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Developing a test-bed for robust research governance of geoengineering: the contribution of ocean iron biogeochemistry

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Geoengineering to mitigate climate change has long been proposed, but remains nebulous. Exploration of the feasibility of geoengineering first requires the development of research governance to move beyond the conceptual towards scientifically designed pilot studies. Fortuitously, 12 mesoscale (approx. 1000 km^2) iron enrichments, funded to investigate how ocean iron biogeochemistry altered Earth's carbon cycle in the geological past, provide proxies to better understand the benefits and drawbacks of geoengineering. The utility of these iron enrichments in the geoengineering debate is enhanced by the GEOTRACES global survey. Here, we outline how GEOTRACES surveys and process studies can provide invaluable insights into geoengineering. Surveys inform key unknowns including the regional influence and magnitude of modes of iron supply, and stimulate iron biogeochemical modelling. These advances will enable quantification of interannual variability of iron supply to assess whether any future purposeful multi-year iron-fertilization meets the principle of 'additionality' (*sensu* Kyoto protocol). Process studies address issues including upscaling of geoengineering, and how differing iron-enrichment strategies could stimulate wide-ranging biogeochemical outcomes. In summary, the availability of databases on both mesoscale iron-enrichment studies and the GEOTRACES survey, along

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with modelling, policy initiatives and legislation have positioned the iron-enrichment approach as a robust multifaceted test-bed to assess proposed research into climate intervention.

This article is part of the themed issue 'Biological and climatic impacts of ocean trace element chemistry'.

1. Introduction

Growing recognition of the potential of geoengineering approaches as a tool to mitigate the effects of anthropogenic CO_2 emissions, and the consequent warming of the planet, has taken place in the last two decades [1–4]. This debate has most recently focused on defining the main characteristics, unknowns and differences between the two main modes of climate intervention—carbon dioxide removal (CDR) and solar radiation management (SRM) [3]. CDR approaches, which include ocean iron fertilization, are viewed as long-term (years to decades) relatively slow, lower risk, climate mitigation tools, relative to those for SRM methods (see summary table in [5]).

In the last decade, the following facets of geoengineering have been explored—policy [6,7], legislation [8,9], economics [10] and societal outreach and perceptions of geoengineering [11]. There have also been proof-of-concept advances [12], several proof-of-concept tests (ocean pipes, [13]) and targeted modelling within the geoengineering model intercomparison project (GEOMIP, [14,15]). Such a timeline of geoengineering components for ocean iron fertilization is detailed in table 1, which also includes the lifetime of the GEOTRACES global survey of trace elements and their isotopes [16]. It is evident from table 1 that in spite of advances in our understanding of the many components that need to be fleshed out in the geoengineering debate, there has been little agreement on research governance (i.e. the integration of research quality, ethics, safety, risk assessment and outreach) for geoengineering (for the wider debate, see http://geoengineering-governance-research.org/the-oxford-principles.php).

At present, there is an impasse on research into this topic for CDR approaches such as ocean iron fertilization owing to the implementation of a de facto moratorium by the United Nations (UN) Convention on Biodiversity (CBD) [8], and also the introduction of more specific legislation by the International Maritime Organization (IMO) [9] following a controversial iron-fertilization of waters in NE Pacific waters by a commercial venture [18]. In the case of SRM approaches to climate intervention [19], progress is also unlikely for research governance owing to issues regarding the controversial outcome of a planned SRM pilot study (stratospheric particle injection for climate engineering [20]). The latter has probably hindered developments in the research governance of stratospheric geoengineering.

Despite this hiatus, there has been a groundswell of support for more detailed scientific-based study into these issues [21,22]. Moreover, the recently released US National Academy of Sciences (NAS) report [5] has advocated: 'However, if society ultimately decides to intervene in Earth's climate, the Committee most strongly recommends any such actions be informed by a far more substantive body of scientific research—encompassing climate science and economic, political, ethical, and other dimensions—than is available at present'. Here, we explore the contention that the intense scrutiny that has been given to many aspects of ocean iron fertilization—from critiques [23–27], to the availability of datasets on 12 mesoscale scientific studies [28], and now allied with the step-wise increase in our understanding of the oceanic iron cycle from GEOTRACES [29]—means that iron fertilization represents a rich and multifaceted database, unprecedented in the field of geoengineering, to help guide the development of geoengineering research governance.

2. Ocean geoengineering—status and wider issues

Ocean approaches are mainly CDR and include nutrient or iron fertilization, induced upwelling using ocean pipes, or the alkalinization of sea water [3,30]. A sole SRM approach, cloud whitening

Table 1. A collation of the range of activities that have centred on ocean iron fertilization and geoengineering in the last decade. GEOTRACES commenced in 2007 [16]. Solid circles denote significant events, and the numbers refer to the reference list, such as (under 'legislation') the UN Convention on Biodiversity de facto moratorium in 2008 [8], and the updated International Maritime Organization (IMO) [9] regulations to include ocean iron fertilization in 2013. Note, no officially recognized ocean iron fertilization geoengineering pilot studies have been sanctioned over this period, nor has there been any agreement on research governance [17]. (Online version in colour.)

GEOTRACES →

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
synthesis		40		3			4	28,56		
experiments				88						
modelling		90			42					59
'pilots'										
policy					98					
legislation			8					9		
outreach							11			

[31–33], proposes to use seawater to derive submicrometre droplets needed to alter the reflectivity of marine clouds. The provenance of these geoengineering approaches range from new ideas such as the ocean pipes [34], that require further discussion [35] and initial validation [13,36] before being considered further, through to well-established concepts such as iron fertilization (table 1). For example, the latter has a series of historical precedents [37–39], has used the findings from 12 mesoscale (i.e. 1000 km^2) scientific studies into the links between changing ocean iron supply and the ocean carbon cycle [40], and also gained insights into issues such as artefacts and deleterious side effects [28,41,42].

Broadly speaking, the CDR approaches can be divided into geochemical, for example those which propose to alter ocean carbonate chemistry, from local to global scales, by shifting alkalinity [30,43,44], and those which advocate a biogeochemical approach by purposefully adding nutrients to the ocean including iron. These CDR approaches have been considered recently within a broader portfolio of geoengineering methods by the US NAS [5] and the IPCC [4], and more specifically by the International Geosphere Biosphere Programme (IGBP) in a review of the potential ecological effects of different geoengineering approaches [45].

3. Synthesis of iron-fertilization effects on climate mitigation: insights and knowledge gaps for geoengineering

In comparison with other geoengineering approaches, such as stratospheric geoengineering [19] or ocean alkalization [43], there is a relatively diverse and rich literature on iron fertilization. These publications span both the science of our understanding of how the iron biogeochemical cycle influences the ocean carbon cycle—from the geological past—to present-day ocean productivity [40,46,47], but also extrapolate these findings, via modelling simulations [42,48–50], in response to claims that iron enrichment could significantly mitigate atmospheric anthropogenic CO_2 loading [51,52]. This in-depth discussion on the role that iron could play in climate mitigation commenced as early as 1991 [53] and has resulted in a vigorous debate thereafter [23,26,27,54]. The debate has also been extended to include ethical, policy and commercial aspects [6,7,10,24,55].

