Iron flux induced by Haida eddies in the Gulf of Alaska

Peng Xiu,[1] Artur P. Palacz,[1] Fei Chai,[1] Eric G. Roy,[1] and Mark L. Wells[1]

Received 27 April 2011; revised 31 May 2011; accepted 2 June 2011; published 13 July 2011.

[1] Mesoscale anticyclonic Haida eddies are proposed to deliver a substantial amount of iron into the Gulf of Alaska (GOA) central gyre, where surface waters experience high-nitrate low-chlorophyll conditions. In this study we calculate an averaged upwelling flux of dissolved iron into the euphotic zone (100 m) of 1.17 μmol m^{-2} d^{-1} based on observed iron profiles and modeled eddy dynamics and resultant vertical velocities. This estimated eddy-derived iron supply rate is comparable with new estimates of pulsed iron fertilization rates from rare volcanic ash deposition events. Despite the relatively small area affected by Haida eddies, they are estimated to contribute about 4.6×10^6 moles of dissolved iron yearly to the GOA, which is equivalent to the annual atmospheric dust deposition. Haida eddies therefore represent a major iron source that should strongly influence the regional biological productivity and carbon budget of the GOA. **Citation:** Xiu, P., A. P. Palacz, F. Chai, E. G. Roy, and M. L. Wells (2011), Iron flux induced by Haida eddies in the Gulf of Alaska, *Geophys. Res. Lett.*, *38*, L13607, doi:10.1029/2011GL047946.

1. Introduction

[2] The biological conditions in the central Gulf of Alaska (GOA) gyre are characterized as high-nitrate-low-chlorophyll (HNLC), in which additional iron plays a key role in stimulating phytoplankton growth [*Boyd et al.*, 2004]. Previous studies showed that there are three major sources of iron into these HNLC surface waters: (1) dust deposition originating from the Asian continent or Alaska [*Jickells et al.*, 2005], (2) horizontal and vertical mixing processes [*Johnson et al.*, 2005], and (3) the physical transport of mesoscale anticyclonic eddies, which move iron-rich waters from the continental shelf into the open ocean [*Johnson et al.*, 2005].

[3] Haida eddies generally form in late fall or early winter along the south shore of the Queen Charlotte Islands (Haida Gwaii), detach from the shelf slope in late winter or spring, and propagate slowly westwards into the central Alaskan gyre. They are baroclinic in the vertical structure with typical diameters of 80~300 km and extending to at least 1000 m depth [*Crawford*, 2002]. Even though iron concentrations in surface waters of young Haida eddies are indistinguishable from those in surrounding HNLC waters, Haida eddies usually show enhanced biological activities [*Whitney and Robert*, 2002] thought to be sustained by an upwelling flux of iron from the iron-rich eddy core waters. The upwelled iron is used rapidly by phytoplankton, and can cause partial drawdown of macronutrient concentrations in surface layers [*Peterson et al.*, 2005]. Upwelling normally is not the primary circulation response in anticyclonic eddies but it can be caused by several mechanisms, such as relaxation of depressed isopycnal during the eddy decay phase, submesoscale features due to the ageostrophic secondary circulation [*Martin and Richards*, 2001], and the coalescence of eddies [*Peterson et al.*, 2005]. However, the large spatial and temporal variability of these and other eddies cause major uncertainties in estimating the extent that deep waters are effectively brought to the surface. Here we use a combined approach of linking *in situ* iron measurements with numerical model results to better estimate the effect mesoscale eddies exert on iron transport to surface waters in the GOA.

2. Methods

[4] Vertical profiles of dissolved (dFe) and total iron (TFe) were measured in May 2007 to characterize iron distribution in an approximately 3 month-old Haida eddy that formed in the winter of 2007 (Haida-2007, Figure 1a). Iron profiles (0–800 m) were collected from Haida eddy source waters at Cape St. James (CSJ) off the southern tip of the Queen Charlotte Islands, the approximate center of Haida 2007 eddy (EC), a station directly outside the eddy (O2), and at ocean station OSP as an eddy-free reference site (Figure 1a). The detailed analysis methods for measuring dFe (0.2-μm filtration) and TFe (unfiltered, analyzed after >6 months of acidification) concentrations were described by *Roy et al.* [2008].

