Iron Model Intercomparison Project (FeMIP)

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1. Summary

The micronutrient iron is at the heart of biological activity in the ocean, shaping marine resources and the global carbon cycle. The iron model intercomparison project (FeMIP) SCOR working group proposes to bring together a diverse set of scientists to deliver new insight into the functioning of the ocean iron cycle, using observations and, in particular, to improve its representation in ocean models. This is important, as the multi-disciplinary work we propose will improve confidence in the projections about how environmental change will affect ocean productivity in iron-limited areas and facilitate the use of numerical models to test hypotheses within a community-driven context of model skill. We aim to produce guidelines for how models can best represent the iron cycle and develop tools for objective interpretations of model skill relative to observations. The impact of underlying inter-model differences in iron cycling will be evaluated and consensus input fields will be produced. Importantly, we will also review how models can take the next important steps and represent the complexity of biological interactions within the iron cycle. A SCOR working group such as proposed here is the only practical means to achieve these important aims.

2. Background and motivation for the working group

2.1 The importance of iron models and their shortcomings

With the recognition that the availability of iron (Fe) plays a central role in shaping biological activity in the ocean [Boyd, et al., 2007; Moore, et al., 2013], most of the numerical models we rely on to test hypotheses and make projections of change now typically represent this resource explicitly. This means that, for example, the projected impact of climate change on biological activity and the carbon cycle in iron-limited regions (e.g. [Bopp, et al., 2013; Cabré, et al., 2014]) can be strongly controlled by how a given model represents the iron cycle [Tagliabue, et al., 2016]. Moreover, due to the central role played by Fe, it is invoked as a potential driver of past changes to the global carbon cycle [Martinez-Garcia, et al., 2014] and as a regulator of both phytoplankton diversity [Ward, et al., 2013] and nitrogen cycling [Monteiro, et al., 2011]. These multi-faceted roles for iron in regulating important components of the coupled ocean-terrestrial-atmosphere system requires that we have good quantitative constraints on its cycling in the ocean, which will raise confidence in the conclusions drawn from numerical models.

Traditionally, numerical model skill is evaluated against global gridded climatologies such as those produced for temperature, salinity, nitrate, phosphate, silicic acid and oxygen by the World Ocean Atlas [Levitus, et al., 2013]. These climatologies can be statistically compared against model outputs to assess model skill and used as initial conditions for model simulations. This process thus provides confidence in the rigour of a given model in reproducing these aspects of the ocean environment. However, despite the importance of Fe to ocean processes, a lack of widespread iron data (in both space and time) has hampered similar efforts to evaluate the skill of iron modelling. Fortunately, there has been a large increase in the availability of Fe measurements over recent years thanks to the GEOTRACES programme [Anderson and Henderson, 2005]. This international effort has begun producing full ocean section distributions for trace elements (including Fe) on a systematic basis and publicly releasing data [Mawji, et al., 2015]. However, the community is still faced with a relatively sparse Fe dataset, relative to those available for the major nutrients. This not only hampers skill assessment, but also in a lack of consensus on appropriate initialisation fields for iron: a crucial component of model results, as seen for the major nutrients.

In response to the greater availability of data, members of this working group initiated a first intercomparison of global iron models with available data [Tagliabue, et al., 2016]. Two important results emerged from this effort: (i) there is a wide variety of residence times for Fe across contemporary models (from 5 to 500 years), with important implications for the sensitivity of the modelled iron cycle to perturbations; and (ii) most models failed to reproduce the broad aspects of the observed Fe distributions, raising concern about the confidence we may have in our iron models and their implications for climate projections. Models that reflected emerging constraints from field observations and process studies often performed better in certain regards, but a given model's complexity was not necessarily the first-order driver of model skill [Tagliabue, et al., 2016].

A stark example of the challenge in modelling Fe comes from the meridional section along the western half of the Atlantic Ocean basin, where the clear water mass structures evident in the distributions of nitrate and phosphate are absent in the iron distribution [Rijkenberg, et al., 2014]. This highlights the unique nature of the ocean iron cycle. Allied to this, the sparse nature of iron data requires us to develop suitable skill metrics to evaluate attempts to represent the unique features of the iron cycle in models.

