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OPINION

Did volcanic ash from Mt. Kasatoshi in 2008 contribute to a phenomenal increase in Fraser River sockeye salmon (*Oncorhynchus nerka*) in 2010?

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ABSTRACT

The effect of a widely distributed phytoplankton bloom triggered by volcanic ash from Alaska (Hamme *et al.*, 2010. *Geophys. Res. Lett.* 37) on juvenile Fraser River sockeye is discussed in terms of the timing of ocean migration and trophic structure of the Gulf of Alaska. Our hypothesis is that the occurrence of a massive diatom bloom in the Gulf greatly enhanced energy ascendancy in the ocean at a time of year when adolescent sockeye migrated from the coast in 2008. We contend this increase in food availability was an important factor for the survival and growth of juvenile sockeye which led to one of the strongest sockeye returns on record in 2010 of 34 million, compared with perhaps the weakest return on record of 1.7 million the previous year.

Key words: diatoms, Fall bloom, Fraser River, Gulf of Alaska, iron, sockeye salmon

INTRODUCTION

The question of whether a wide-scale phytoplankton bloom across the subarctic Pacific caused by volcanic ash from the August 2008 eruption of Mt. Kasatoshi could have caused the 2010 phenomenal run of 34 million sockeye salmon to the Fraser River, compared with only 1.7 million in the previous year and ~6 million the following year (2011), may forever remain an enigma due to the lack of precise ecological and chemical data available at the time. The recently released Cohen Commission's Interim Report (a Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River; http://www.cohencommission.ca/en/InterimReport) looking into both the disastrous returns in 2009 and unexpectedly large run in 2010, does not provide any explanation for these extreme events. However, based on the large 2010 run, it suggests sockeye retain the ability to recover to historical levels. It is our contention that the highly productive 2008 Fall bloom stimulated by volcanic ash at the time that the adolescent salmon were migrating to sea, should be considered amongst the possible causes for the strong return. For future considerations of sockeye salmon abundance, it would appear useful to discuss whether these events were entirely fortuitous, or whether some cause and effect relationship can be established. There has been no explanation for this phenomenal event based on population dynamics and our presentation here is to offer an explanation based on trophodynamic concepts.

THE EVENTS

In the Gulf of Alaska, Hamme *et al.* (2010) documented the eruption of Mt. Kasatoshi and described the distribution of ash, showing that it covered a large portion of the Gulf in 2008. This coverage was similar to the area generally known to be occupied by Fraser River sockeye salmon (Walter *et al.*, 1997; Fig. 1). In addition, and almost at the same time, Hamme *et al.* (2010) showed that there was a substantial increase (ca. ×3) in chlorophyll over most of the Gulf, and that this was largely due to a bloom of diatoms. The bloom was attributed to the addition of iron to the Gulf which is known to be lacking in this nutrient (Martin *et al.*, 1989), particularly in respect to diatom growth, during the summer months. These events were not unique since other volcanoes are known to have caused increased phytoplankton production when ash becomes mixed with surface waters (e.g. Lin *et al.*, 2011).

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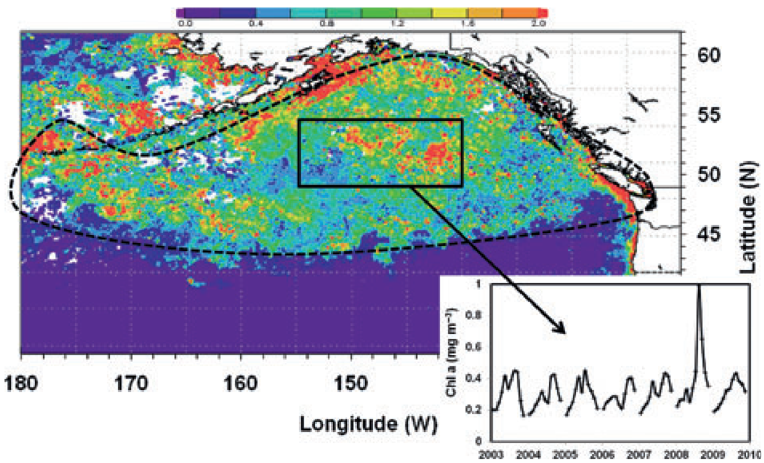
Figure 1. Main panel, satellite chlorophyll *a* for August 2008 from Giovanni (online data system, developed and maintained by the NASA GES DISC), linearly scaled from <0.2 (purple) to >2 mg m^{-3} (red, scale bar at top). Approximate range of BC sockeye salmon is noted by a dashed line. The inset plots monthly chlorophyll *a* for the period 2003 through 2009 averaged over the area in the box shown in the upper panel (49.5–55N, 140–155 W).



