Answers to comments of anonymous referee #2:

General Comments

This paper describes a simulation of the fertilizing effect of volcanic ash deposited in the aftermath of the Kasatochi 2008 eruption to the iron-limited NE Pacific Ocean. The model simulation indicates that iron, contained in the volcanic ash, triggered a phytoplankton bloom. A comparison with observed carbon dioxide drawdown at the surface suggests that the model is in agreement with a set of observations.

It is, to-date, a relevant scientific question if, or to what extent, the current generation of biogeochemical models is capable to simulate the limiting effect of iron. The approach to simulate a "natural" iron fertilization experiment, such as a massive deposition of volcanic ash, is up-and-coming. To this end, I think that this is a very important paper! As regards the present form of the manuscript, however, I feel that it lacks essential information. Bluntly put, it is not clear what kind of model the authors are using and, second, if the model is realistic. I suggest to complete the model description and to append additional model evaluation.

Following to the reviewer's suggestion, the model description is extended in the revised version of the manuscript and further model evaluations are added. See below for more details.

Specific Comments

• The model description is incomplete or at least convoluted: According to pg. 9234, ln. 9: "regional scale ocean ..." a regional scale model is applied. pg. 9238, ln.1 raises some doubt about that: "We focus here on one-dimensional column applications around the buoy Papa (50N, 145W) although the model is set-up in three dimensions." And finally, pg. 9238 ln. 9 seems to contradict that: "it appears appropriate to neglect horizontal advection and diffusion in this column model study." Hence the reader is left uncertain on the issue if it is a 3-D model or not. I was also baffled by the comment that the seasonal cycle of the mixed layer depth is prescribed (pg. 9238, ln. 5). In summary, I have the impression that the physical model is rather special. This calls for (1) an exhaustive documentation including all underlying equations and in (and out) going fluxes and data, and (2) a comparison of the simulated physics with observations (e.g., sea surface temperature measurements from space).

We agree with the reviewer, that the model description was incomplete in the original manuscript, which was noted also by reviewer 1. The meteorological forcing data introduced on page 9237, lines 18-21 of the original manuscript have been interpolated to a 5°x5° latitude-longitude grid between 175.5-132.5°W and 40-60°N consisting of 10 x 4 grid cells, as the original purpose was to carry out 3-D model simulations. At this horizontal resolution it appears appropriate to neglect horizontal advection and diffusion, in particular as the focus of this study is on the summer months, where wind speed is considerably lower compared to the rest of the year (see Whitney and Freeland, 1999). The coarse model resolution, however, leads to instabilities at the boundaries, so that we decided to carry out 1-D column model simulations. Therefore, the results presented in the manuscript are representative for a 5°x5° area from 145-150°W and 47.5-52.5°N, including the location of the station Papa in the middle of the eastern edge. These additional explanations are now included in the revised manuscript.

A vital element of the paper is the simulated effect of iron. As regards the iron cycle, however, the information given is very generic (pg. 9237, ln. 4) and does not allow for a reproduction of the results. In order to be of interest to other scientist the paper must contain (or reference) all model equations and associated parameters.

We agree with the reviewer, that the description of the iron cycle is too vague in the original manuscript. We added the iron model equations and associated parameters as supplementary information to the paper.

• Additional model evaluation needs to be appended: The only model evaluation there is, is a comparison with surface pCO2. Because there is so much more data available at station PAPA, a mean reviewer might conclude that the model-data comparison is cherry-picked. One way to proceed could be: (1)Run the model to equilibrium (without the addition of iron contained in volcanic ash) and compare it with a climatological seasonal cycle of macronutrients. (2) The Hamme et al. (2010) paper compares chlorophyll, gross primary production, net community production and phytoplankton concentrations measured during the bloom with data from other years. A comparison of this data with simulations would be very meaningful.

