Title
Workshop highlights iron dynamics in ocean carbon cycle

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External Iron Inputs

The deposition of mineral dust in the oceans is a key source of iron that modulates biogeochemical processes. Attempts to model transport and deposition of mineral dust are increasing in complexity and accuracy. Still, modeled deposition rates in remote regions can disagree by a factor of 10 or more. More direct measurements of aerosol concentration and deposition—both wet and dry—are required. Significant efforts are under way to develop autonomous, moored instruments to measure these quantities. Such efforts should be encouraged. Solubility of iron in aerosols deposited on the ocean also remains a large uncertainty. Results from laboratory studies span a range of at least an order of magnitude.

Continental margins are also a large source of iron. Much of the iron is derived from re-suspended sediments. Because this sedimentary iron is not directly coupled to macronutrients in the source water, iron limitation also occurs in the coastal zone. The coastal ocean accounts for 20% of ocean primary productivity, and perhaps 50% of the carbon export from surface to deep waters and 90% of carbon burial in sediments. The effect of iron on coastal ecosystems may be significant in the global carbon cycle. However, iron inputs from continental margin sources to the ocean's interior are not yet included in any of the global iron models. The source area for re-suspended iron is much smaller on narrow continental shelves in the modern ocean than on broad shelves, and iron limitation is more frequent in these areas. Iron limitation of coastal primary production may be particularly important at low stands of sea level during the glacial maxima.

Iron Regulation of Ecosystem Processes

Just one decade ago, there were intense debates about the role of iron in controlling biogeochemical processes. Eight open ocean iron fertilization experiments have been conducted since then in the high-nitrate, low-chlorophyll waters of the equatorial Pacific, Southern Ocean, and the sub-Arctic North Pacific. All have shown enhanced rates of primary production and biomass accumulation following iron addition. Iron enrichment experiments conducted in bottles during the U.S. JGOFS programs have shown a remarkable commonality in the level of iron that stimulates a community response. Community growth and nutrient uptake rates have a half-saturation constant of approximately 0.1 nM Fe, when fitted with a Michaelis-Menten (Monod) model, in nearly all pelagic environments. Such parameterizations have formed the basis for incorporation of iron into most global ecosystem models.

Future efforts must focus on experiments that provide information at the individual phytoplankton species or functional group level. It is apparent that the differential response of each functional group plays a role in sustaining the ecosystem, exporting carbon, and altering nutrient availability.

Modeling ecosystems at the species and functional group level may prove problematic, though. Detailed information is required for each group, and the resulting model complexity is difficult to interpret and apply in high-resolution global simulations. Considerable discussion focused on the need to develop simpler relationships that encompass the diversity of functional groups and their impacts on biogeochemical processes through parameters such as plankton size.

Today, most models assume that iron is recycled in a similar manner and at similar rates to the macronutrients. However, iron may behave differently than macronutrients within phytoplankton cells and within ecosystems. Further, iron is not likely to behave uniformly in different species or functional groups. Observations made over the last decade suggest that Fe/C ratios are much more variable than N/C or N/P ratios in plankton and the water. Detailed measurements of key elemental ratios (Fe/C/N/P/Si/$CaCO_3$) using clean techniques could answer many of our remaining questions about iron and carbon cycling in the oceans.

Many discussions at the workshop focused on iron speciation. It is now known that >99% of the dissolved iron in the upper ocean is strongly complexed by organic molecules. Many marine micro-organisms are capable of producing iron binding ligands, but the sources and sinks, lifetimes, and turnover rates between ligand pools and the processes that govern these transformations are simply unknown. The bio-availability of various iron species—dissolved versus particulate, organically bound versus inorganic—is poorly known. Phytoplankton and bacteria have a complex array of Fe acquisition systems; for example, siderophore mediated uptake, reductases, ligand production, and phagotrophy. Processes such as photochemistry cause redox cycling of iron between different chemical species, thereby modifying bio-availability. There also appears to be some degree of species specificity in the forms of iron accessed by prokaryotes and eukaryotes. Such processes are included in models, if at all, with very simple parameterizations.

