects may occur. Further research is required to clarify the unknown but potential consequences because it will at some stage be necessary to make informed judgements about the political, legal and scientific acceptability of such action.

Various instruments in international law deal in both generic and specific terms with the marine environment. As previously noted, the primary objective of the original LC72 (and further strengthened by its 1996 Protocol) is to protect and preserve the marine environment from pollution. This article argues that both the action of, and the substance used in, open-ocean iron fertilisation experiments may constitute 'pollution' under LC72/Protocol. Significantly too, LC72/Protocol compels parties to act in a precautionary manner in the face of scientific uncertainty – an approach that is gaining increased favour in international environmental law. Scientists argue that 'certainty' is a misleading concept but, of course, it *is* possible to evaluate risk and often this is what the law seeks in relation to the regulation of precarious behaviour.

The LOSC, too, imposes general obligations on all States to protect and preserve the marine environment and to prevent, reduce or control pollution.[26] While it permits and encourages scientific research, LOSC clearly compels States to accept responsibility and liability for pollution of the marine environment.[27] If the action and the substance are deemed unacceptable under LC72/Protocol, they are also likely to contravene the spirit and intent of LOSC.

A further factor relating to the unknown consequences of iron fertilisation is its efficacy. For example, because it is not known exactly how much carbon will be sequestered, for how long, or how efficiently, the question of the

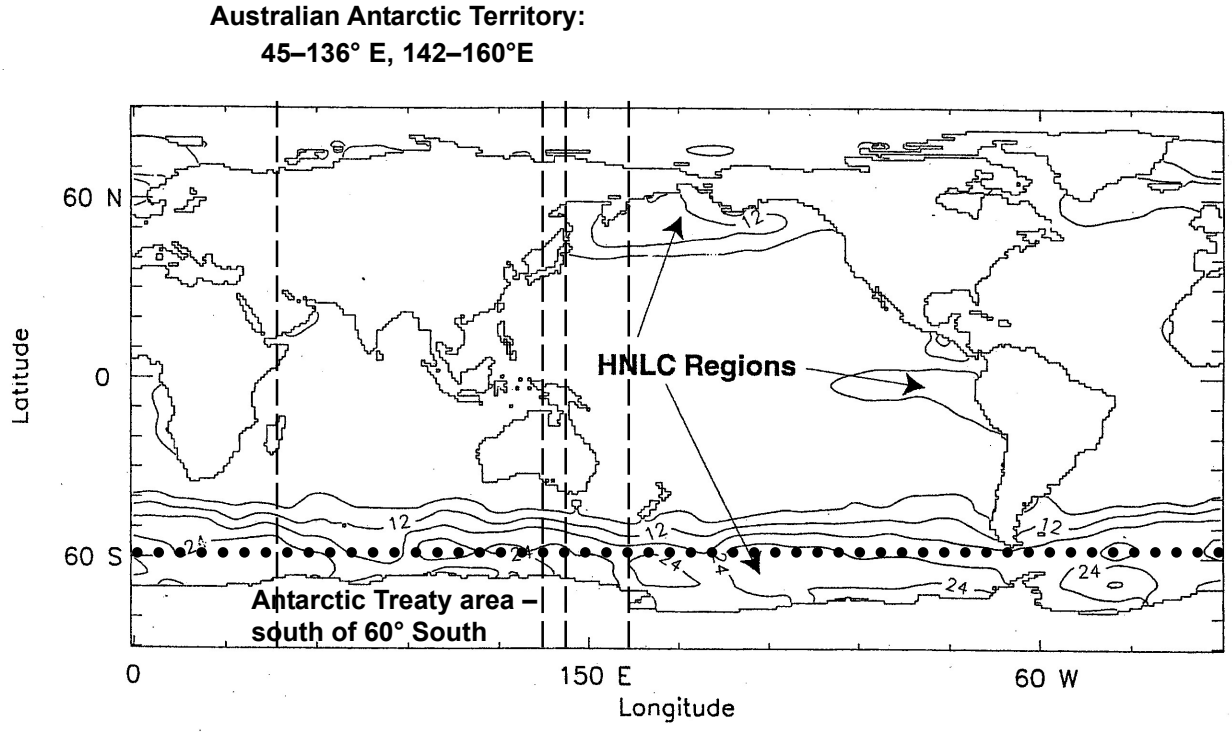


Figure 1: Map of nitrate concentrations at 25m from Levitus *et al.* (1993) showing the HNLC regions. Additional lines of latitude and longitude not to scale.