ECOLOGICAL SETTING

The Gulf of Alaska is one of several ocean areas known as high nutrient/low chlorophyll (HNLC) regimes because of the abundance of major nutrients (e.g. phosphate, nitrate and silicate) but lack of iron (Martin *et al.*, 1989). A major source of iron to the subarctic Pacific is transport and mixing from continental margins by eddies (Crawford *et al.*, 2005) or by ocean currents (Lam *et al.*, 2006). Nishioka *et al.* (2007) estimated that winter mixing and other vertical transport processes supplied most of the dissolved Fe, with the western subarctic gyre receiving about four times more iron than the Gulf of Alaska due to oceanic transport from the Asian coast. Thus the wide-scale bloom attributed to volcanic ash deposition in 2010 was a rare event in the eastern gyre.

Iron is known to be an essential element for the growth of diatoms (e.g. Hutchins and Bruland, 1998). Very low levels of iron in the Gulf explains why there is a dominance of small flagellates in the Alaskan (Eastern) Gyre relative to the Western Gyre (Hashimoto and Shiomoto, 2000), the latter having higher levels of winter nutrients (Whitney, 2011) and less iron limitation (Lam *et al.*, 2006; Nishioka *et al.*, 2007). The difference in primary producers is carried through to a greater total zooplankton abundance, and to a greater abundance and larger body size of calenoid copepods in the Western gyre versus the Gulf of Alaska (Saito *et al.*, 2011). Not surprisingly, the western Pacific has more abundant fisheries and a greater diversity of fish (PICES Special Publication 2, 2005).

The above brief discussion of two significantly different ecosystems found at the same latitude in the North Pacific Ocean brings us to an understanding of how Gulf of Alaska waters could have been changed to produce exponentially more sockeye salmon due to a relatively brief event, such as the eruption of Mt. Kasatoshi. The relationship between primary producers and fish production is not one that is generally used by fisheries scientists in attempting to forecast or understand fish abundance. And yet, from numerous papers that have shown a correlation between primary producers and fish production (e.g. Iverson, 1990; Ware and Thomson, 2005), it is clear that ocean phytoplankton photosynthesis in the pelagic environment is related to the quantity of fish produced. Largely separated from these papers are others which then show that the length of the food chain from primary producers to fish governs the efficiency of energy transfer from plants to animals (e.g. Ryther, 1969). Further, the elaboration of food chain transfers into the size spectrum of all living organisms in the pelagic environment (Sheldon *et al.*, 1982) has given rise to the general concept that 'bigger is better' in primary to tertiary transfers in the pelagic environment. Thus, in general, energy captured by photosynthesis ascends to larger organisms more efficiently the shorter the food chain and the larger the prey size. Since phytoplankton vary in cell size from pico- to macro-dimensions (ca. 1–1000 μm in linear dimensions or nine orders of magnitude on a volumetric scale) it is reasonable to ask if an event that produced a sudden diatom bloom, in waters that were previously dominated by nanoplankton, might energetically boost fish production?