Nitrogen fixation may play a key role in altering the pool of fixed nitrogen and carbon export in the ocean. The iron requirements for *Trichodesmium* spp., a key nitrogen-fixing cyanobacterium, are approximately ten-fold higher than for most open ocean phytoplankton. Great progress in understanding the impacts of this high iron requirement on nitrogen fixation have been made in recent years through field and laboratory observations and satellite data analysis. Nitrogen-fixing diazotrophs have only recently begun to be incorporated into marine ecosystem models.

Carbon and Iron Export

We have a basic understanding of the role of iron in stimulating the onset of phytoplankton blooms, based on bottle experiments and open ocean iron fertilizations. Our understanding of the fate of carbon produced by iron enrichment is much poorer. It is not apparent how iron impacts carbon export, a key variable in regulating atmospheric composition. Discussions at the meeting suggested that small-scale (~10 x 10 km) fertilization experiments may not achieve the high biomass conditions conducive to carbon export. Horizontal diffusion appears to dilute the patches with unfertilized, low-biomass waters, and particle concentrations do not reach a point where aggregation and sinking occur. One recommendation from the workshop was that future open ocean iron fertilization experiments be of sufficient scale (~100 x 100 km) to enhance the likelihood of observing export.

The workshop discussions also highlighted how little we understand about how dissolved iron is removed from the upper ocean by adsorption onto sinking particles. Biological uptake can remove only a small fraction of the dust and coastal iron added each year. The rest must be removed through adsorption onto particles and then sinking to the sediments, yet little is known.

Tremendous advances in our understanding of iron cycling in the ocean have been made during the past 10–15 years, and we now recognize iron as a keystone regulator of biogeochemical functioning. It is also clear that the chemistry of iron can be exceedingly complex. Further, it is unlikely that complex models of iron cycling with many, poorly constrained parameters will lead to successful prognostic models and a predictive understanding of the effects of iron on ocean biogeochemistry. Modeling community members at the meeting clearly called for parameterizations that might lead to relatively simple equations of iron chemistry and ecosystem response to iron concentration.

The JGOFS Workshop on Iron Dynamics in the Carbon Cycle was held 17–19 June 2002. A complete report of the meeting is available on the U.S. JGOFS Synthesis and Modeling Web Page (http://usjgofs.whoi.edu/mzweb/iron/iron_rpt.html).

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The Wind Program in the Future

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Launched in November 1994, the Wind spacecraft is several years beyond its design life and well into the extended mission phase. Consequently, in 2001, NASA decided that henceforth, Wind should be kept at the forward libration point to be used as a "hot spare" for the Advanced Composition Explorer (ACE) spacecraft. Nonetheless, despite its age, Wind has proven reliable, long-lived, and highly productive, and it continues to produce solar wind magnetic field and other data of the highest quality. Thus, NASA has accepted a proposal to continue Wind operations in a cost-effective manner to ensure that data will be taken continuously and archived in level-zero and in key parameter form for use by the entire scientific community.

Table 1 shows the eight instruments on Wind, their present operating conditions, and their key capabilities. Analysis of data from these instruments has yielded both important individual results and essential support for investigations involving other spacecraft, such as Polar, Geotail, Solar and Heliospheric Observatory (SOHO), and Fast. Wind has made important contributions to reconnection studies in the magnetosphere and the interplanetary medium, provided tracking information on the propagation of CMEs from the Sun to Earth, and made unique observations of solar energetic particle events, including the discovery of thousand-fold enhancements of heavy ions in impulsive flare events.

Wind has also addressed the large-scale topology of magnetic cloud structures in the interplanetary medium through measurements of bi-directional streaming, and provided to the magnetospheric community solar wind measurements of high quality for modeling and prediction purposes. In astrophysics, Wind has provided important timing and directionality information on the gamma-ray bursts class of stellar objects.