[5] An eddy-resolving circulation model based on the Regional Ocean Model System (ROMS) was used to simulate mesoscale eddies [*Xiu et al.*, 2010]. Following the eddy detection method of *Henson and Thomas* [2008], 3-day averaged modeled sea surface height anomaly (SSHA) data were used to label and track eddies larger than 80 km in diameter, lasting longer than 3 months, and occurring and moving westward in the Haida region during 1993–2008.

[6] We consider only the iron fluxes associated with upwelling rather than net vertical velocities (accounting for upward and downward motion) and average them over the entire eddy field since we assume that the phytoplankton community takes up iron as rapidly as it is supplied [*Martin and Richards*, 2001]. This approach provides an upper limit but more realistic assessment of iron inputs fueling the phytoplankton community. The vertical iron flux was calculated across two depth thresholds, 100 m (the mixed layer depth) and 50 m (the euphotic zone in summer) [*Peterson et al.*, 2005]. We also used iron data from the Haida-2001 eddy [*Johnson et al.*, 2005] at its 0-month and 7-month ages to gain preliminary insight to eddy aging effects on our annual flux estimates. Details on the method used to

[1]School of Marine Sciences, University of Maine, Orono, Maine, USA.

0094-8276/11/2011GL047946

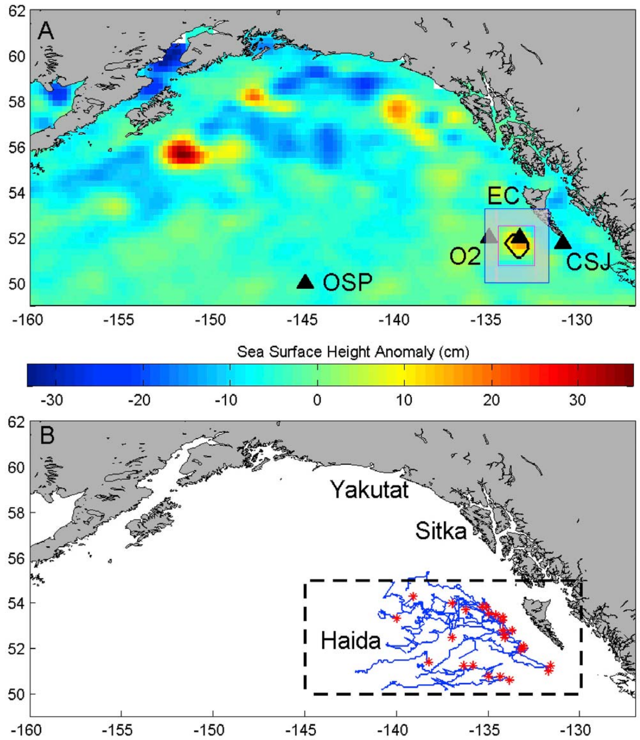

Figure 1. (a) Spatial distribution of sea surface height anomaly on May 13, 2007. The data comes from a merged and gridded satellite product produced and distributed by AVISO (http://www.aviso.oceanobs.com/). Locations of in-situ measurements are denoted by black triangles. The black contour line highlights the core area of an anticyclonic eddy in the Haida region. The magenta box is the eddy box encapsulating the eddy core, and the reference frame is the shaded area between the magenta box and the blue box. (b) All the tracks of those westward propagating eddies identified from model outputs during 1993–2008 in the Haida region. For those eddies lasting longer than one year, we only show the first-year track here. Red asterisks are used to show the starting positions of the eddies.

calculate the vertical iron flux within and outside the eddy are provided in the auxiliary material.[1]