We note that in addition to the comparison of modelled and measured pCO_2 in surface sea-water at Papa, the original manuscript also contained a comparison of modelled and measured pH in surface sea water at Papa (see page 9239, line 22-26). Nevertheless, we agree with the reviewer, that further evaluations of the model results are necessary, in particular during undisturbed conditions to increase confidence in the model to be able to realistically reproduce undisturbed und disturbed situations. Therefore the evaluations shown below are added to the revised manuscript.

As already written in the original manuscript on page 9238, line 12-13, the 1-D model is run for two years with the first year serving as spin-up time. We added to the revised manuscript that the 1-D model was in quasi-equilibrium after this one year, as simulation results for the third model year resemble that of the second year. It should be noted that for a 1-D column model set-up with limited dynamical variability, quasi equilibrium conditions are reached much faster than for a 3-D model set-up.

Tab. 1 Measured fluxes and concentrations under undisturbed and disturbed conditions around station Papa:

	NCP (mmol C m^{-2} $d^{-1)}$ undisturbed / disturbed	Silicate (μmol / l) undisturbed / disturbed	Nitrate (μmol / l) undisturbed / disturbed
Measurements	5-15[1)] / 20-40[1)], 30-60[2)]	10-22[1),3)] / 5[1)], 5-12[2)]	9-13[3)] / 2-10[2)]

[1)] Hamme et al. (2010), [2)]Lockwood et al. (2012) , [3)]Witney and Freeland (1999)

Tab. 2 Modelled depth integrated NPP (net primary production) and NCP (net community production) of the upper 10 m.

mmol C m^{-2} d^{-1}	Reference 2008	Reference 2008 + Kasatochi
1 Aug NPP	5.26	5.26
31 Aug NPP	16.38	33.92
1 Aug NCP	2.25	2.25
31 Aug NCP	10.66	25.45

Tab. 2 shows two snapshots of the simulation results: The first one at August 1 before the Kasatochi eruption and the second one at August 31 about 2 weeks after the arrival of ash at Papa. For both runs, the undisturbed ('Reference 2008') and the disturbed run ('Reference 2008+Kasatochi'), the net primary production NPP (gross production – autotroph respiration) and net community production NCP (NPP – heterotroph respiration) are equal for August 1. The value of NCP for the upper 10 m extrapolated to the surface ocean including the water column to the mixed layer depth (~20-40m) falls in the lower range of the values given in Tab. 1. It is interesting to observe that the NPP nearly doubles from the undisturbed to the disturbed case, while the NCP increase was about 250%. This effect was caused in the model by an increase of bacterial respiration in the disturbed run in which bacterial activity was stimulated while at the same time they have to compete with phytoplankton for more exhausted inorganic nutrients.

