The multiple roles of dust in ocean biogeochemistry

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THE OCEAN IS IMPORTANT IN THE CARBON CYCLE

(IPCC AR5)

ocean contains ca. $50\times$ as much carbon as the atmosphere

it currently takes up ca. $1/4$ of anthropogenic carbon emissions
CARBON INCREASES WITH DEPTH

Dissolved inorganic carbon (DIC) is lower at the surface than at depth.

This keeps atmospheric $pCO_2$ lower than for a 'well-mixed' ocean.

DIC at depth increases with 'age' from Atlantic to Pacific.

(Key et al., 2004)
THE REASON: BIOLOGICAL CARBON PUMP

biological production in the ocean occurs mostly near the surface (light!)

aggregation & defecation produce particles that are large enough to sink

at depth, organic material is respired by animals & bacteria, releasing carbon

mixing & circulation bring carbon back to the surface on timescales from 10 to 1000 years

(Passow et al., 2014)
HOW IS BIOLOGICAL ACTIVITY DISTRIBUTED?

- net primary production in the ocean $\approx 50-60$ PgC yr$^{-1}$, same as on land, but biomass lower by a factor of 100!
- biological production is high where mixing and circulation bring nutrients to the surface and there is enough light
HOW CLOSED IS THE SYSTEM?

biological production in the surface ocean requires nutrients (N, P, Fe, Co, Zn, . . .)
sinking moves then down with carbon
at depth, biomass is remineralized
return of nutrients to the surface, depends on the residence time of the element
some residence times:
- Phosphorus: 25000 years
- Nitrogen: 3000 years
- Iron: 10-100 years

(Passow et al., 2014)
DUST AS NUTRIENT INPUT

- Dust deposition brings in N (largely anthropogenic), P (from minerals), Fe (also from minerals).
- Globally, the input is minor compared to internal recycling for elements with long residence time, such as N and P.
- For elements with short residence time, such as Fe, it is important.
CONSEQUENCE OF THE SHORT RESIDENCE TIME OF Fe

- High-Nutrient-Low-Chlorophyll regions: despite enough nitrate and phosphate little net primary production
- what is missing is iron; crosses mark iron fertilization studies
ARTIFICIAL AND NATURAL IRON FERTILIZATION

- artificial iron fertilization (left, SOIREE): iron is distributed over a patch of $\approx 100 \text{ km}^2$
- natural iron fertilization (right, Crozet island): an island serves as iron source for its otherwise iron-poor surroundings

both have been shown to lead to elevated chlorophyll, NPP, ...
Iron distribution in the ocean is complex.

Iron concentration along a section through the Western Atlantic (Rijkenberg et al., 2014) due to the short residence time, iron distribution is strongly affected by local sources and sinks. Iron is hard to measure in seawater; problem of contamination, reliable measurements start around 1985.
IRON IS PARTICLE REACTIVE

iron in oxic seawater is mostly Fe(III)
solubility of inorganic Fe(III) is extremely low:
< 0.1 nmol kg$^{-1}$ at typical ocean pH
→ iron is lost much faster from the ocean than nitrogen or phosphorus

loss proceeds via scavenging on particle surfaces, accelerated by aggregation of small colloids

(Honeyman and Santschi, 1989)
A CRISIS A LONG TIME AGO

ocean oxygenation caused iron to precipitate; iron became scarce for marine biology!
many exploited iron ores are created this way; especially ‘banded iron formations’
e.g. in South Africa

Holland, 2006
IRON CHEMISTRY IS COMPLICATED

Iron can exist in many different forms in seawater:

- inorganically bound in redox states Fe(III) and Fe(II)
- Fe(II) is soluble, Fe(III) precipitates
- in oxic seawater, Fe(II) is quickly oxidised
- photochemical processes can produce Fe(II)
- strong organic iron-binding substances exist in seawater
- typically, 99% of iron is bound to these ligands

This iron *speciation* greatly affects iron loss, dust iron solubility, iron uptake ...
binding of iron to organic ligands prevents rapid scavenging
two main types of ligands proposed: degradation products, such as
porphyrins, and siderophores, produced by bacteria under iron
limitation
production / degradation pathways probably as varied as ligand origins

Witter et al., 2000
IT IS EVEN WORSE..

Gledhill et al., 2012

besides redox speciation and organic complexation, iron species can be anything between dissolved, colloidal and small particles

speciation influences residence time

modelling iron cycling in the ocean is not trivial! Iron model intercomparison (FEMIP) (Tagliabue et al. 2016)
THE MAIN EXTERNAL IRON SOURCE: DUST DEPOSITION

• dust carries lots of iron into the ocean
• but only a small (and variable) fraction dissolves!
• dissolution depends on wet/dry deposition, atmospheric history, but especially iron chemistry in the water
• but: dust also brings in particle surfaces → scavenging!