2.2 The Challenge

Ultimately, improving the modelling of the ocean iron cycle will come from a better understanding of the key processes from both modelling and observations. Broad conceptual understanding is emerging regarding the importance of certain sources and the key facets of the internal cycling of iron, but we lack the quantitative insight that will yield suitable model parameterisations. For example, despite being represented as a key Fe source to the ocean since the very first models [Archer and Johnson, 2000; Parekh, et al., 2005], the amount of Fe supplied by dust deposition still varies widely among contemporary models [Tagliabue, et al., 2016]. In recent years, hydrothermal sources have been recognised as a potentially important Fe source [Klunder, et al., 2011; Nishioka, et al., 2013; Resing, et al., 2015], but are only included in two current global iron models [Tagliabue, et al., 2016]. Equally, evidence for unique aspects to Fe biological cycling and interior ocean regeneration is accumulating [Boyd, et al., 2015; Strzepek, et al., 2012; Tagliabue, et al., 2014; Twining and Baines, 2013; Twining, et al., 2014], but many models still represent these processes very simply, with close coupling to phosphorus cycling. The goal of the FeMIP working group is to assemble an iron model intercomparison project, cutting across different modelling and working closely with observational communities, to address these key challenges. The goal of FeMIP rests on the nexus between observational and modelling science and is three-fold:

(i) to provide our best understanding of how Fe should be represented in global climate models and to develop tools for consistent evaluation of model skill
(ii) to deliver the necessary combination of observation and theoretical insight to parameterise the key processes regulating internal Fe cycling
(iii) to appraise the state of the art and key outstanding gaps in our understanding in the impact of Fe on biological processes.

2.3 Why a SCOR Working Group

We have already shown willingness in the community to conduct this work via our initial intercomparison effort [Tagliabue, et al., 2016]. However to achieve further progress, there needs to be a concerted effort for dialogue between the relevant communities to help improve iron modelling. These communities are diverse and include the modellers themselves, those taking the iron observations (e.g. GEOTRACES), iron chemistry experts, experts in phytoplankton physiology and those investigating iron sources (e.g. atmospheric chemists). This FeMIP working group will assemble this diverse set of scientists to work jointly towards delivering a set of clear objectives that will have wide impact and resonance across the larger ocean and climate scientific communities, ranging from global coupled climate modellers, paleoclimatologists, and IPCC experts to microbial biologists and chemists. The multi-disciplinary and international work we propose would be impossible to support in any other way (e.g. from national or European funding).

3. Terms of reference

(Objective 1, O1) To identify best practices for minimum complexity representations of the iron cycle in models, with options given for more advanced aspects, and publish the guidance in a peer-reviewed paper.

(Objective 2, O2) To develop tools for a wide variety of platforms to validate global model results in a standardised way and make these available via a peer-reviewed publication and a website.

(Objective 3, O3) To facilitate a focussed intercomparison of iron models to constrain the impact of varying residence times and a consensus dust deposition scheme and publish the results in a peer-reviewed journal.

(Objective 4, O4) To review how to represent biological interactions in the iron cycle, the linkages to key phytoplankton species and the interactions with zooplankton and bacteria, as well as broader connections with other biogeochemical cycles and publish the results in a peer-reviewed journal.

4. Work Plan

To deliver O1 we will initially review (using expertise from the working group) the state of the different levels of ocean iron cycle complexity from current models. In parallel, we will assess the key aspects of iron cycling that are crucial for global climate models. This step will be expedited by dialogue between modellers and observationalists on the working group. We will then determine the minimum number of iron pools and the underlying processes to be included in global models. Finally, we will produce governing equations in a unified mathematic notation and default parameter values necessary for parameterisation and test these across a subset of models (e.g. using a relatively simple iron model and one of the most complex models as end members). As part of this effort, we will produce consensus initialisation fields that can be used by the global ocean modelling community. At this point, we will write a peer-reviewed paper in the open access journal *Geoscientific Model Development* (GMD) describing the theoretical underpinning and practical implementation of our recommended minimum complexity iron scheme and initial conditions. Options for the representation of more advanced processes will be included as optional.

To deliver O2 we will review the main computing platforms (e.g., R, Matlab, Ferret and Python) to perform analyses of model skill and identify a platform leader from amongst the working group membership to lead the development of the skill scripts. We will then agree on a common set of model skill metrics and diagnostic plots required to evaluate model performance, as well as a reference iron database from the observations. Each platform leader will be responsible for writing the code, which will be tested against a common model from the initial FeMIP work. An important part of Objective 2 will be the maintenance of ‘consensus values’ from users to have a community benchmark for contemporary model skill (mean or median, with associated error). This mirrors the efforts made in the observational community with the “SAFe” [Johnson, et al., 2007] trace metal reference samples. A short tutorial to demonstrate how these tools are used will be produced.