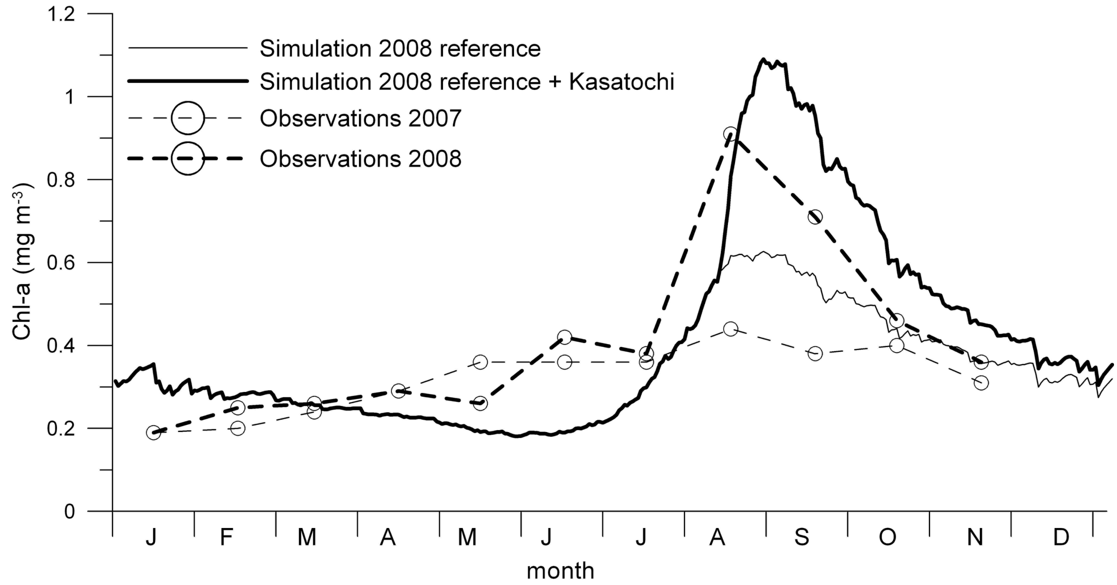

Fig. 1 Comparison of observed Chl-a concentrations at Papa for 2007/2008 (Hamme et al., 2010) and simulated Chl-a concentrations for 2008 with and without iron fertilisation in August 2008.

The comparison between observed Chl-a concentrations at Papa for 2007 and 2008 shows reasonable agreement with the simulated concentrations for the 2008 undisturbed and 2008 disturbed scenario, respectively. Applying a ratio of C:Chl = 120 (Marchetti et al., 2007), the chlorophyll concentration was calculated from the phytoplankton carbon content. The difference of maxima between the disturbed and undisturbed case is about 0.5 mg m^{-3} for both the observations and the simulation. The simulated largest difference was 2 weeks later than the observed ones. This might be caused by the prescribed climatologic mixed layer depth (MLD) of 40 m in August. Observations of 2008 by the Argo fleet suggest a lower MLD of about 20 m (http://www.pac.dfo-mpo.gc.ca/science/oceans/data/projects/argo/MLD/Mld2784.gif).

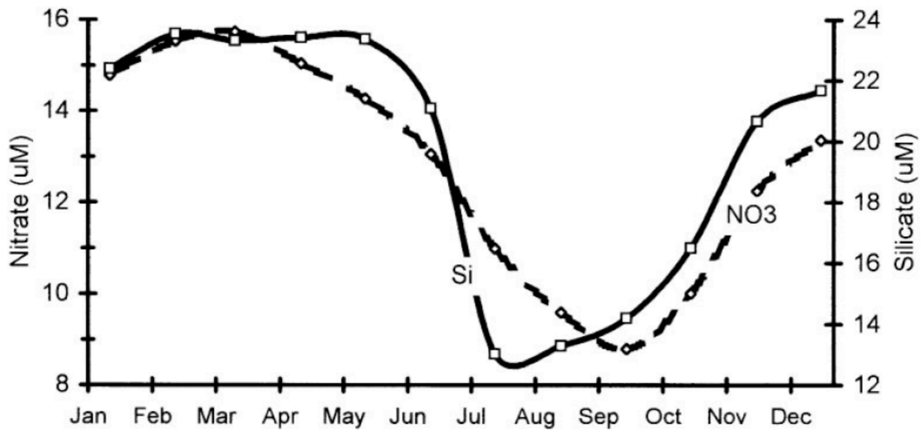

Fig. 2 Annual cycle of surface nitrate and silicate: climatological data from Whitney and Freeland (1999).