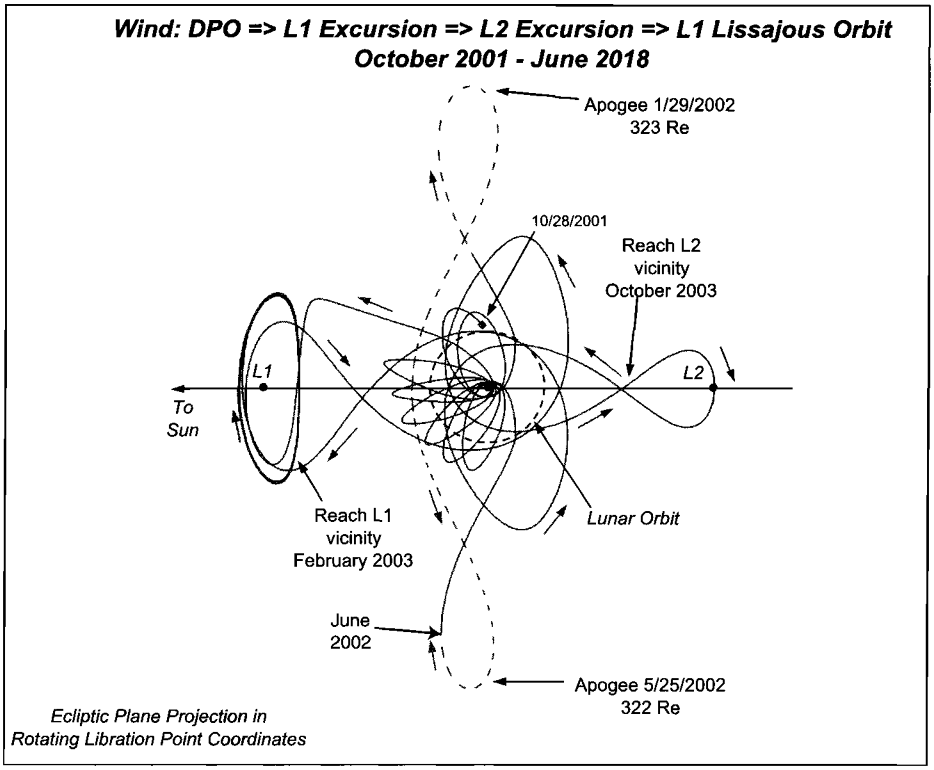

Fig. 1. As the dates show, Wind will reach its apogee at 322 Re over the dusk hemisphere of Earth in mid-2002. It then enters the petal orbits to adjust its phase with respect to the Moon. Encounter with the Moon takes Wind to the vicinity of L1, which it reaches in February 2003. After making a loop around L1, it travels to L2, which it reaches in October 2003, and it makes another loop there. Wind then returns to L1, where it enters a lissajous orbit in late 2004. Since the spacecraft does not enter orbit, very little fuel is required for the L1-L2-L1 transit. The Wind payload mass was such that the equivalent of 600 m/s of fuel was carried into orbit; of that, 140 m/s is still available.

Table 1. WIND Instruments

Instrument	Key Measurement	Status	Comments
WAVES	Radio tracking of CME shocks	Normal	Unique radio tracking capability
SWE	Solar wind plasma	Normal*	Most-utilized data set for solar wind plasma observations
MFI	Solar wind magnetic field	Normal	Most-utilized data set for solar wind magnetic field
3D Plasma	keV-MeV solar particles	Normal	Sole source of lower energy flare-related particles--Crucial for comparisons with the RHESSI mission
SMS	Solar wind ions	2/3 operational	Solar and solar wind abundance and composition measurements
EPACT	Solar energetic particles	Normal	Unprecedented time resolution and dynamic range--Sole replacement for ACE instrumentation
TGRS	Transient gamma-ray bursts	Normal	First high resolution spectrographic survey of cosmic gamma-ray bursts
KONUS	Continuous monitoring of gamma-ray bursts to 10 MeV	Normal	Essential element in gamma-ray bursts timing network

* VEIS electron spectrometer damaged, reconstituted - same quantities measured.

Wind Campaigns

A number of brief campaigns will be carried out by the primary investigator teams in collaboration with those of other spacecraft. These are summarized in Table 2. Some of the campaigns—those dependent on solar events, for example—will be ongoing due to the unpredictable nature of the events, but will actually be conducted only for the duration of the events themselves.

