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

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Abstract

The effect of volcanic ash on the sockeye salmon population of the Gulf of Alaska in 2008 is discussed in terms of how the trophic structure of the Gulf may have been changed. Contrasts in trophic structure of the food chains in the eastern and western gyres of the Pacific are presented in order to show how size of photosynthetic organisms are an important factor in explaining energy ascendancy in the oceans. The conclusion reached is that the input of ash containing iron was certainly a contributing factor to the increase in sockeye numbers from one to thirty million, following the activity of the volcano.

Introduction

The question of whether volcanic ash from the August 2008 eruption of Mt. Kasatoshi could have caused the 2010 phenomenal run of 30 million sockeye salmon to the Fraser River, compared with 1 million in the previous year, may forever remain an enigma due to the lack of precise ecological and chemical data available at the time. However, 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.

The Events

In the Gulf of Alaska, Hamme et al (2010) documented the eruption Mt. Kasatoshi and described the distribution of ash showing that it covered a large portion of the Gulf. 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.* x 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 (Martin et al., 1989) to be lacking in this nutrient, 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).

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 lacking in iron (Martin et al., 1989). A major source of iron to the subarctic Pacific is thought to be dust which helps establish its nutrient like profile throughout the water column (Johnson et al., 1997). However, dust events almost never account for increases in phytoplankton growth in the Gulf, rather transport from continental margins by eddies (Crawford et al., 2005) or by ocean currents (Lam et al., 2006) appear to support any diatom increases. Indeed, Nishioka et al. (2007) estimated that winter mixing and other vertical transport processes supplied as much or more dissolved Fe than dust, with the western subarctic gyre receiving about 4 times more 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.

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 has higher levels of winter nutrients (Whitney, submitted) and is much less iron limited (Nishioka et al, 2007). This 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, starting perhaps with 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 to 1000 microns in linear dimensions or 9 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 to 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 (2001). 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 (Fig.1). Additional data on zooplankton (DFO, 2009) indicates that the diatom bloom was followed by a large increase (ca. biomass x 3) in 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).

Additional points and questions arising from this discussion are: -

1) 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 year growth curve of the sockeye salmon. As with all animal growth curves, growth is lowest 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.

2) 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 which is not iron limited re diatom growth and their abundance is governed by factors independent of the more open waters of the Gulf.

3) 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.

4) 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

Our conclusion from this discussion is that the volcanic emission of iron rich dust in 2008 caused a massive late summer bloom of diatoms that enhanced the food chain for young sockeye salmon in the Gulf shortly after they migrated into their oceanic habitat. It was not an exclusive event because other mechanisms for enhancing algal production and increasing food chain efficiency exist, as discussed above, and could have had an additional effect on salmon production. However, 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 may occur in the future, although any eruption also requires a weather system to transport ash across these HNLC waters and produce the rain needed to help deposit this particulate form of iron.

References

Crawford W.R., Brickley, P.J., Peterson, T.D., Andrew C. Thomas, A.C. 2005. Impact of Haida Eddies on chlorophyll distribution in the Eastern Gulf of Alaska. Deep-Sea Res. II **52**, 975–989

DFO. (2009) State of the Pacific Ocean 2008. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2009/030 21pp.

Hamme, R.C., Webley, P.W., Crawford, W.R., Whitney, F.A., et al. 2010. Volcanic ash fuels anomalous plankton bloom in subarctic northeast Pacific Geophys. Res. Letters **37**: doi:10.1029/2010GL044629.

Hashimoto, S. and Shiomoto, A. 2000. High-west and low-east in April and no trend in August in chlorophyll a concentration and standing stock in the subarctic Pacific in 1999, Bull. Jap. Soc. Fish. Oceanogr. **64**: 161-172.

Hutchins, D.A. and Bruland, K.W. 1998. Iron limited diatom growth and Si:N uptake ratios in a coastal upwelling regime Nature, **393**: 561-564.

Iverson, R.L. 1990. Control of marine fish production. Limnol. Oceanogr. **35**: 1593-1604.

Johnson, K.S., Gordon, R. M. and Coale, K.H. 1997. What controls dissolved iron concentrations in the world ocean? Mar. Chem. **57**, 137-161.

Lam, P.J., Bishop, J.K.B., Henning, C.C., Marcus, M.A., et al. 2006. Wintertime phytoplankton bloom in the subarctic Pacific supported by continental margin iron. Global Biogeochem. Cycles **20**, doi:10.1029/2005GB002557.

LeBrasseur, R.J., McAllister, C.D. and Parsons, T.R. 1979. Additions of nutrients to a lake leads to greatly increased salmon catch. Environ. Cons. **6**: 187-190.

Lin, I. I., Hu, C., Li, Y., Ho, T.Y., et al. 2011. Fertilization potential of volcanic dust in the low-nutrient low-chlorophyll western North Pacific subtropical gyre: Satellite evidence and laboratory study. Global Biogeochem. Cycles **25**: pp 12.

Martin, J.H., Gordon, M.R., Fitzwater, S.E. and Broenkow, W.W. 1989. VERTEX: phytoplankton/iron studies in the Gulf of Alaska. Deep-Sea Res. **36**, 649-680.

Nishioka, J., Ono, T., and Saito, H. 2007. Iron supply to the western subarctic Pacific: Importance of iron export from the Sea of Okhotsk, J. Geophys. Res. **112**, C10012, doi:10.1029/2006JC004055.

Parsons, T.R. (1979). Some ecological. experimental and evolutionary aspects of upwelling ecosystems. S. African J. Sci.**75**:536-540

Parsons, T.R. and Lalli, C.M. 2003. Jellyfish population explosions: Revisiting a hypothesis of possible causes. La Mer. **40**: 111-121.

Pices Special Publication 2. 2005. Eds. Perry, R.I. and McKinnel, S. COML report: Maine Life in the North Pacific: The known, unknown and unknowable. Commercially important fish and invertebrates. 30pp.

Ryther, J.H. 1969. Photosynthesis and fish production in the sea. The production of organic matter and its conversion to higher forms of life vary throughout the world's oceans. Science **166**: 72-76.

Saito, R., Yamoguchi, A., Saitoh, S-I., Kuma, K. and Imai, I. 2011. East-west comparison of the zooplankton community in the subarctic Pacific during summers of 2003-2006. J.Plankton Res. **33**: 145-160.

Saito, R., Yamoguchi, A., Saitoh, S-I., Kuma, K. and Imai, I. in press. An east-west comparison of hydromedusa *Aglantha diitale* in the subarctic Pacific during the summers of 2003-2006. Can. J. Fish. Aquatic Sci.

Sheldon, R.W., Sutcliffe, W.H. and Drinkwater, K. 1982. Fish production in multispecies fisheries. Can. Spec. Publ. Aquatic Sci. **59**: 28-34.

Walter, E.E., Scandol, J.P, and Healey, M.C. 1997. A reappraisal of the ocean migration pattern of Fraser River sockeye salmon (*Oncorhynchus nerka*) by individual-based modelling. Can. J. Fish. Aquat. Sci. **54**: 847.858.

Ware, D.M. and Thomson, R.E. 2005. Bottom-up ecosystem trophic dynamics determine fish production in the North-east Pacific. Science **308**: 1280-1283.

Whitney, F.A. submitted. Nutrient variability in the mixed layer of the subarctic Pacific Ocean, 1987-2010. J. Oceanogr.

Figure 1. 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 shows the typical distribution of chlorophyll in August, this example from 2005.