The policy and legislative issues surrounding ocean iron fertilization have been informed more indirectly; a series of other events have been running in parallel with this debate. First, the controversy surrounding the Lohafex scientific research voyage revealed the opacity of some of the fledgling ocean policy legislation that had been introduced by both UN CBD (de facto moratorium) and the IMO to pierce the policy vacuum on this topic [8]. Second, the impromptu unlawful iron fertilization in the waters off Haida Gwaii (northeast Pacific) led to a more detailed debate on governance and regulations needed to prevent such events taking place on the high seas [18]. This has helped to develop the current stance advocated by an influential scientific journal that 'research into climate engineering must proceed—even if it turns out to be unnecessary' [21].

4. Assessing the role of GEOTRACES in informing the geoengineering debate

A review of the 12 mesoscale purposeful ocean enrichment scientific studies, along with those at naturally occurring high-iron open-ocean sites such as Crozet [40], provides a useful point of departure to appraise the contribution of the GEOTRACES global survey to this debate. Boyd *et al.* [40] targeted three central issues around the interplay between ocean iron enrichment and the ocean carbon cycle that require more research to enhance our understanding

— macronutrient use and ecosystem responses,
— modes of Fe supply and
— coupling of Fe–C biogeochemical cycles.

For each of these issues, they put forward the following hypotheses:

(1) The magnitude and stoichiometry of macronutrient and Fe supply to high-nutrient, low-chlorophyll (HNLC) surface waters will both determine whether natural blooms are transient or sustained.
(2) The magnitude of Fe available to the biota will be determined by the mode of Fe supply and in particular by the subsequent mobilization and retention of this Fe by upper-ocean processes.
(3) The relative importance of the processes that set particulate Fe/C ratios and their controlling factors will vary both regionally and seasonally.

The aims of this study are first to assess how the various components of the GEOTRACES programme—survey lines and process studies—advance these three hypotheses; second, with this additional knowledge and insights can we further refine these hypotheses and transform them into new research questions and third, how does our new understanding of the global iron cycle add to the existing body of knowledge (that by necessity we will briefly review here) and assist us to better assess the challenges and benefits of ocean geoengineering using iron fertilization. We commence by synthesizing recent scientific findings since Boyd *et al.* [40] on the role that iron fertilization could play in ocean geoengineering, then step through the key findings of GEOTRACES survey and process studies to address each of our aims.

5. Status of ocean iron fertilization and the geoengineering debate

The cessation of mesoscale iron enrichment experiments following the Lohafex 'incident' in 2008 [8] has resulted in the debate regarding the suitability of ocean iron fertilization as a geoengineering approach to be advanced in three distinct ways. First, through a retrospective examination of some of the datasets from the 12 mesoscale ocean iron-enrichments [28] and naturally fertilized blooms [56–58]; second, via targeted CDR modelling experiments [42,50,59] and third, from insights gained on the fate of surface ocean carbon at depth during naturally occurring bloom events (often iron-mediated, [60]) and their impact on the oceans' biological pump [60–62].

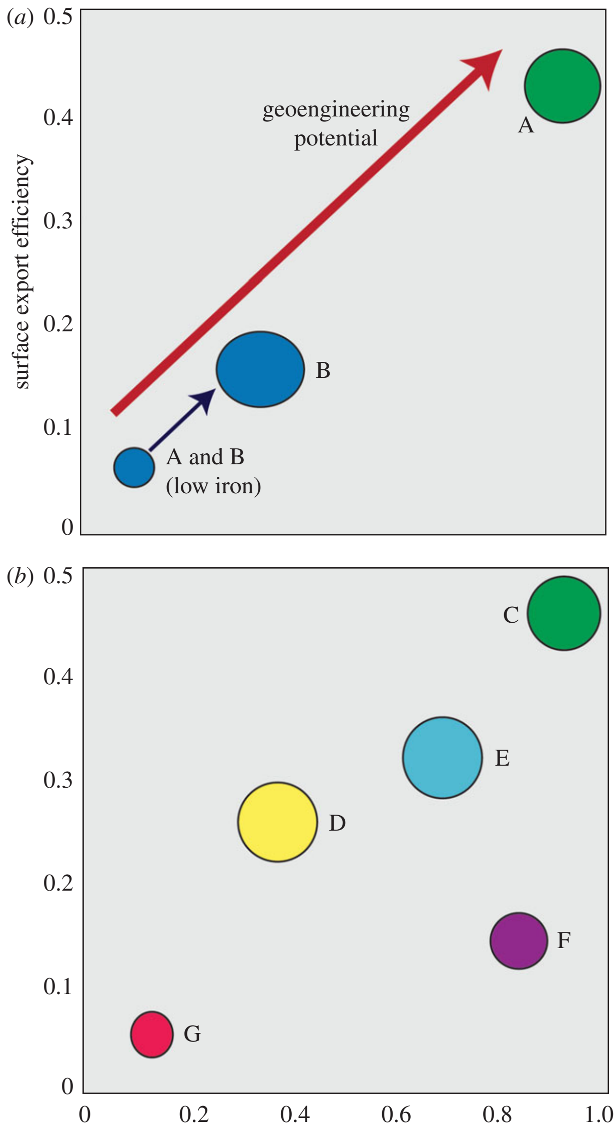

Figure 1. Comparison of the efficiency with which phytoplankton carbon is exported from surface waters (surface export efficiency, as a proportion of primary production, after [65]), and then through subsurface waters (as a proportion of surface export, after [65]) for: (*a*) iron-enrichments (A, Southern Ocean EiFex study [64]); B, North Pacific SERIES study [63]; 'A and B low iron' = export under ambient low iron conditions at each site). (*b*) Naturally occurring diatom blooms at various sites across the global ocean (C, northeast Atlantic; D,E, open Southern Ocean; F, coastal Southern Ocean, (C–E from [65]; F from [66]) cross-referenced with export efficiency from low iron waters (G = [63]). The area of each circle is proportional to primary production at each site.