The Ramaty High Energy Spectronscopic Imager (RHESSI) campaign, already in progress, will help ascertain more about the nature of solar flares by observing X rays and gamma-rays with RHESSI, and particles from solar flares using Wind. Particles between 30 keV and 100 MeV are emitted from active regions at the bottoms and tops of prominences at the time of flares and will reach Wind later. Wind also has the unique WAVES experiment, which can detect solar type III events, whose electrons can be observed in situ with the 3 Dimensional Particles [3DP] instrument. The higher energy ions can be observed, and their composition can be determined using the EPACT instrument on Wind.

The second campaign, "Petals," will exploit the need to phase Wind with the Moon to deflect the spacecraft to L1. The apogee of these eccentric orbits in the equatorial plane is at about 90 Re and the perigee is at 5–15 Re in the magnetotail. There will be more than 10 magnetopause crossings, and a number of days will be spent in the tail in the region where reconnection has already been shown to occur.

One way to increase the forecast time for space weather predictions would be to move a solar wind monitor to twice the L1 distance (~500 Re) from Earth toward the Sun, increasing the warning time to 60–90 min. However, it is currently not known what degradation in forecast accuracy would be incurred over such a distance. One of the goals of the Living With a Star (LWS) Solar Sentinel element is to gain such an understanding. By an excursion of Wind to L2, ~250 Re behind Earth, it may be possible to resolve the science question. Combining ACE L1 observations with Wind measurements at L2, it would be possible to directly examine geo-effective structures as seen at L1 and later at L2. By correlating the Wind and ACE observations, the "Trailblazer" campaign will determine the feasibility of forecast improvements.

The "Interplanetary (IP) Events" campaign, which is already in progress, is aimed at comparing ACE and Wind observations of major solar events and magnetic clouds and comparing them with the magnetic cloud theories. This campaign will also continue after Wind is in orbit at L1.

The "Storms" campaign is similar to IP, but it is aimed at determining the geo-effectiveness of solar wind disturbances. The Wind data provide a unique perspective on these phenomena, including with WAVES, the ability to radio track CMEs to Earth, and with 3DP, to investigate the origin and structure of CMEs through dispersion analysis of the 1–40 keV solar electrons. Wind/SWE sometimes returns the only reliable solar wind proton data during solar events associated with large fluxes of energetic particles. During the campaign, other spacecraft will also measure the magnetosphere response of geoeffective events.

Table 2. WIND Campaigns

Campaign	Purpose	Duration	Collaborating Spacecraft	Comments
RHESSI	Solar Flare Mechanisms	~2 years	RHESSI* SOHO	Energetic electrons and ion distributions
Petals	Substorms and Magnetic Reconnection	4 1/2 months	POLAR CLUSTER Geotail	Magnetosphere-related studies
Trailblazer	Solar Sentinel Test	20 months	ACE SOHO	Solar wind propagation over 500 Re with Wind at L_2
IP Events	2D topology of interplanetary structures	intermittent	ACE	Wind at 350 Re ahead and behind Earth in orbit
Storms	Geoeffective Storms	intermittent	ACE Cluster POLAR Fast	

* The RHESSI spacecraft has been renamed in memory of Reuven Ramaty.

The Wind Trajectory

Out of the many dynamical models that were computed, Figure 1 depicts the earliest and most economical way for Wind to transfer out of the distant prograde orbit and transition to L1. The intervening six "petal" orbits are required to enable the lunar conjunction needed to go to L1. Following a single pass at L1, a transfer from L1 to L2 and back is proposed to implement the Solar Sentinel "Trailblazer" campaign. Final insertion into a Lissajous orbit at L1 will occur in August 2004. The Lissajous at L1 was chosen because it requires a minimum of orbital maintenance and will permit Wind to monitor the solar wind and energetic particles and track CMEs for about 8–10 years, well into the Solar Terrestrial Relations Observatory (STEREO) era. It has been proposed that Wind go directly to L1 after the petal orbits to support an "L1 Cluster" mission, involving ACE, SOHO, DSCOVR (Triana), and Genesis. These alternatives are currently under review.