0378-777X/01/$12.00 © 2002 IOS Press

overall net benefit of artificially enhanced ocean sequestration is difficult to answer. Clearly, more scientific research is required before this can be determined.

Unknown consequences on the marine environment and the poorly understood efficacy of sequestration therefore make the legal and political arguments less well defined. What can be discerned, however, is the role that both the location of the activity and the nationality of the proponents play in jurisdictional issues.

5. Location

Open-ocean iron fertilisation experiments have been carried out in areas of HNLC concentrations (see Figure 1). The most suitable regions of the Southern Ocean for iron fertilisation are south of 55º South in maritime space considered by some to be 'high seas'. This designation invokes rights and obligations derived from several international legal instruments: in addition to the general obligations to protect and preserve the marine environment derived from LOSC and LC72/Protocol as discussed above, Antarctic-specific legal instruments are involved because HNLC areas extend south of 60º South, coinciding with the area of application of the Antarctic Treaty.[28] These include, but are not restricted to, the Treaty, its 1991 Protocol on Environmental Protection (Madrid Protocol),[29] and the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR).[30]

The 1959 Antarctic Treaty gives Parties rights to make decisions for the good governance of the Treaty Area, that is, the region south of 60° South.[31] The 45 Parties to the Treaty (including Australia) must also heed the instructions contained within the 1991 Madrid Protocol to the Treaty. The Protocol, with the same area of application as the Treaty, requires the Parties to commit themselves to:

… the comprehensive protection of the Antarctic environment and dependent and associated ecosystems.[32]

Almost all research activities in the Antarctic area are permitted on the grounds that scientific research has priority. With the entry into force of the Madrid Protocol in 1998, however, greater restrictions were placed on research by the requirement to conduct environmental impact assessment (EIA) prior to an activity being undertaken. If open-ocean iron fertilisation experiments are conducted in the Southern Ocean south of 60° South, EIA of the activities is required. This obligation is implemented through the domestic legislation of Parties to the Madrid Protocol, including Australia.

The Protocol, through its Article 8 and Annex 1, prescribes three levels of environmental evaluation, corresponding with three likely levels of impact. These are a preliminary assessment (PA) and where there is predicted to be a *less than minor or transitory impact*, no further action is required. If, however, a greater risk is indicated, an Initial Environmental Evaluation (IEE) is required; if the determination is a *minor or transitory impact* only, the activity can still proceed. Progressively more information is required with each level of assessment, and greater restrictions may come into play. The highest level of assessment, a Comprehensive Environmental Evaluation (CEE), ensures that significant activities with the potential to cause *more than a minor or transitory impact* are scrutinised (publicly as well as through the formal Antarctic Treaty meeting processes), evaluated and either accepted, modified or rejected on merit.

In addition, the marine living resources convention, CCAMLR, applies to, *inter alia*, '… all … species of living organisms' found within its area of application, that is south of the Antarctic Convergence (now commonly referred to as the Antarctic Polar Front).[33] Activities must conform with CCAMLR's conservation principles, especially those embodied in Article II.3(b) regarding 'maintenance of the ecological relationships between harvested, dependent and related populations of Antarctic marine living resources.' CCAMLR is a free-standing instrument of international law, historically attached to the Antarctic Treaty, but with an independent Secretariat. Adherence to CCAMLR conservation principles is implemented through the domestic legislation of signatory states (including Australia).

A further complication, as Figure 1 indicates, is that HNLC areas suitable for fertilisation are also located within Australia's Antarctic Territory EEZ, proclaimed in 1994 just prior to the entry into force of LOSC. It is widely recognised that seven claims to Antarctic territory have existed since before the entry into force of the Antarctic Treaty. However, these claims are not widely accepted, as is the prerogative of any state in international law. This situation has transpired because the Treaty's Article IV states that the territorial claims – along with the right to make claims – remain *status quo ante* and that nothing shall affect this situation during the life of the Treaty. Clearly, *where* the action takes place is of significant importance in determining jurisdiction.