To deliver O3 we will first assign two champions to steer this intercomparison work and identify the participants available to conduct additional model experiments, with the aim to encompass a range of residence times. We will choose a series of reference dust deposition schemes and participants will conduct parallel experiments to assess model sensitivity. Linking to Associate Member expertise on these issues will be crucial. A further set of idealised perturbation experiments across the range of models will assess the impact of different underlying residence times to the biogeochemical response on different space and time scales.

Delivering O4 requires reaching out across the full scope of expertise we have assembled from Full and Associate members. We have a broad suite of observational experts who will review key aspects of the biological cycling of Fe: bioavailability, phytoplankton Fe uptake, different iron requirements among diverse phytoplankton species, zooplankton and bacterial recycling and linkages to other biogeochemical cycles (e.g. carbon cycling, nitrogen fixation, silica cycling, food web structure). In detailed dialogue between modellers, experimentalists and observationlists, we will then identify the key phenomena that need to be represented and review how they may be parameterised in models. This will proceed via simplified model experiments at reduced dimensions (e.g. 1-dimensional models) that will made available to the community for further testing with future observational information and may ultimately be used in global scale models.

We plan to hold four annual working group meetings by stretching the funding available from SCOR and other sources, by meeting in conjunction with other related meetings to minimize airfare costs.

Month 1: Kick off meeting. This will focus on planning, with emphasis on O1 and O2, but with reference to O3 and O4. Key champions will be tasked for O1 and O2 and sub-groups will be assembled. We will assign a writing team for the short *Eos* article (Deliverable 1).

Months 1-12: Work on O1 and O2, submit and publish *Eos* article announcing working group.

Month 12: 2nd working group meeting timed to coincide with Ocean Sciences or similar conference. Results from work on O1 and O2 will be presented and reviewed by the group. Work will begin on planning O3. While it is anticipated that O1 will require feedback and continued work, it is planned that O2 will be completed and we will discuss and decide how to publicise the results. At this meeting we will begin discussing work for O4 via presentations on the current state of the art in ocean models and, importantly, emerging paradigms from observational and experimental studies.

Months 12-24: Continued work on O1 and work on O3. Publicise results of O2 via peer-reviewed paper or website (as decided at 2nd working group meeting).

Month 24: 3rd working group meeting. Finalise results of O1 and decide on dissemination strategy. Further discussion of the key processes needed for O4, emphasising the identification of well described phenomena from observations. Sub-group assembled to lead write up key phenomena for O4.

Months 24-36: Continued work on O3 and work on O4.

Month 36: 4th working group meeting. Presentation of results from O3 and writing of peer-reviewed paper. Review of potential means to represent key phenomena identified for O4 in global ocean models.

Months 36-48: Finalising and submitting peer-reviewed paper for O3. Continued work on O4, finalising and submitting paper.

Month 48: Final symposium – we will seek co-sponsors for this workshop, including GEOTRACES, the Ocean Carbon and Biogeochemistry programme (USA), the marine biogeochemistry forum of the Challenger Society (UK), SOLAS and IMBER, as well as others identified in due course. The aim of the symposium will be to highlight progress made in the linking observational work on the internal cycling of Fe to its representation in models. A key challenge for the symposium will be to consider how to extend theory for Fe to other important micronutrients that are at present ignored by biogeochemical models.

5. Deliverables

(1) Inform the community of this working group via a short article in *Eos* or similar publication.

(2) Produce a website to share and publicise our goals and meetings, as well as the outputs of the working group. Contributes to delivering O2.

(3) A peer-reviewed paper in GMD detailing the equations allowing the minimum level of complexity needed to capture important aspects of the iron cycle in climate models, as well as a consensus initialisation field. Delivers O1.

(4) A set of scripts for common data processing platforms, linked to a reference database that produce standardised metrics for model skill, with consensus values updated and publicised via the website. Delivers O2.

(5) A peer-reviewed paper detailing the results of the intercomparison of different dust deposition schemes and the sensitivity of models with varying residence times to fluctuations in iron supply. Delivers O3.

(6) Presentation of the O1, O2 and O3 at international ocean sciences meetings to publicise the findings and stimulate uptake and discussion. Delivers O1-3.