Re-examination of the subset of mesoscale iron enrichment experiments that resulted in sustained measurements of changes to ocean export reveal two distinct trends for the SERIES [63] 2004 and EIFEX [64] studies that are shown in figure 1. The diatom bloom that resulted from the Southern Ocean EIFEX study was a relatively efficient (based on metrics formulated in [65]) conduit for iron-mediated carbon sequestration into the oceans' interior. In contrast, the SERIES experiment was a relatively inefficient pathway of iron-enhanced carbon export to depth. Together, these two findings suggest that a wide range of responses to iron-driven export might occur. Although they are a small dataset, they encompass the wide range of efficiencies of surface export and subsurface C sequestration observed for naturally occurring blooms in the northeast Atlantic and Southern Oceans (figure 1*b*). It is well established that a wide range of individual factors and their interplay probably set the export efficiency from blooms, including 'seed stock' of phytoplankton versus that of grazers, and the stoichiometry of nutrient : iron supply [40]. Hence, the disparate outcomes of the mesoscale iron enrichments highlighted in figure 1*a* probably reflect 'end-members' for bloom export efficiency as observed across different ocean regions [65].

Modelling studies, on iron fertilization specifically [50] or on CDR geoengineering in general [59], point to the importance of both timescales and basin-scale characteristics of physical circulation in delaying the mitigation of climate change through CDR approaches, and the sequestration efficiency of iron fertilization, respectively. The US National Academy of Sciences (NAS) [5] report on CDR also advocated the need for multiple year deployments of CDR approaches and a long-term (decades) return, in terms of C sequestration, from this approach. If ocean geoengineering requires a decadal scale CDR campaign to be able to mitigate rising CO_2 levels, how does this influence the design of further research into iron fertilization? Regional-specific issues such as circulation [50] and the wide spatial range of the export efficiency of blooms (figure 1) raise issues about the best regions to conduct further research into iron fertilization. Moreover, how typical are iron fertilization experiments conducted in 1 year or season (owing to often subtle shifts in conditions, or seed stocks, see the SEEDS I and II NW Pacific iron-enrichments [40] for example), of a multi-year CDR campaign? These are some additional issues, over and above the three hypotheses put forward in Boyd *et al.* [40] that require addressing.

6. GEOTRACES surveys—revealing new pathways for iron supply

The potential need for a multidecadal CDR campaign such as for iron fertilization would result in a sustained addition of iron to the ocean, with many unknowns (such the indirect effect of acidification from remineralized carbon [41,67] on iron bioavailability) regarding the fate of this 'anthropogenic' iron, or its impact on the ocean iron cycle. GEOTRACES is providing a framework of regional survey lines with which to assess the iron cycle in unprecedented detail. Such scrutiny will provide the baseline (akin to that from the GEOSECS or CLIVAR programmes) with which to assess interannual variability (for example using moored sensors (MITESS, [68]) repeat sections (GO-SHIP, www.go-ship.org/) or satellite-derived proxies [69]) in the ocean's iron cycle.

These assessments will be invaluable in appraising how iron biogeochemistry will be altered as ocean conditions are influenced by climate change. For example, any increases in the upper-ocean iron inventory [70] that boosted biological CO_2 drawdown [40], via increased supply and/or bioavailability, could offset the principle of 'additionality' (a concept central to the Kyoto protocol [71] but which did not apply to the oceans under this protocol) of purposeful iron fertilization. Additionality is defined in 3/CMP.1, Annex, paragraph 43 as follows: 'A CDM (i.e. akin to CDR) project activity is additional if anthropogenic emissions of greenhouse gases by sources are reduced below those that would have occurred in the absence of the registered CDM project activity. In other words, additionality is the requirement that the greenhouse gas emissions after implementation of a CDM project activity are lower than those that would have occurred in the most plausible alternative scenario to the implementation of the CDM project activity'.

The survey lines conducted zonally and meridionally across ocean basins have resulted in an exponential increase in dissolved and particulate iron datasets, and also major increases in iron-binding ligand datasets [72]. The availability of an open access intermediate data product (IDP) makes these data collation widely available [73]. Examination of the IDP, and the associated publications, reveals a wide range of high-resolution features (figure 2) which provide insights that help to address some of the hypotheses in [40] and moreover raise additional issues not previously considered. For example, the widespread availability of paired dissolved iron and nutrient data along survey lines, can readily be linked to archives of satellite ocean colour to begin to explore the validity of the assertion in [40] that 'The magnitude & stoichiometry of macronutrient & Fe supply to HNLC surface waters will both determine whether natural blooms are transient or sustained'.