6. Jurisdiction

In 1994 Australia gazetted a 200 nm Exclusive Economic Zone (EEZ) seaward from the coastline of its continent and external territories, including the Australian Antarctic Territory (AAT). If iron fertilisation experiments are conducted by Australian nationals, or are located in waters under the jurisdiction of the Commonwealth of Australia, requirements of Australian law must be met. It is likely that as well as an EIA, the proponents will require a permit. These obligations derive from, *inter alia*, the *Antarctic Marine Living Resources Conservation Act* (1981) (AMLRC Act, Commonwealth) which implements CCAMLR and the new, overarching *Environmental Protection and Biodiversity Conservation Act* (1999) (EPBC Act, Commonwealth).

It could be argued that Australian nationals involved in open-ocean fertilisation experiments anywhere in the Southern Ocean south of the CCAMLR area would require a permit under section 9.1(b) of the *AMLRC Act* because of the likelihood that phytoplankton (classified as 'Antarctic marine living resources') will be 'interfered with'. Various levels of perceived environmental impact will require different environmental evaluations, but finally a decision to permit an activity to proceed, or other-

0378-777X/01/$12.00 © 2002 IOS Press

wise, will be based on the best estimate of environmental consequences.

The *EPBC Act* provides a basis for the Minister to decide whether an action that has, will have, or is likely to have a significant impact on certain aspects of the environment, should proceed. It does so by prohibiting a person from taking an action without the Minister having given approval or decided that approval is not needed.[34] Under Subdivision F – Marine Environment section 23 there is a requirement for approval of activities involving the marine environment in Commonwealth marine areas. Commonwealth marine areas include the Australian EEZ off the AAT and waters over the continental shelf zone.[35] This section contains a prohibition on activities that have, will have or are likely to have a significant impact on the environment.[36]

Courtesy: GEO 3

Conclusion

The activity of open-ocean fertilisation for the purposes of carbon sequestration or enhanced fish stock biomass is not dealt with directly by any of the legal instruments mentioned in this article, nor within the broader range of both national and international law relevant but not specifically evaluated here. Nor does the activity of ocean fertilisation directly address the global problem of reducing CO_2 emissions at their source or the gross over-capitalisation and over-exploitation of marine living resources. In fact, it raises many more questions than it answers.

What can be concluded is that if open-ocean fertilisation experiments in the Southern Ocean HNLC regions are proven to induce adverse effects in the marine ecosystem, the process will be thought of as politically difficult to sustain, legally indefensible and socially unacceptable by the broader Australian community. The oceans are considered sacrosanct; while their carrying capacity for sequestered carbon is thought to be limitless, to interfere with natural oceanic processes without being certain of either the efficacy or the consequences of the science is risky, to say the least.

Because Australia has not yet ratified the Kyoto Protocol and the modalities of carbon credit trading have not been finalised, the issues are largely academic at this stage. It is likely, therefore, that the legal and political aspects will develop in parallel with the scientific and technological ones.

Notes:

1 This unpublished article was originally presented to the Australian Academy of Technological Sciences and Engineering 2001 Symposium 'Looking South – Managing Technology, Opportunities and the Global Environment', 20–21 November 2001, Hobart, Tasmania. The author wishes to thank Professor Aynsley Kellow, School of Government, University of Tasmania and Professor Stuart Kaye, School of Law, James Cook University, Cairns, for their comments and suggestions on an early version of this article. The responsibility for errors remains with the author.

2 Four recent open-ocean iron fertilisation experiments are IronEx I and IronEx II conducted in the equatorial Pacific and SOIREE and EisenEx in the Southern Oceans. For a simple explanation of some of this research see 'The role of iron as a Micro-nutrient', Chapter 3 in C.S. Wong and Shuichiro Hirai (1997) 'Ocean Storage of Carbon Dioxide: A Review of Oceanic Carbonate and CO_2 Hydrate Chemistry'. IEA Greenhouse Gas R&D Programme, Cheltenham, UK.