3. Results and Discussion

[7] The dFe concentrations in surface waters at Station EC (0.16 μmol m^{-3}) were an order of magnitude lower than that measured at Station CSJ (1.45 μmol m^{-3}) (Figures 2a and 2b), representing the rapid removal by biological processes. Concentrations of dFe increased sharply with depth at EC to a maximal value of ~2.0 μmol m^{-3} between 400 m and 800 m; very similar to that measured in deep waters at CSJ (Figures 2a and 2b). The iron concentrations outside Haida-2007 at Station O2, and further offshore at OSP were substantially lower with similar vertical distributions, indicating a broad uniform background condition for the Haida eddy region (Figures 2c and 2d). Surface dFe concentrations at O2 were 0.12 μmol m^{-3} (comparable with 0.16 μmol m^{-3} in EC surface waters) and increased with depth to 0.64 μmol m^{-3} at 800 m. dFe concentrations in surface waters at OSP were 0.08 μmol m^{-3} and increased to 0.57 μmol m^{-3} at 800 m, in agreement with previous studies [*Nishioka et al.*, 2001; *Johnson et al.*, 2005].

[8] There were 26 westward propagating eddies tracked in the model in the Haida region during 1993–2008. Figure 1b shows the eddy genesis positions and propagation tracks during the first year, with eddies becoming established near the shelf break and moving westward into the GOA. A summary of the mean properties of modeled Haida eddies are provided in the auxiliary material. Mean positive vertical velocities were calculated during each time step (3 days) within the eddy box, the reference frame, and at OSP (Figure 3). Day 1 was set as the time when an eddy was first captured, and the mean velocities of all eddies were calculated for one year forward to estimate the annual upward flux.

[9] Vertical velocities calculated across the 100 m depth in the eddies generally decreased from 1.8 m d^{-1} to 0.6 m d^{-1} during the first 200 days, and then remained relatively constant for the remainder of the year (Figure 3). Vertical velocities within the reference frame region followed a similar pattern, decreasing from 1.2 m d^{-1} to 0.2 m d^{-1} over the first 200 days. By comparison, vertical velocity at OSP remained very stable at 0.05 m d^{-1} during the year. The calculated vertical velocities at 50 m generally were much smaller than at 100 m, though their temporal patterns were similar (Figure S1). More details are provided in the auxiliary material.

[10] The upwelling supply of iron to surface waters has been hypothesized to be significant in the Haida eddies, with *Johnson et al.* [2005] estimating an upwelling flux of labile iron at 150 m of 0.23–0.25 μmol m^{-2} d^{-1} in the Haida-2000 and Haida-2001 eddies, and *Roy* [2009] estimating a flux of 0.21 μmol m^{-2} d^{-1} dFe across ~200 m for Haida-2007. These flux estimates are based on an empirically derived but poorly constrained vertical velocity of ~0.1 m d^{-1}; much lower than observed in our model experiment. Here, our more detailed model assessment gives upwelling fluxes of 0.95 μmol m^{-2} d^{-1} across 100 m when temporal decay of dFe in the eddy core is considered, and 1.17 μmol m^{-2} d^{-1} when the upper core dFe concentrations are held constant, as might occur by resupply from below (Table 1). Although these fluxes are reduced by 73% with a seasonal shallowing of the thermocline to 50 m depth, they still remain an order of magnitude higher than that in the eddy-free area (Figure S2). These findings suggest that Haida eddies likely represent a major source of new iron to GOA surface waters that is not adequately considered in the previous studies and current global and regional biogeochemical models.

[11] The scale of these enhanced iron inputs to surface waters can be put into perspective by comparison with atmospheric inputs; the other major iron source to the GOA (Figure 4). Using an annual mean GOA dust deposition rate of 0.5 g m^{-2} year^{-1} [*Mahowald et al.*, 2005], 5% elemental composition for iron, and a variable solubility of 0.54%–3.2% for Asian dust [*Schroth et al.*, 2009], the annual average contribution of aerosol deposition to the dFe budget is ~0.01–0.04 μmol m^{-2} d^{-1}, or 1–2 orders of magnitude less than estimated within our modeled Haida eddy. The implication is that order of magnitude fluctuations in aerosol

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL047946.