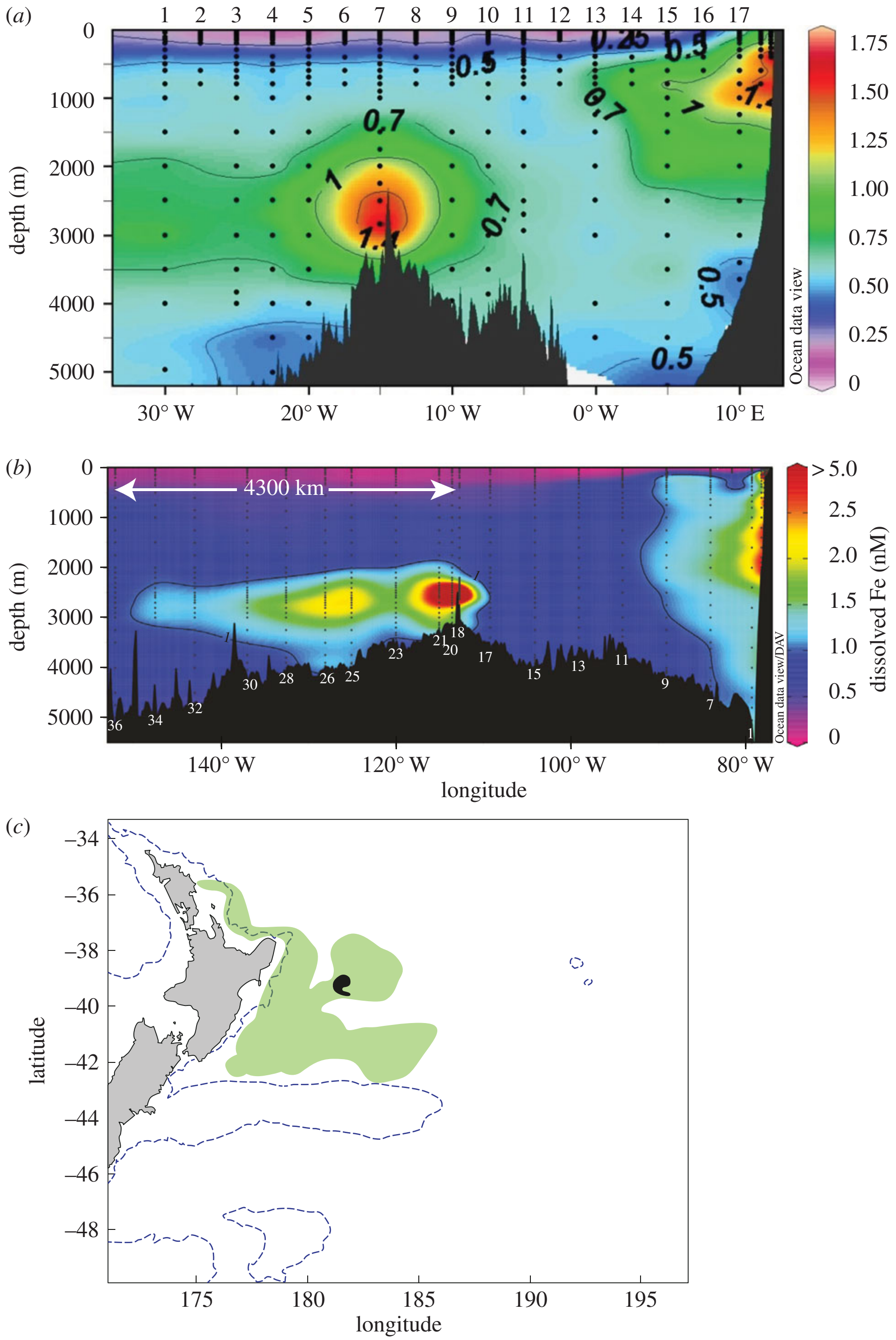

Figure 2. Examples from GEOTRACES of detailed mapping of a range of source mechanisms for the supply of new iron. Panels (*a*) and (*b*) reveal hydrothermal 'bull's-eyes' along oceanic ridges in the Atlantic [74] and Pacific [75] basins. (*c*) The likely trajectories (green lines) of offshore transport of high-iron coastal waters into an offshore eddy feature (denoted by black feature centred on approx. 39 S and approx. 179 W [76]).

GEOTRACES is also providing a new appreciation of other modes of iron supply—such as hydrothermal [74,75]—and their geographical sphere of influence at the basin scale and beyond (figure 2*b*). Furthermore, there is a growing appreciation that iron supply mechanisms alone will

Table 2. A summary of modes of iron supply to the ocean (modified from [69]). Climate change will alter significantly the magnitude of some (such as those linked to the cryosphere) but not all (for example hydrothermal supply or island wakes) of these supply terms. The GEOTRACES project is helping to better define the magnitude of these terms, regionally (figure 2) and globally (modelling, FeMIP, [29]).

Fe supply	source	nature of supply
aerosol	atmosphere	seasonal/episodic
upwelling	deep ocean	continuous
diffusive	subsurface waters	continuous
sedimentary	lateral	continuous
ice melt	surface	seasonal
iceberg drift	surface	seasonal
hydrothermal	deep ocean	continuous
island wake	lateral and vertical	continuous
eddy transport	lateral	semi-continuous
bathymetric	deep ocean	continuous

not necessarily deliver iron to the upper ocean, and hence the hypothesis [40] that 'the magnitude of Fe available to the biota will be determined by the mode of Fe supply and in particular by the subsequent mobilization and retention of this Fe by upper-ocean processes' requires refinement. For example, iron supply requires other 'carriers' such as ligands and/or buoyancy to stabilize and/or enhance the long distance supply of iron to the upper ocean [69,75,77].

The GEOTRACES survey lines, together with datasets on iron stable isotopes [78] help to establish unequivocally the provenance of iron supply. Moreover, these IDP datasets help with the identification of regions, such as the Western South Atlantic [69] in which multiple sources of iron (aerosol, eddies, sedimentary) are present, which may buffer regional primary productivity from interannual variability (or climate-change-mediated shifts) in iron supply from individual mechanisms. Consideration of the different permutations of iron supply mechanisms (and their associated 'carriers') should improve our understanding of the relationship between modes of iron supply (table 2) and the range of phytoplankton responses, that are evident from figure 1.

The collation of iron supply mechanisms in table 2 helps to inform how each of these sources will be altered in the future (see discussion in [70]). For example, some will be modified by ocean global change—such as the cryosphere in the Southern Ocean—which plays a key role in the interplay of the iron and carbon cycles [39], and hence is probably the main area being considered for ocean iron fertilization. In contrast, other modes of iron supply such as hydrothermal [74] are unlikely to change unless there is a major reorganization of deep ocean circulation [77].

The global GEOTRACES survey contains additional datasets, such as on iron binding ligands [79] and biological measurements (from phytoplankton pigments to metallo-proteomics, http://www.geotraces.org/science/biological-parameters) that will also be of value when assessing the suitability of a particular region, such as the Southern Ocean or northwest Pacific, as a test-bed to explore ocean geoengineering. Such biological datasets will in the future enable a better demarcation of provinces where productivity is controlled by iron limitation versus co-limitation (by iron and other environmental factors) which is invaluable information for any provincial assessment of ocean geoengineering. The Saito *et al.* [80] study provides a snapshot of the type of datasets that will increasingly become available through GEOTRACES (with plans to include such biological datasets in the next IDP, see website), and which begin to provide compelling links with some of the GEOTRACES process studies. Together, these approaches will enhance our understanding of the range of responses, across ocean regions to iron fertilization.

A further major contribution of the GEOTRACES survey that will have important implications for future assessment of the efficacy of ocean geoengineering is their value as a validation dataset for modellers. GEOTRACES has been a catalyst for global modelling simulations, resulting in the recent FeMIP model intercomparison study [29] which compared the outputs from 13 global ocean biogeochemistry models with GEOTRACES-derived iron distributions. Wide-ranging simulated iron distributions were evident from FeMIP, and the more sophisticated models that incorporated multiple iron sources and (rudimentary) recycling pathways did better than less complex parametrizations [29]. Significantly, in the context of geoengineering, FeMIP also cautioned against placing too much confidence on model runs, customized to explore the effects of large-scale ocean iron fertilization, from the current suite of iron biogeochemistry models.

7. GEOTRACES process studies—assessing the fate of biological iron uptake

The GEOTRACES survey lines have been complemented by a smaller number of process studies to target particular locales such as oxygen minimum zones (see http://www.geotraces.org/science/cruise-overview/process-studies); to further investigate regions which have high sustained iron supply including Kerguelen [81,82]; or to provide detailed studies of the inter-relationships between iron uptake, recycling and export (FeCycle II, [76,83]). As for the survey lines, the process studies can shed light on hypotheses 1–3 from [40].

Process studies provide additional insights, to those from the survey lines, into hypotheses 1 and 2, and in particular they advance the third hypothesis on Fe/C ratios, which the survey lines (and integrated suite of vertical profiles, see figure 2*a*,*b*) have limited capacity to do so. A GEOTRACES process study at Kerguelen—KEOPS II [82]—has enhanced our understanding of diatom bloom dynamics under naturally occurring conditions of sustained iron and nutrient supply. Specifically, by targeting several different regions downstream of Kerguelen that are each characterized by persistent iron supply, but at different supply rates (low/medium/high, [84], the KEOPS II study was able to probe the relationship between bloom magnitude, export efficiency and iron supply rates. Surprisingly, the highest observed downward carbon export was in waters characterized by a sustained but moderate Fe supply (figure 3). Moreover, across different 'subregions' different diatom assemblages and export efficiencies were recorded, leading Trull *et al.*, in their conclusions [84], to pose the question 'Does adding more Fe result in smaller diatoms and less export?'.