(7) A review article, aimed at *Nature Geoscience* or similar, detailing how to represent important biological linkages in the iron cycle and their connections to wider biogeochemical cycles. Delivers O4.

(8) Organise a co-sponsored symposium to bring observational and modelling scientists together around topic of the review article and towards extending the work done with Fe to other important micronutrients.

6. Capacity building

Numerical models provide an excellent platform for capacity building as many global model codes are open source (e.g. NEMO, MITgcm) and the major barrier to progress is often theoretical understanding rather than expensive equipment. Better dialogue between those taking the iron measurements, conducting experiments on the role of iron in the organism and the modellers is crucially important, but often hampered by lack of common language and forum for the discussions. Moreover, the area of Fe modelling would clearly benefit from a wider user base, applying a suite of theoretical approaches. However, new users are often held back due to the apparent complexity of the ocean Fe cycle. We will provide several practical contributions to aid the uptake and proliferation of biogeochemical modelling. These efforts will link strongly with the activities of the Ocean Model Intercomparison Project as part of the World Climate Research Programme efforts (see Sec 9.2) and will maximise the inclusion of Fe within these ‘IPCC-class’ models.

Our vision is to open up better dialogue between modellers and observationalists/experimentalists by bringing together these groups in focused forum (this proposed working group). We also envision increasing access to Fe modelling to a wider user base through the activities of this working group. Four practical steps will achieve this. First, the wide distribution of a recommended minimum complexity set of equations and parameters for the modelling of Fe biogeochemistry via Objective 1 will provide a simple means for new users to include Fe cycling in their models to facilitate further development. Moreover, as we will provide options for including more advanced aspects that are linked to working group members there will be clear opportunity for mentorship in further developing understanding. Second, the suite of model skill evaluation scripts and datasets that we will distribute via Objective 2 will facilitate the entry of new ways of modelling Fe cycling by providing a community accepted means of benchmarking model skill. It is anticipated that this will work in a similar way to consensus values for Fe samples that have facilitated new laboratories joining international efforts. We will prepare a short web based video to explain how our model skill scripts should be used. Third, our website and publication efforts will focus effort on understanding the ocean iron cycle, from both modelling and observational standpoints. Finally, we will conduct two training days at the final symposium aimed at training advanced level graduate students that are already working on ocean modelling in use of our recommended iron cycle model and evaluation scripts. Overall, these activities will maximise the building of long lasting global capacity within this important topic.

7. Composition of Working Group

FeMIP has 10 Full and 10 Associate members that bring together state-of-the-art skills in iron cycling modelling, biogeochemical modelling, model skill evaluation and coupled climate modelling, as well as experimental work that will inform on key requirements and future developments. The Full Members are responsible for the delivery of our objectives, while the Associate Members provide important input from the complimentary fields (e.g iron observation, biological cycling, dust deposition) and additional modelling platforms (e.g. intermediate complexity models). Our Full members represent 7 different nations, including 2 emerging/developing nations (South Africa and Turkey). Moreover, we include a number of early career researchers as Full members, which will aid their career development [Urban and Boscolo, 2013].

7.1 Full Members:

Name	**Gender**	**Place of Work**	**Expertise**
Alessandro Tagliabue (co-chair)	M	University of Liverpool United Kingdom	Global iron and biogeochemical modelling
Stephanie Dutkiewicz (co-chair)	F	MIT USA	Ecosystem and biogeochemical modelling
Olivier Aumont	M	IRD/LOCEAN France	Global iron and biogeochemical modelling
Tatiana Ilyina	F	Max Planck Institute for Meteorology Germany	Global biogeochemical and coupled climate modelling
Fanny Monteiro	F	University of Bristol United Kingdom	Modelling links between biogeochemistry, biology and climate
J. Keith Moore	M	UC Irvine USA	Global iron and coupled climate modelling
Yeala Shaked	F	IUI – Eilat Israel	Iron biouptake and bioavailability
Marcello Vichi	M	University of Cape Town South Africa	Global biogeochemical and coupled climate modelling
Christoph Völker	M	Alfred Wegener Institute Germany	Global iron modelling
Mustafa Yücel	M	Middle East Technical University, Turkey	Iron observation