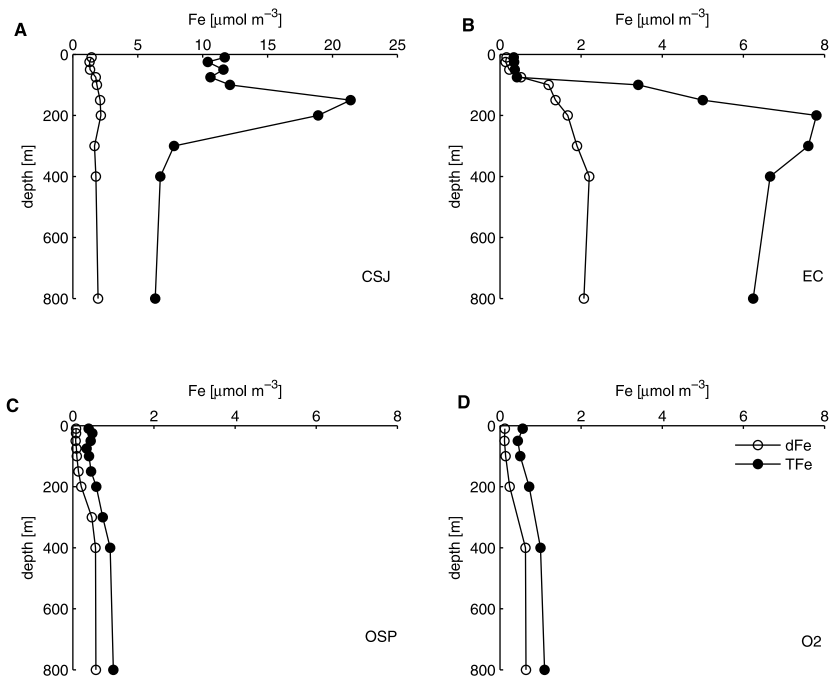

Figure 2. Measured dissolved iron (dFe) and total iron (TFe) profiles in different locations: (a) CSJ; (b) EC; (c) OSP; and (d) O2. Note that, CSJ uses a different x-axis scale.

transport potentially will have less impact on iron-limited production in the GOA than will changes in Haida eddy formation and dynamics. For example, the rate of iron enrichment by mesoscale eddies is on par with deposition during explosive volcanic events (Figure 4). The eruption of Kasatochi volcano in August 2008 enhanced phytoplankton growth in the subarctic Pacific [*Hamme et al.*, 2010], and required a flux of 0.06–6.0 μmol m^{-2} d^{-1} of dissolved iron to match the measured CO_2 drawdown [*Langmann et al.*, 2010]. Put into a broader perspective, the estimated mean rate of dFe supply associated with Haida eddies at 100 m is also comparable with upwelling inputs in the equatorial Pacific, another HNLC region where productivity depends on rates of dFe supply [*Palacz et al.*, 2011]. In contrast to rare and episodic volcanic events, Haida eddies are persistent mesoscale features that continuously inject iron into surface waters.

[12] The total annual iron budget of iron sources to the Haida region (shown in Figure 1b) reveals the dominance of oceanic input fluxes of dFe (Table 1). With an average of

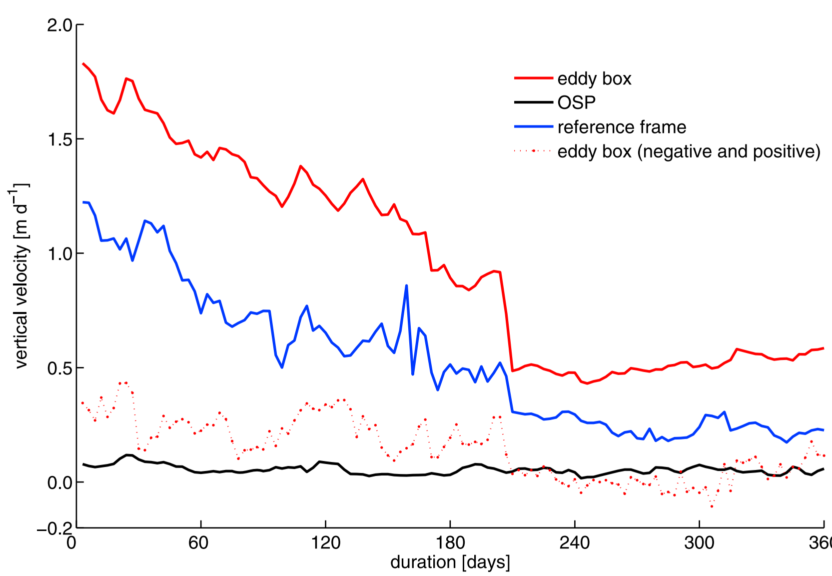

Figure 3. Modeled mean upward vertical velocities at 100 m in the eddy box, in the reference frame and at OSP during the first year of the lifespan of the eddies.