The mode of iron supply at Kerguelen differs from that in subtropical Pacific waters, which were the focus of the FeCycle II GEOTRACES process study [76]. FeCycle II followed the temporal evolution of a spring diatom bloom in a region where prior offshore lateral iron supply provides sufficient iron to a counter-clockwise eddy (figure 2*c*) to fuel a spring diatom bloom. Such a transient iron supply results—as expected—in a shorter bloom (days/weeks, figure 4*a*) compared with that at Kerguelen. Together, these process studies offer insights into hypotheses 2 and 3 above, by providing estimates of the upper-ocean retention (versus the downward export) of the 'new' iron by the upper-ocean foodweb.

During FeCycle II, the winter reserve inventory of new iron was taken up by both large and small phytoplankton and also by heterotrophic bacteria, with the last two groups potentially driving the diatoms into iron limitation (figure 4*b*). In the case of FeCycle II, microbial control, rather than conventional environmental control (i.e. iron and/or nutrient limitation) of the bloom dynamics was evident, with implications for ocean geoengineering. Additional experiments during FeCycle II revealed that iron recycled via grazing can be strongly bound to ligands, which may alter its bioavailability to different taxa including bloom-forming diatoms [76]. The quasi-Lagrangian nature of FeCycle II enabled estimates of retention that help evaluate hypothesis 2 above. The ratio of retention of iron versus new iron supply was 0.36 (0.18/0.50) (i.e. estimated from a 0.08 $\mathrm{nmol\,l^{-1}}$ biotic iron pool and a 0.1 $\mathrm{nmol\,l^{-1}}$ dissolved iron pool)/(0.5 $\mathrm{nmol\,l^{-1}}$ winter reserve new dissolved iron inventory)). Despite, this degree of retention of 'new iron' by the biota, the biotic iron pool in FeCycle II was comparable to that in FeCycle—a quasi-Lagrangian study

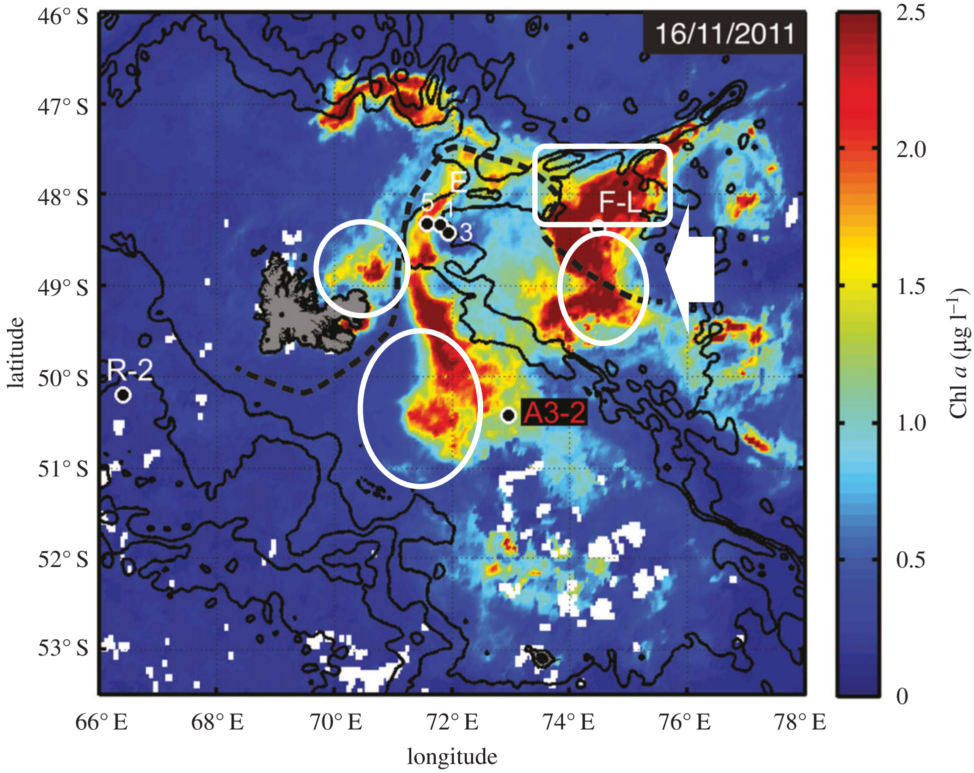

Figure 3. An ocean colour image from MODIS from mid-November 2011 highlights four distinct iron-fuelled surface chlorophyll features (vertical coloured scale bar in mg chlorophyll m^{-3}) that were sampled during the KEOPS II GEOTRACES process study [82]. The highest measured downward POC export was in a region with sustained but moderate iron supply (open circle to the left of horizontal arrow). Other regions sampled, clockwise (open symbols) from top left are Kerguelen coastal waters; Polar Front plume; recirculating feature and the plateau (redrawn from [84]).

in high nitrate low chlorophyll low Fe waters [83]. This finding suggests that recycled iron can play an equally influential role in setting biotic iron inventories as modes of new iron supply—a further insight that is pertinent to the ocean iron fertilization geoengineering debate.

8. Ramifications of GEOTRACES for ocean geoengineering

GEOTRACES studies have considerably advanced the hypotheses put forward in [40], and also raised additional questions and issues that are pertinent to the debate centring around ocean geoengineering. For example, the construction of a baseline iron distribution database enables any shifts, regionally or globally, that are detected by future biogeochemical surveys to be conspicuous and hence to eventually be linked to either climate variability or change. Such shifts in iron biogeochemistry can readily be explored, using the increasing sophistication of iron biogeochemical models [29]. Any changes in the inventories of iron, and/or in the response of the biota to altered iron bioavailability (including the influence of ocean acidification, [85]) provides valuable information on the envelope of natural variability that ocean geoengineering (such as by multi-year ocean iron fertilization) would have to be superimposed upon (figure 5*a*).