3 See, for example, Sallie W. Chisholm, Paul G. Falkowski, John J. Cullen 'Dis-Crediting Ocean Fertilisation' *Science* 294: 309–10 (12 October 2001).

4 United Nations Conference on Environment and Development: Framework Convention on Climate Change, 9 May 1992. Hereinafter FCCC. Available at: www.unfccc.de/resource/conv/index.html.

5 FCCC Article 2.

6 FCCC Preamble and Article 4.1(d).

7 FCCC Article 4.2(a).

8 FCCC Article 4.2(d).

9 An introduction to the Kyoto Protocol and a downloadable PDF version are available at www.unfccc.de/resource/protintr.html.

10 Kyoto Protocol Articles 2(ii) and 2(iv).

11 See ABC News Online Report of 05.06.02: 'Federal Government delays Kyoto consideration, Japan signs' at www.abc.net.au/news/2002/06/item20020605000444_1.htm.

12 Information on the number of ratifications and accessions to the Protocol can be found at www.unfccc.de/resource/kpstats.pdf.

13 Kyoto Protocol Article 6.1.

14 Kyoto Protocol Articles 6.3, 6.1(a) and 6.1(c).

15 FAO: www.fao.org/DOCREP/003/X8002E/x8002e04.htm.

16 United Nations Convention on the Law of the Sea (LOSC). The full text of the Convention is available at www.un.org/Depts/los/convention_agreements/texts/unclos/closindx.htm.

17 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1972). Known variously as the London Convention or LC72. The full text and interpretation of LC72 is available at www.londonconvention.org. The Parties negotiated a Protocol in 1996 that will eventually replace LC72. Downloadable comparative PDF versions of the text of LC72 and the Protocol are available from the above URL.

18 LC72 Protocol Annex 1 Article 1.

19 LC72 Protocol Article 1.4.2.2.

20 LC72 Protocol Article 2.

21 LC72 Protocol Article 1.10.

22 LC72 Protocol Articles 3.1 and 3.3.

23 The simplified version of the so-called 'iron hypothesis' is that, according to Martin (1990, 1992) 'iron availability limits the growth of phytoplankton in HNLC waters around the world'. Quoted in Wong and Hirai (1997) p. 29. A second part of the hypothesis is that CO_2 is delivered to the deep ocean via the enhanced biological processes.

24 See LOSC Part XIII generally and Article 240.

25 See Chapter 3 generally in Wong and Hirai.

26 See LOSC Part XII generally for rights and duties regarding protection and preservation of the marine environment.

27 LOSC, especially Article 235. With regard to the right to conduct marine scientific research in the water column outside an exclusive economic zone (EEZ), see Article 257. The specific responsibilities and liabilities associated with this are articulated in Article 263.3.

28 Antarctic Treaty, done in Washington on 01 December 1959, entered into force 23 June 1961, reprinted in 402 UNTS 71 (1959)

29 'Madrid Protocol', done in Madrid on 04 October 1991, *reprinted in* 30 ILM 1455 (1991). Annex IV of the Protocol invokes the International Convention for the Prevention of Pollution from Ships (1973) and its Protocol of 1978 – known as MARPOL 73/78. Links on the following URL will provide a complete overview of the role of MARPOL 73/78 in global ocean protection from pollution: www.imo.org/Environment/mainframe.asp?topic_id=197.

30 CCAMLR, done in Canberra on 20 May 1980, entered into force 07 April 1982, reprinted in 19 ILM 827 (1980).

31 Antarctic Treaty, Articles IX and VI.

32 Madrid Protocol, Article 2.

33 For the scope and coordinates of the CCAMLR area of application, see Article 1.

34 EPBC Act section 11.

35 EPBC Act section 24 defines Commonwealth marine areas.

36 EPBC Act section 23.

MAP REFERENCE:

Levitus S., Conkright M.E., Reid J.L., Najjar R.G. and Mantyla A. (1993) 'Distribution of nitrate, phosphate and silicate in the world oceans' in *Progress in Oceanography* 31(3): 245–273.

0378-777X/01/$12.00 © 2002 IOS Press