7.2 Associate Members:

Name	**Gender**	**Place of Work**	**Expertise**
Alex Baker	M	University of East Anglia, United Kingdom	Dust supply of iron
Philip Boyd	M	University of Tasmania Australia	Coupled biological and chemical iron cycling
Peter Croot	M	Galway University Ireland	Iron speciation and chemical cycling
Christel Hassler	F	University of Geneva Switzerland	Cycling of iron binding ligands
Jun Nishioka	M	Hokkaido University Japan	Iron distributions in the Pacific and Indian Oceans and colloidal iron cycling

Maite Maldonado	F	University of British Columbia, Canada	Biological iron cycling through the food web
Kazuhiro Misumi	M	CRIEPI Japan	Iron cycling in global models, working on aggregation dynamics
Mark Moore	M	University of Southampton United Kingdom	Biological iron limitation and requirements
Andy Ridgwell	M	UC Riverside USA	Earth system models of intermediate complexity
Benjamin Twining	M	Bigelow USA	Determinations of phytoplankton and zooplankton iron demand

8. Working group contributions

Alessandro Tagliabue is involved in the development of the PISCES model iron component, initiated the FeMIP process and has strong links into the GEOTRACES community via membershop of their steering committee and co-chair of Data Management Committee.

Stephanie Dutkiewicz maintains the biogeochemical – biological component of the MIT DARWIN project model (including iron cycling), with a particular focus on diversity of phytoplankton resource requirements.

Olivier Aumont develops and maintains the iron and ocean biogeochemical components of the PISCES model.

Tatiana Ilyina is a climate modeller (MPI) and represents the needs of this community as end users of the working group's outputs.

Fanny Monteiro is a modeller working on the nexus between biogeochemical cycling, biological activity, and past and future climate (e.g. the role of iron dust deposition on nitrogen cycling).

J. Keith Moore develops and maintains the iron and ocean biogeochemical components of the BEC model, with a particular focus on dust iron input.

Yeala Shaked has a long track record in observing and modelling iron bioavailability and biouptake.

Marcello Vichi develops and maintains the iron and ocean biogeochemical components of the BFM model.

Christoph Völker develops and maintains the iron and ocean biogeochemical components of the RECoM model.

Mustafa Yücel is an expert in the speciation of iron, especially nanoparticulate forms that are thought to dominate supply from dust and hydrothermal vent systems

9. Relationship to other programmes and SCOR working groups

9.1 Other SCOR Working Groups

The activities of SCOR Working Group 139 on organic ligands and in particular the development of ligand datasets and model closures, as well as SCOR/InterRidge Working Group 135 on hydrothermal energy transfer, which provided inputs on hydrothermal iron plumes, will be of benefit to our group (Objective 1). Our working group will interface well with current SCOR Working Group 145 on chemical speciation, with the potential to provide a platform for the wide testing of their chemical speciation models for iron through a range of model platforms. SCOR Working Group 149 is concerned with the responses of ocean biota to environmental change and will ultimately benefit from new models of biological Fe cycling (Objective 4) to assess future projections.

9.2 Ocean Model Intercomparison Project (OMIP) and World Climate Research Programme (WCRP)

The OMIP is an international effort aimed at intercomparing global biogeochemical models that are used in the next IPCC set of simulations as part of the WCRP. We will benefit the activities of OMIP by producing consensus recommendations for model parameterisations, spin up times and initial conditions for Fe (Objective 1). Moreover, our set of skill metrics (Objective 2) will be invaluable of model appraisal. Ultimately, our deliverables as part of Objectives 1 and 2 will facilitate the representation of Fe within a wider set of IPCC global coupled climate models, enhancing confidence in their projections. For example, at present, no consensus exists within OMIP on iron input fields or initial conditions.

9.3 GEOTRACES

Our work is closely linked to that of the GEOTRACES programme. We will make use of their datasets to deliver Objective 2, facilitated by Tagliabue acting as co-chair of their Data Management Committee. Moreover, our activities within Objective 4 will link strongly to ongoing ‘bioGEOTRACES’ efforts. We anticipate GEOTRACES being invited to co-sponsor our final workshop.

9.4 SOLAS and IMBER

Both the SOLAS and IMBER programme will benefit from our work. For example, Objective 3 is aimed at constrained iron deposition from dust, which is a key SOLAS aim. Equally, efforts to improve the representation of Fe cycling by the biological community links strongly to the objectives of the IMBER programme. We anticipate both SOLAS and IMBER being invited to co-sponsor our final workshop.

10. Key references

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Appendix (5 papers per full member)

Alessandro Tagliabue

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