The likelihood of future variability in iron supply [70], and evidence of present-day significant natural variability in both iron [86] and carbon biogeochemistry [87] place important constraints, and also quantify thresholds, on the detection and attribution of the impacts of ocean geoengineering (figure 5*b*). Such natural variability in the iron and carbon cycles also raises concerns regarding additionality [71]. Although the Kyoto protocol [71] did not explicitly apply

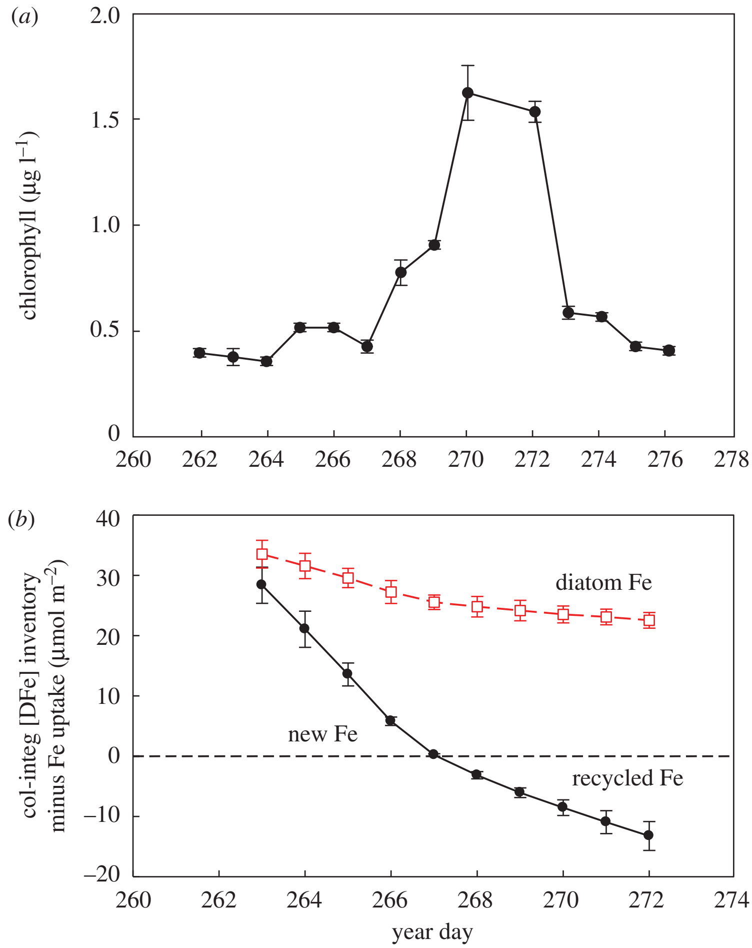

Figure 4. The FeCycle II GEOTRACES process study of Boyd *et al.* [76] investigated (*a*) the iron biogeochemistry during the initiation, development and decline of a spring diatom bloom in the subtropical waters east of New Zealand (figure 2*c*). Panel (*b*) reveals a rapid transition from 'new' to regenerated iron (i.e. a marked decrease in the Fe ratio) and also highlights the low iron requirements of the diatom bloom at this locale. (Online version in colour.)

to any form of ocean carbon mitigation (see Discussion in [88]), such a hurdle is likely to apply to any ocean geoengineering approach, with a requirement to demonstrate enhanced mitigation over and above naturally occurring carbon sinks such as reported in [87].

Figure 6 provides a specific example to illustrate the issue of additionality. The eddy targeted by the Lohafex iron-enrichment resulted in a bloom [89], but so did an eddy and filaments near the Lohafex-targeted eddy—that were presumably naturally iron-enriched (figure 6*a*). Given that there are more than 4000 eddies in the Southern Ocean (figure 6*b*,*c*) which is a potential target area for ocean geoengineering, then interannual variability (and/or multi-year climate change influences—figure 5) in iron supply and their knock-on effect on phytoplankton blooms can have a potentially large influence on the magnitude of additionality required for multi-year CDR methods.

The impetus and test-beds, from GEOTRACES surveys and process studies, to improve model parametrizations for Fe biogeochemistry will also bolster GEOMIP [92] specifically with more realistic and robust representations of upscaling of ocean iron fertilization. Prior modelling simulations such as in [93] are instructive as they reveal the inherent difficulty in detecting and attributing purposeful iron-mediated changes in downward export across multiple years, or in the case of Chai *et al.* [93] multiple releases—as might be the case with different geoengineering

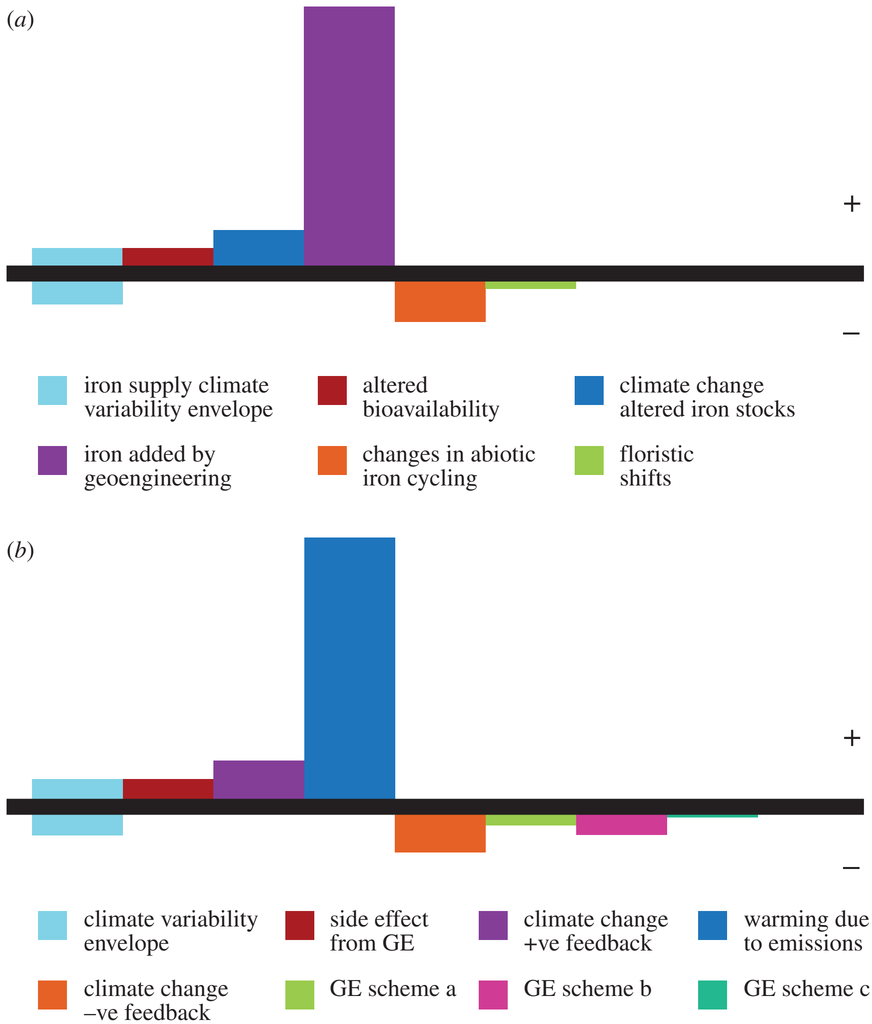

Figure 5. A major challenge for all ocean geoengineering approaches, including iron fertilization, is the detection and attribution of carbon sequestration, and any side effects on the ocean system. Panel (*a*) illustrates this challenge using hypothetical changes (+ denotes increases) in iron stocks and/or bioavailability that will likely be mediated by natural variability (such as El Nino Southern Oscillation, see [86] for example) or climate change (see discussion in [70]). These changes to the ocean iron cycle will be concurrent with any large-scale fertilization and may either amplify or diminish the effect of such geoengineering. Panel (*b*) denotes a similar range of naturally occurring and/or climate-change-driven ocean carbon sinks (denoted by +) or sources (represented by −) which will place important constraints, and sets thresholds on the detection and attribution of geoengineering activities. Owing to many unknowns, it is problematic to provide scale bars for each panel, but natural (physically mediated) carbon sinks of 0.6 Pg C over a decade have been reported for the Southern Ocean [87].