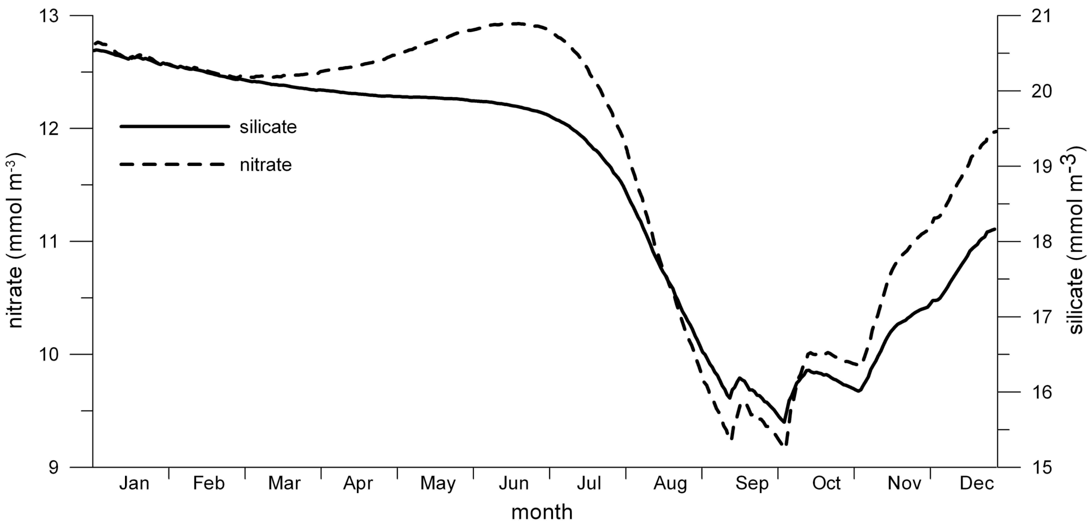

Fig. 3 Modelled Annual cycle of surface nitrate and silicate for the reference run 2008 (without iron fertilisation in August).

Fig. 3 shows that the new model setup results in surface nitrate and silicate time series which compares reasonable well with measurements (Fig. 2), even though the exact values and the timing of the climatologic data could not be reproduced for the situation in 2008.

Technical Corrections (incomplete list)
Some of the figures are of very poor quality, e.g., axis and colorbar labels of figure 5 are not readable.

The size of figure titles, axis labels, legends and colour bars has been increased in the revised version of the manuscript.

I think the reference to the sockeye salmons is not really needed to make the paper *work.*

We agree with the reviewer that the manuscript presents enough results also without the discussion of the sockeye salmon return runs connected to the Kasatochi fertilization event. However, as the manuscript is able to present a considerable increase in zooplankton biomass after the fertilization of the NE Pacific with iron from volcanic ash (see Fig. 5 in the document answering reviewers 1 comments), which has not been shown before to our knowledge, this result represents an important indication for the connections between the Kasatochi eruption and record Fraser River salmon returns. Therefore, we kept the discussion in the revised manuscript.

Replace "near surface" in the title of figure 7 with actual depth.

Done

Figure 8: add the 2007 simulation of ECOHAM;

As already mentioned in the original manuscript on page 9237, lines 18-21, we processed meteorological forcing data for the year 2008. In the revised manuscript we further clarified, that although the 1-D model is run for two years with the first year serving as spin-up time without volcanic ash fertilization to reach quasi equilibrium, this is done by running the model repeatedly with 2008 meteorological forcing data (a usual procedure). Therefore, model results for 2007 are not available.

Figure 10: a measure of the quality of the respective model simulations, such as correlation or RMS, would be nice (to be put into the text). Also, I would replace "factor" with actual deposition.

As suggested by the reviewer, we added the actual deposition values in the caption of Fig. 10. A statistical analysis of the agreement of model simulation results with measurements is not included, as the only parameter that was modified in the different model simulation results was the iron flux to the ocean.

Figure 9: I agree that the exact timing of the ash deposition is uncertain to some extent. Hence, I like the idea of the authors to test a suite of deposition scenarios. However, because the volcano erupted in August, I would skip all deposition scenarios prior to this date.

Different to the reviewer's suggestion, we kept all month in Figure 9. The sensitivity study was not conducted because of the uncertainty in the exact timing of the ash deposition from Kasatochi, which is in the order of a day only. The sensitivity study was conducted to illuminate the general dependency on the time of the year of any volcanic eruption with volcanic ash deposition over the NE Pacific to fertilise the surface ocean. Clarifications are added to section 5.1 of the revised manuscript.