(Jickells et al., 2005)
OTHER SOURCES OF IRON

besides lithogenic dust, there are also other sources of iron:

- rivers
- sediment diagenesis
- hydrothermalism
- cosmic dust . . .

but for all of them, most of the iron is lost as particles close to the source.

quantification of different iron sources is ongoing, large uncertainties so far!
TROPICAL ATLANTIC: DOMINATED BY DUST

relative role of the different iron sources along a section across the subtropical/tropical Atlantic estimated from isotopic composition of dissolved iron

- sediment diagenesis
- hydrothermalism
- suspended sediment particles
- saharan dust

→ in the tropical and subtropical Atlantic, dust dominates as source of iron

(Conway et al, 2014)
BUT: DUST ALSO SCAVENGES DISSOLVED IRON

(Wagener et al. 2010)

dissolved iron decreases after dust addition in mesocosms;
dust can act as dFe sink

is that important in the open Atlantic, where often biogenic particles dominate?
needs understanding & modelling of particle dynamics!
PARTICLE DYNAMICS

aggregation processes (Jackson and Burd 2015)

typical marine aggregate (Iversen, pers. comm.)

dust brings in mostly micrometer-sized particles
these hardly sink on their own
sinking dominated by larger, mixed organic/inorganic aggregates
Lithogenic material in the Atlantic

particulate Fe along section A16N (Barrett et al. 2012)

much new information on lithogenic particles from A16N and US Geotraces Atlantic Zonal Transect (Barrett et al. 2012, 2015, Lam et al. 2015, Ohnemus et al. 2015)

- increased pFe under dust plume
- high pFe at the surface, minimum around 100m depth, then again increase
- deep lithogenic particle concentration dominated by small particles
- large fraction of lithogenics highest around 100 m depth, higher towards African coast

indicates dynamic aggregation / disaggregation cycle
MODEL SETUP

global biogeochemical model REcoM including the iron cycle (Hauck et al. 2013, Völker and Tagliabue 2015)

added model for lithogenic particles with two size classes (fine dust and faster-sinking aggregates)

quadratic aggregation and linear disaggregation of particles

lithogenic particles included as additional scavenging agents for dissolved iron

scavenging proportional to particle concentration

rate equal for organic and lithogenic particles
MODELLED VS. OBSERVED PARTICULATE Fe

particulate Fe along section A16N (Barrett et al. 2012)

modelled particulate Fe (nM) along section A16N
**MODELLED VS. OBSERVED pFe**

Modelled pFe (nM) along A16N

Obs’d pFe along A16N (Barrett et al. 2012)

Some agreement, but also some disagreement:

+ pFe concentration in the right order of magnitude
+ Minimum in particle concentration around 100m depth
+ Size-class distribution consistent with Ohnemus et al. (2015)
  - Surface pFe concentration somewhat high → aggregation rate?
  - Deep pFe maximum too deep → variable disaggregation?
  - Deep pFe maximum too far north → dust deposition?
  - Shelf-derived nepheloid layers absent
EFFECT ON DISSOLVED Fe

- dFe with dust only as Fe source
- dFe with dust as Fe source and as additional scavenging
WHY THE REDUCTION? RESIDENCE TIME OF DFe

residence time (stock/total loss rate in years) of dissolved iron varies by several orders of magnitude

affected by scavenging on dust/biological particles and biological uptake

distribution of residence time agrees quite well with data-based estimates (Usher et al. 2013)
GLOBAL EFFECT AT SURFACE

surface dFe difference between a run with/without lithogenic particles present as scavenging agent

scavenging by lithogenic particles
- reduces surface dFe directly in high-deposition regions
- but hardly everywhere else
GLOBAL EFFECT AT DEPTH

**dFe difference (2000 m depth)** between a run with/without lithogenic particles

- dFe reduction more widespread at depth
- 1st cause: lateral transport of fine lithogenic material
- 2nd cause: downstream effect of localized scavenging
- reduces deep water dFe

Atlantic – Pacific gradient

caveats: strength of effect depends on scavenging residence time, at present highly tuned in ocean iron models (Tagliabue et al., 2016) also affected by ligand excess (Völker and Tagliabue, 2015)
SO, IS DUST A SOURCE OR A SINK OF dFe?

so: how much source, how much sink?
generally, dFe source stronger than vertically integrated sink; but depends somewhat where you look!
SOME CONCLUSIONS

- Lithogenic particles in the Atlantic modeled with a 2-size-class model
- Both aggregation and disaggregation important
- Reproduces some features of observed distributions of lithogenic particles
- Brings surface dFe distributions under the dust plume more in line with observations
- Affects on the global deep dFe distribution through lateral transport
- Allows to quantify the role of scavenging and compare it to local sources
- Need to go further in developing more process-oriented iron models, making use of the available and coming GEOTRACES data