consortia operating in a particular region. Figure 7 presents a series of simulations across the 1995 annual cycle following simulated multiple iron releases in the Equatorial Pacific. They demonstrate the key role of ocean circulation and currents in rapidly dispersing—in this case, from east to west across almost the entire basin within in 300 days.

The implications of lessons learnt from GEOTRACES process studies for better understanding the key mitigating factors in ocean geoengineering include the need for more detailed investigations into the relationship between iron supply rate and diatom community structure on setting export efficiency [84]. This will require a combination of laboratory culture physiology studies, *in situ* mesocosms, and more studies in high-iron natural laboratories such as Crozet [94], as it is problematic to investigate the iron supply versus community response relationship

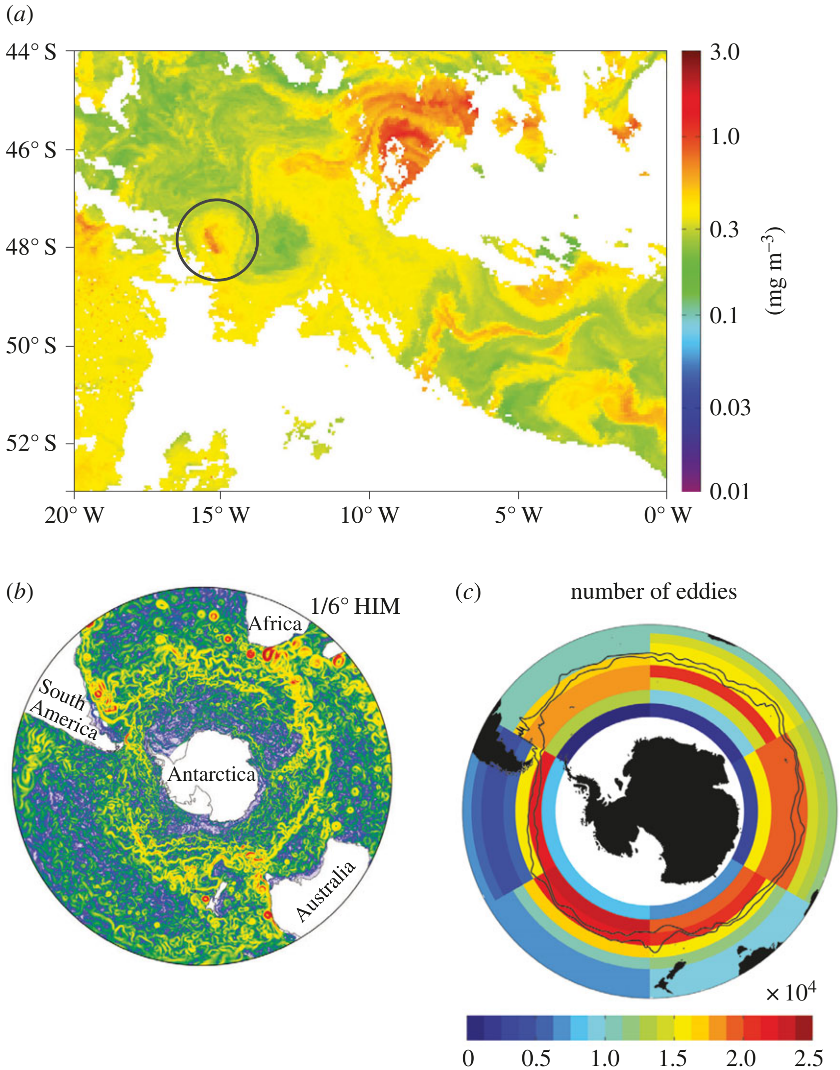

Figure 6. The concept of additionality (a key principle under the Kyoto protocol, 1997 [71]) is demonstrated for ocean geoengineering by (*a*) a MODIS ocean colour image of the iron-stimulated chlorophyll concentrations (mg m^{-3}, scale bar) within the eddy (circled) that was fertilized by the Lohafex experiment [89]. Other naturally fertilized highly productive eddies and filaments (horizontal arrow) are evident in the vicinity of the Lohafex eddy pointing out the difficulties in assessing additionality of large-scale iron fertilization in the Southern Ocean if multiple year campaigns are required. Panels (*b*) and (*c*) denote the large numbers of eddies that characterize the Southern Ocean based on high-resolution (1/6°) physical modelling [90] and from a census of satellite altimetry datasets [91], respectively.

using an individual mesoscale iron enrichment [40]. Moreover, the legal status of conducting further mesoscale experiments is uncertain under the current legislation (the UN CBD de facto moratorium; [9]—revised regulations in following the Haida Gwaii 'rogue' iron fertilization, see [18]). Other lessons from GEOTRACES for ocean geoengineering are the possibility of multiple iron sources supplying a particular region that together may lead to sustained productivity and export, such that additional purposeful iron fertilization would not stimulate these fluxes further. Moreover, in some oceanic regions, climate change is projected (with the caveat of major uncertainty regarding the future alteration of the dust flux) to increase iron supply to many oceanic provinces [95] with ramifications for the additionality of multi-year ocean geoengineering.