Figure 2b: Is it possible to give this in units nmol iron /m2

According to the reviewer's suggestion the unit mm/d is converted to µmol Fe/m^2/d.

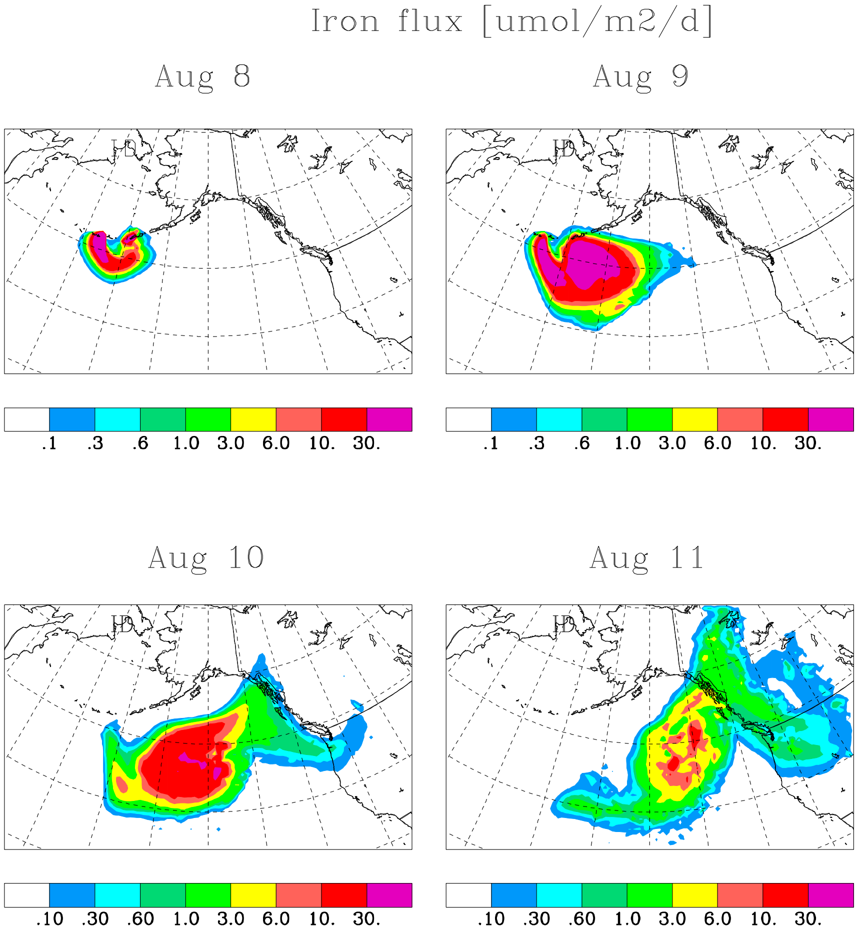

Fig. 3. Modelled daily fluxes of volcanic iron into the NE Pacific Ocean (µmol Fe/m^2/d).

Figure 3: What about remineralization of detritus in the water column?

According to the suggestions of reviewer 1, we clarified that we model the iron cycle of dissolved iron. As schematically demonstrated in Fig. 3, the model takes into account only the dissolution of iron from the sediments. However, for the one-year cycle investigated in the manuscript, this does not play a role at the location of Papa in the NE Pacific Ocean, with an approximate ocean depth of 4250 m. The pelagic remineralisation flux of iron had been implemented in the model but due to the small amount (0.96 µmol Fe m^{-2} yr^{-1}) left out in Fig. 3 of the original manuscript. In the revised manuscript we added these fluxes in the corresponding diagram.

Figure 1: How is the "ash cloud position" defined? What is a "coast buffer"?

We deleted the coast buffer from Fig. 1 of the original manuscript (see below Fig. 4), because it is not of interest to the current manuscript. We added to the caption of Fig.1: '… based on MODIS level 1b data at 11 and 12 µm using Brightness

Temperature Difference (BTD).'