The concept of differences in primary production having a large effect on the type of pelagic predators was discussed by Parsons (1979) and Parsons and Lalli (2002). These discussions presented the view that the whole ecosystem of a pelagic environment could be changed depending on the size and type of primary producer and that the two extremes of a low energy ecosystem resulted in a dominance of jellies (e.g. cniderians) while a high-energy ecosystem produced abundant fish and whales, as in upwelling areas of the world. Recently Saito *et al.* (in press) have shown that the Gulf of Alaska is generally dominated by a high abundance of the jellyfish *Aglantha digitale* with much smaller number being present in the Western Gyre. Thus, in two geographically similar water masses, two rather different ecologies have come to dominate as caused by the difference between diatom and flagellate ecology at the base of the food chain.

THE VOLCANIC IMPACT

The proposal in this discussion is that a shift from flagellate to diatom ecology in the Gulf was produced by iron-rich dust from a volcano in the summer of 2008 (Fig. 1). Additional data on zooplankton (DFO, 2009) indicates that the diatom bloom was followed by a large increase (ca. biomass ×3) in opportunistic zooplankton as measured by Continuous Plankton Records (CPR) data taken from the Gulf in 2008 following the diatom bloom (CPR – Fig. 3 *loc. cit.* from S. Batten).

Since sockeye salmon are known to consume a wide spectrum of zooplankton including euphausiids, amphipods, copepods, cladocerans and pteropods, the young fish would have benefitted from the bloom of opportunistic zooplankton (LeBrasseur, 1966).

These events followed a pattern of Fall blooms in the Gulf (Fig. 1) which were singularly enhanced in 2008 at a time when adolescent sockeye were entering the ocean environment. Since the ash particles would have sunk through the euphotic zone, the occurrence of this plankton bloom can be hypothesized to have been sustained long enough to enhance the survival and growth of adolescent Fraser sockeye (satellite chlorophyll was elevated by >50% over the 2003–2009 average in August and September 2008), but not necessarily especially beneficial for other species of salmon on different migration schedules or feeding strategies.

Additional points and questions arising from this discussion are:

- Why were the 2008 salmon that returned in 2010 so super abundant compared with the 2009 salmon which were present at the same time ? The answer to this may be found in the 4 yr growth curve of the sockeye salmon. As with all animal growth curves, growth is lowest at the beginning and end of their life cycle. The salmon returning in 2010 would have been adolescent, or in the midpoint of their growth cycle, and could benefit most from the enhanced diatom/zooplankton food chain.
- Another question is why the Alaskan salmon fishery did not show such a phenomenal increase in 2010? Salmon from this fishery live in a highly productive coastal regime and Bering Sea which are not iron limited in regard to diatom growth and their abundance is governed by factors independent of the more open waters of the Gulf.
- While other volcanoes have been known to fertilize the oceans (*loc.cit.*), the effect of Icelandic volcanoes on the Atlantic biota at the same latitude have not caused the same surge in fisheries because the Atlantic is not one of the HNCL ecosystems and would not benefit from additional iron.
- Experimental evidence exists that salmon production can be enhanced directly by the addition of nutrients, such as was described in lake experiments (LeBrasseur *et al.*, 1979).

CONCLUSIONS

We hypothesize the volcanic emission of iron-rich dust in 2008 that caused a massive late summer bloom of diatoms enhanced the food chain for young sockeye salmon in the Gulf shortly after they migrated into their oceanic habitat. Satellite chlorophyll shows a Fall bloom is an annual event triggered by increased mixing (Fig. 1), thus may be an underappreciated factor in Fraser River sockeye survival. The 2008 bloom was an exclusive event in magnitude and timing. However, other mechanisms for enhancing algal production and increasing food chain efficiency exist, as discussed above, and could also stimulate salmon production. We believe this is not the first time such an event has occurred in the Gulf; in 1956 a large volcanic eruption in Kamchatka was believed to have caused the unusual run of about 20 million sockeye in 1958, although the event does not seem to have been scientifically documented beyond newspaper reports. Due to the volcanic activity around the Pacific rim, it is possible that such events will occur in the future when weather system are favorable for transporting and depositing iron-rich ash across these HNLC waters.

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