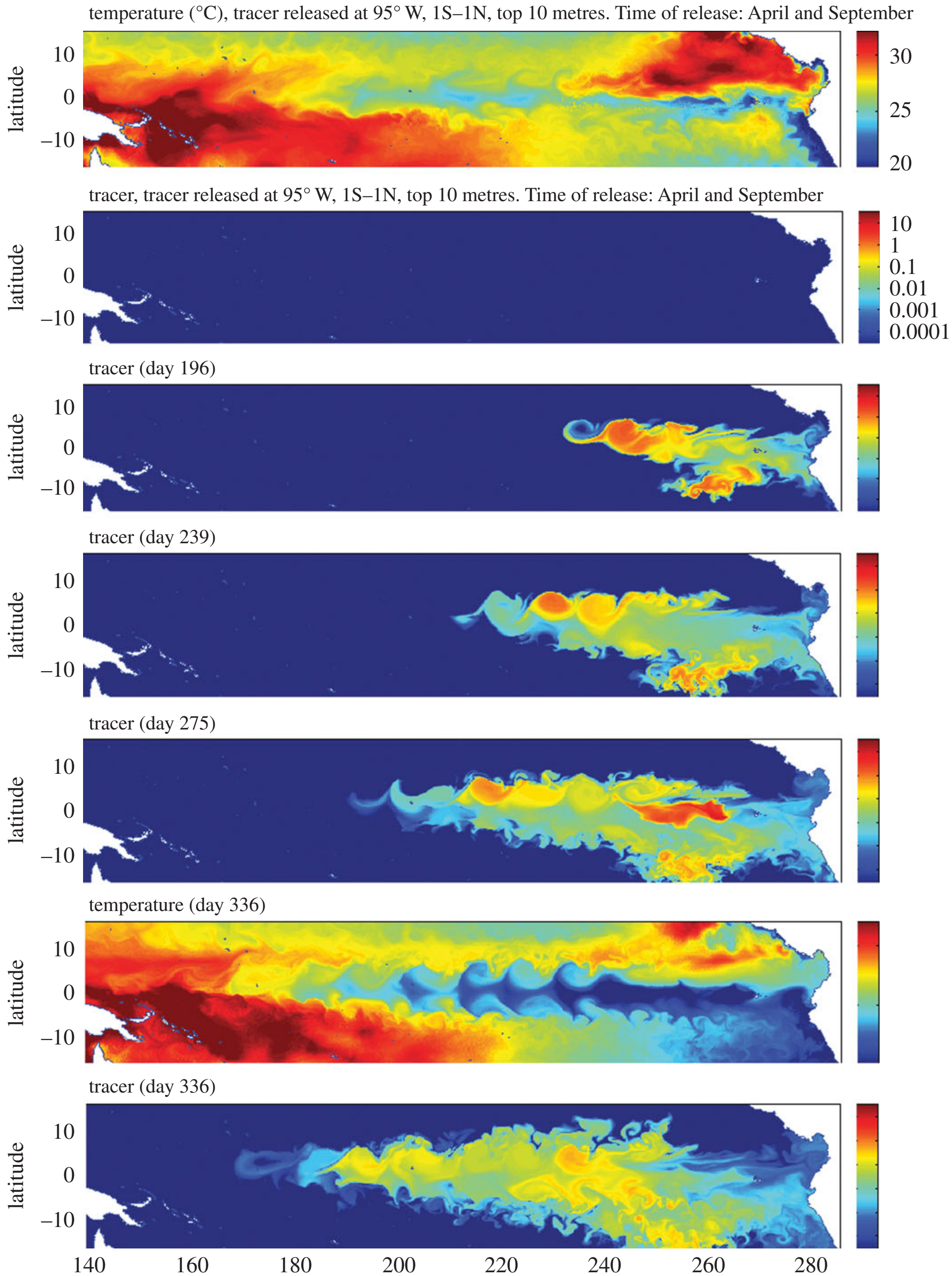

Figure 7. Discrete sampling of a model simulation of point source tracer releases (near the Galapagos Islands) in the HNLC waters of the Equatorial Pacific (sea surface temperature and tracer distribution). The tracers mimic the lateral propagation of multiple purposeful iron fertilization of the low latitude ocean (released at 10 m depth, in April and then in September 1995) sampled on year days 90 (i.e. just before the April release, upper two panels), 196, 239, 275 (just after the September release) and 336. Model simulations were presented in [93].

Although GEOTRACES process studies have revealed more about the role of ligands and bioavailability and their control within pelagic foodwebs [72,79], it remains to be seen how pertinent these findings might be to any developments in ocean geoengineering. There has been debate and also patents lodged [51] on different ways to add iron to the ocean—for example, micro- or mini-pellets that have 'slow release' complexed iron. However, it is possible that climate change-mediated shifts in bioavailability (photochemistry, siderophore production) could alter iron supply to organisms in a future ocean [70,85].

9. Ocean iron fertilization—a model to debate research governance on geoengineering?

The debate into geoengineering is currently at an impasse surrounding research governance. The recommendations from national academies [3,5], editorials from influential science journals such as *Nature* and *Science* [20–22] and perhaps some of the implications of the language around 'CO_2 negative emissions' from the late 2015 'COP21' accord point to the need to come up with a test-bed to assess the merits and drawbacks of geoengineering by first conducting multidisciplinary research to provide a well-rounded appraisal of climate intervention. Such a test-bed will enable other geoengineering approaches such as ocean alkalization [30,43,44] to learn invaluable lessons from other methods that have had a long time line of much closer scrutiny, often through both direct (policy) and indirect (scientific experiments) approaches (table 1).

We advocate that the 20 years of debate into the pros (including enhanced downward export flux) and cons (deleterious side effects such as toxin-producing diatoms) of ocean iron fertilization [6,7,23,25,54,96] along with research at the mesoscale (approx. 1000 km^2) in a wide variety of locales with different initial conditions (physics, chemistry and biology) make this potential geoengineering method the most promising candidate to frame the debate into research governance. The GEOTRACES global survey datasets, and our consequent enhanced understanding of the iron cycle, add further strength to making a case for iron fertilization to be the test-bed for research governance for all candidate geoengineering methods. In particular, the links that can—in the near future—be built across the FeMIP [29] and CDR component of GEOMIP [14,92] communities can help to run more accurate and realistic modelling scenarios, which during the current impasse is the best way to develop and progress the ocean geoengineering debate. A suite of 'thought experiment' simulations can provide invaluable findings to flesh out the current somewhat static debate into research governance.

10. Conclusion

Despite the optimism generated for the mitigation of climate change in late 2015 by the COP21 agreement, it is highly unlikely that the geoengineering/climate intervention issue is passé [97]. Hence, at some point in the near future, the issue of research governance must be addressed and resolved [5,21]. Scientists should take a lead into this debate [98], and we advocate that ocean iron fertilization can be used as the test-bed to shape this debate based on 20 years of prior and vigorous discussion, and by using datasets that provide insights and raise questions arising from prior large-scale ocean manipulations. GEOTRACES has been able to address and refine the hypotheses put forward by the last major synthesis [40] into this issue. Moreover, GEOTRACES is providing the framework to permit robust regional and global assessment of interannual variability in the ocean iron cycle. This will lead to a better understanding of how a changing climate will influence both the ocean iron cycle and the magnitude of the coupling between the ocean iron and carbon cycles on longer timescales. Such a joint investigation of iron and carbon biogeochemistry is an essential stepping stone in better understanding whether the efficacy, safety, side effects and rapidity of climate mitigation by ocean iron fertilization (or other geoengineering methods) is feasible.

Competing interests. We declare we have no competing interests.

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