Table 1. Summary of the Haida Region Eddy and Reference Area Statistics for the Case With a Euphotic Zone of 100 m Depth[a]

Parameter	Eddy (Fe Decay)	Eddy (No Fe Decay)	Reference Frame	OSP	Dust
vertical velocity	0.96 (0.43–1.83)	0.96 (0.43–1.83)	0.53 (0.17–1.22)	0.05 (0.02–0.12)	
dFe flux	0.95 (0.09–2.21)	1.17 (0.52–2.21)	0.07 (0.02–0.17)	0.01 (0.002–0.01)	0.03 (0.01–0.04)
TFe flux	6.41 (0.18–23.8)	7.97 (1.54–23.8)	0.26 (0.09–0.61)	0.02 (0.01–0.05)	
Total dFe (10^6)	3.73 (0.35–8.69)	4.60 (2.04–8.69)	5.30 (0.27–22.5)	5.30 (0.27–22.5)	4.54 (1.51–6.06)

[a]The results show the mean and range of vertical velocity (m d^{-1}), iron flux (μmol m^{-2} d^{-1}) and total dFe into the euphotic zone in the Haida region (mol yr^{-1}). Velocities are calculated from the 1993–2008 eddy mean time series. Eddy fluxes are averages from estimates based on iron concentrations obtained from Haida-2001 [*Johnson et al.*, 2005] and our Haida-2007 eddies. Total amount of dFe for the reference region is the average of the conditions in the reference frame and at OSP.

1.6 eddies annually propagating westward in the Haida region, an average lifetime of 279 days and eddy area of 8807 km^2 (Table S1), the upwelled iron contribution into the 100 m euphotic zone is ~4.6 × 10^6 moles of dFe per year (without assuming dFe decay). Vertical and horizontal mixing processes, such as oceanic background mixing, winter mixing, and turbulence, taken here as the mean of OSP and reference frame fluxes, contribute another ~5.3 × 10^6 moles per year to the dFe budget. Averaged Asian dust deposition delivers ~4.5 × 10^6 moles of dFe per year in the Haida region. Considering another dust source from glacial flour, *Crusius et al.* [2011] estimated 1.1 × 10^6–7.1 × 10^6 moles of dFe per year into the entire GOA, which is expected to be lower in the Haida region due to the long distance from the source. Though these estimates would vary greatly when choosing a different solubility rate, a different season or a specific eddy, these budget calculations suggest that oceanic sources of iron into the Haida region can be as important as atmospheric on the annual scale.

[13] Assuming a Fe:C ratio of 2.5 μmol:mol in the Haida region [*Maldonado and Price*, 1999], eddy input of dFe would result in ~2.2 × 10^7 tons of organic carbon converted from total CO_2. This estimate is in agreement with previous estimates of new production based on seasonal nutrient drawdown, 1.52 × 10^7 [*Wong et al.*, 2002a] and 1.45 × 10^7 [*Wong et al.*, 2002b] tons carbon per year in the Haida region. Considering 3.6–5.4% of surface particulate organic carbon is expected to sink to the deep ocean in the subarctic ocean [*Buesseler et al.*, 2007], the net removal of total CO_2 by Haida eddies is estimated to be 0.8 × 10^6–1.2 × 10^6 tons carbon each year. This implies Haida eddies are important sources linking physical and biogeochemical processes in the GOA region.