We would be very interested in discussing possible future campaigns with readers. Wind level-zero data is freely available. A new Web site currently under construction will eventually serve as the Wind bulletin board for such matters.

During the next few years, the Wind investigations can carry out a valuable program of collaborative investigations, many more than are required to justify the modest funding needed.

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NSF Geosciences Advisory Committee Soliciting Input

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The Geosciences Advisory Committee of the U.S. National Science Foundation (NSF) is soliciting the views and concerns of the geosciences community in advance of a meeting of the committee scheduled for 6–8 November at NSF headquarters in Arlington, Virginia. At this meeting, the committee will consider inter alia, current and future geosciences plans and programs, facilities, interactions with other NSF directorates, and other issues of concern to the community. The draft agenda is available at the Web site here.

The chair and members welcome and solicit the views and concerns of the community so they may better represent their constituencies at upcoming committee meetings. To contact current members with views and suggestions, or to obtain additional information about the Advisory Committee, including meeting summaries and agenda, see: http://www. geo.nsf.gov/geo/about/advisory.htm.

The NSF Directorate for Geosciences supports a broad range of innovative research focusing on understanding and predicting Earth's environment and its habitability. The Advisory Committee for Geosciences consists of representatives of the wider geosciences community, and advises NSF, the Directorate, and its divisions of atmospheric sciences, ocean sciences, and Earth sciences. The committee consists of about 18 members who serve terms of three years. The current chair is Joyce Penner of the University of Michigan.

The committee provides overall oversight of GEO programs and performance, and guides long-term planning and strategies for improving geoscience research and education. At its Spring 2002 meeting, the committee considered potential initiatives in fresh water, natural hazards, biogeosciences, and cyber-infrastructure. In addition, the committee reviewed activities in education and diversity, and discussed GEO strategies for communication with the science community.

MINERAL AND ROCK PHYSICS FOCUS GROUP

Outstanding Student Awards

AGU's Mineral and Rock Physics Focus Group will formally award their 2002 Outstanding Student Awards at the M&RP-SEDI Reception. The reception will be held 7 December, during the 2002 Fall Meeting in San Francisco, California.

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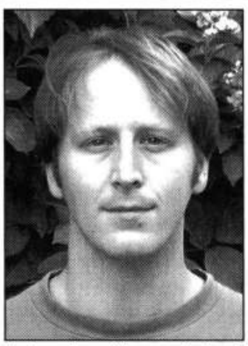
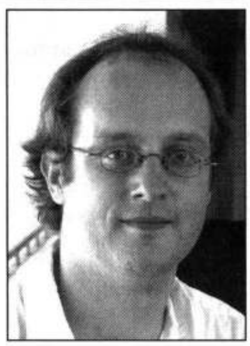
Sébastien Merkel received a M.Sc. in physics from the École Normale Supérieure de Lyon in France in 1997. He is presently finishing a



Ph.D. thesis titled "Elasticity and preferred orientations in the deep Earth: an experimental approach" under the supervision of Philippe Gillet at the École Normale Supérieure de Lyon in collaboration with Russell J. Hemley from the Geophysical Laboratory, Carnegie Institution of Washington. Sébastien's research interests include ultra-high pressure mineralogy, elasticity, and rheology. He will start as a postdoctoral fellow at the University of Tokyo later this year.

Gerd Steinle-Neumann received his Ph.D. from the University of Michigan in Ann Arbor in 2001 for a thesis titled "Physics of iron and Earth's inner core." He worked under the



supervision of Lars Stixrude and in collaboration with Ronald E. Cohen from the Geophysical Laboratory, Carnegie Institution of Washington, where he is currently a Carnegie Fellow. Gerd uses computational theory to study physical properties of Earth materials in order to interpret geophysical observations and understand experimental data. The methods applied are based on nuclear charges and electrons only, and have been shown to have predictive power in many fields of material sciences. Gerd will start as an assistant professor at the University of Bayreuth, Germany, later this year.