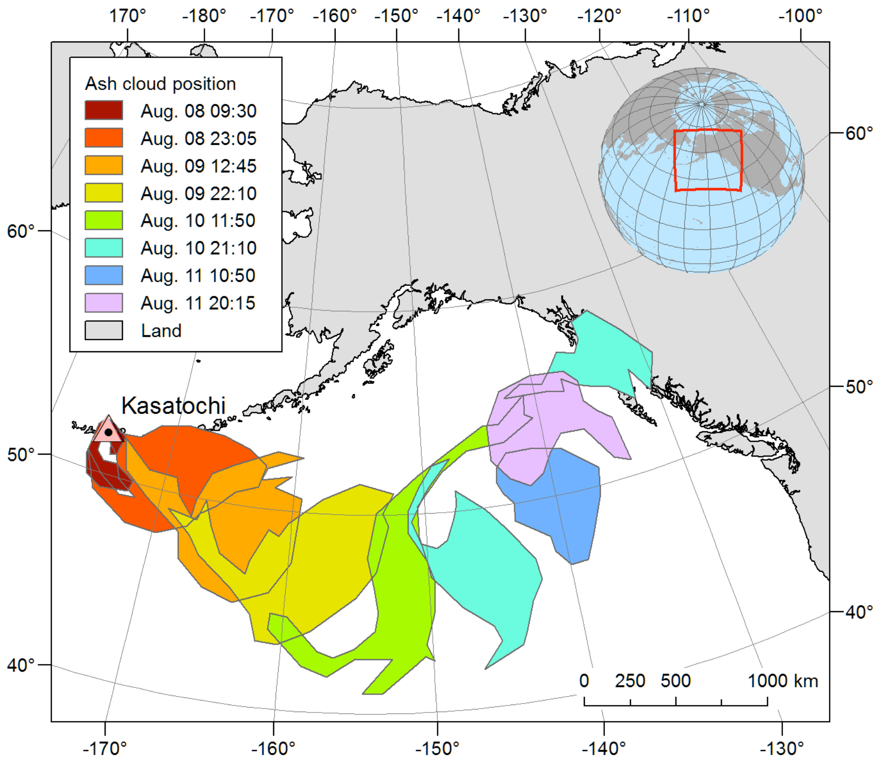

Fig. 4. Atmospheric dispersion of the Kasatochi ash cloud from 8 August to 11 August 2008 based on MODIS level 1b data at 11 and 12 μm using Brightness Temperature Difference (BTD) (from Langmann et al., 2010a).

pg. 9243, ln. 11: "planed" => planned

done

5.2 "Amount of volcanic ash and associated ...": Add a discussion of that uncertainty, that is related to processes in the water column which partition iron into its bioavailable and unavailable forms.

As suggested by the reviewer, the following discussion is added to section 5.2: 'Further uncertainties result from the complexity of the iron biogeochemical processes in the ocean, which are only partly understood: Bio-availability of iron in the ocean water column is influenced by its chemical forms (speciation, redox state, ligands), biological cycling, and the different uptake strategies of the phytoplankton and bacteria communities (Boyd and Ellwood, 2010, Breitbarth et al., 2010). Iron co-limitations and interactions with other nutrients and trace metals affect the residence time of iron in the surface ocean, and untimately the bioavailability of iron. Volcanic ash particles, for example, do not only supply soluble iron, but also particle surfaces which can act as scavengers for iron (Baker and Croot, 2010).'

pg. 9238, ln. 13: why is the model not run into a quasi equilibrium?

As already stated in the original manuscript on page 9238, line 12-13, the 1-D model is run for two years with the first year serving as spin-up time. We added that the 1-D model was in quasi-equilibrium after this one year, as simulation results for the third model year resemble that of the second year. It should be noted that for a 1-D column model set-up with limited dynamical variability, quasi equilibrium conditions are reached much faster than for a 3-D model set-up.

References:

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