4. Conclusions

[14] Comparison of oceanic and atmospheric iron supply rates (μmol m^{-2} d^{-1}) reveals that Haida eddies on average may provide a far more significant immediate source of bio-limiting iron (1.17 μmol m^{-2} d^{-1}) for local phytoplankton productivity than dust deposition (0.03 μmol m^{-2} d^{-1}), and that iron inputs associated with these eddies processes can be as important as large volcanic eruption events. Despite the relatively small area affected by Haida eddies, they are estimated to contribute about 4.6 × 10^6 moles of dissolved iron yearly to the GOA, or equivalent to the annual atmospheric dust deposition. Therefore, the iron transport by mesoscale anticyclonic eddies to the GOA HNLC region is expected to play a key mechanism in regulating biological productivity and carbon budget.

[15] **Acknowledgments.** This research has been supported by grants from NASA, USGS and NSF for F. Chai and M. L. Wells. Thanks to John Crusius for providing helpful comments on this paper.

[16] The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

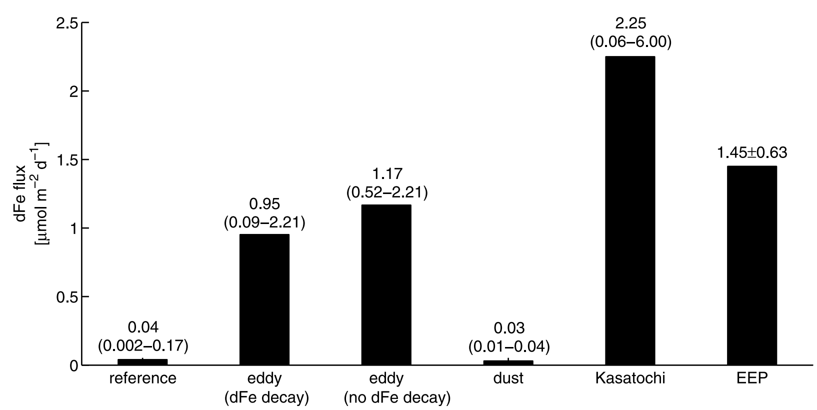

Figure 4. Comparison of mean iron fluxes from atmospheric and oceanic sources (100 m): mixing in Haida eddy reference area; upwelling flux associated with a single Haida eddy; dust deposition in Haida region; 2008 Kasatochi volcano contribution to the Haida region and upwelling in the Eastern Equatorial Pacific (EEP). The reference is calculated as the mean of the reference frame and OSP.

References

Boyd, P. W., et al. (2004), The decline and fate of an iron-induced subarctic phytoplankton bloom, *Nature*, *428*, 549–553, doi:10.1038/nature02437.

Buesseler, K. O., et al. (2007), Revisiting carbon flux through the ocean's twilight zone, *Science*, *316*, 567–570, doi:10.1126/science.1137959.

Crawford, W. R. (2002), Physical characteristics of Haida eddies, *J. Oceanogr.*, *58*, 703–713, doi:10.1023/A:1022898424333.

Crusius, J., A. W. Schroth, S. Gassó, C. M. Moy, R. C. Levy, and M. Gatica (2011), Glacial flour dust storms in the Gulf of Alaska: Hydrologic and meteorological controls and their importance as a source of bioavailable iron, *Geophys. Res. Lett.*, *38*, L06602, doi:10.1029/2010GL046573.

Hamme, R. C., et al. (2010), Volcanic ash fuels anomalous plankton bloom in subarctic northeast Pacific, *Geophys. Res. Lett.*, *37*, L19604, doi:10.1029/2010GL044629.

Henson, S. A., and A. C. Thomas (2008), A census of oceanic anticyclonic eddies in the Gulf of Alaska, *Deep Sea Res., Part I*, *55*, 163–176, doi:10.1016/j.dsr.2007.11.005.

Jickells, T. D., et al. (2005), Global iron connections between desert dust, ocean biogeochemistry, and climate, *Science*, *308*, 67–71, doi:10.1126/science.1105959.

Johnson, W. K., L. A. Miller, N. E. Sutherland, and C. S. Wong (2005), Iron transport by mesoscale Haida eddies in the Gulf of Alaska, *Deep Sea Res., Part II*, *52*, 933–953, doi:10.1016/j.dsr2.2004.08.017.

Langmann, B., K. Zakšek, and M. Hort (2010), Atmospheric distribution and removal of volcanic ash after the eruption of Kasatochi volcano: A regional model study, *J. Geophys. Res.*, *115*, D00L06, doi:10.1029/2009JD013298.

Mahowald, N. M., A. R. Baker, G. Bergametti, N. Brooks, R. A. Duce, T. D. Jickells, N. Kubilay, J. M. Prospero, and I. Tegen (2005), Atmospheric global dust cycle and iron inputs to the ocean, *Global Biogeochem. Cycles*, *19*, GB4025, doi:10.1029/2004GB002402.

Maldonado, M. T., and N. M. Price (1999), Utilization of iron bound to strong organic ligands by plankton communities in the subarctic Pacific Ocean, *Deep Sea Res., Part II*, *46*, 2447–2473, doi:10.1016/S0967-0645(99)00071-5.

Martin, A. P., and K. J. Richards (2001), Mechanisms for vertical nutrient transport within a North Atlantic mesoscale eddy, *Deep Sea Res., Part II*, *48*, 757–773, doi:10.1016/S0967-0645(00)00096-5.

Nishioka, J., S. Takeda, C. S. Wong, and W. K. Johnson (2001), Size-fractionated iron concentrations in the northeast Pacific Ocean: Distribution of soluble and small colloidal iron, *Mar. Chem.*, *74*, 157–179, doi:10.1016/S0304-4203(01)00013-5.

Palacz, A. P., F. Chai, R. C. Dugdale, and C. I. Measures (2011), Estimating iron and aluminum removal rates in the eastern equatorial Pacific Ocean using a box model approach, *Deep Sea Res., Part II*, *58*, 311–324, doi:10.1016/j.dsr2.2010.08.012.

Peterson, T. D., F. A. Whitney, and P. J. Harrison (2005), Macronutrient dynamics in an anticyclonic mesoscale eddy in the Gulf of Alaska, *Deep Sea Res., Part I*, *52*, 909–932.

Roy, E. G. (2009), The detection and biogeochemistry of trace metals in natural waters, Ph.D. thesis, Univ. of Maine, Orono.

Roy, E., M. L. Wells, and D. W. King (2008), The persistence of Fe(II) in surface waters of the western subarctic pacific, *Limnol. Oceanogr.*, *53*, 89–98, doi:10.4319/lo.2008.53.1.0089.

Schroth, A. W., J. Crusius, E. R. Sholkovitz, and B. C. Bostick (2009), Iron solubility driven by speciation in dust sources to the ocean, *Nat. Geosci.*, *2*, 337–340, doi:10.1038/ngeo501.

Whitney, F., and M. Robert (2002), Structure of Haida eddies and their transport of nutrient from coastal margins into the NE Pacific Ocean, *J. Oceanogr.*, *58*, 715–723, doi:10.1023/A:1022850508403.

Wong, C. S., et al. (2002a), Seasonal cycles of nutrients and dissolved inorganic carbon at high and mid latitudes in the North Pacific Ocean during the Skaugran cruises: Determination of new production and nutrient uptake ratios, *Deep Sea Res., Part II*, *49*, 5317–5338, doi:10.1016/S0967-0645(02)00193-5.

Wong, C. S., et al. (2002b), Time-series study of the biogeochemistry of the North East subarctic Pacific: Reconciliation of the C_{org}/N remineralization and uptake ratios with the Redfield ratios, *Deep Sea Res., Part II*, *49*, 5717–5738, doi:10.1016/S0967-0645(02)00211-4.

Xiu, P., F. Chai, L. Shi, H. Xue, and Y. Chao (2010), A census of eddy activities in the South China Sea during 1993–2007, *J. Geophys. Res.*, *115*, C03012, doi:10.1029/2009JC005657.

F. Chai, A. P. Palacz, E. G. Roy, M. L. Wells, and P. Xiu, School of Marine Sciences, University of Maine, Aubert Hall, Orono, ME 04469, USA. (peng.xiu@maine.edu)