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REPLY COMMENT

Physical and ecological uncertainties in the widespread implementation of controlled upwelling in the North Pacific Subtropical Gyre

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ABSTRACT: Based on the recent hypothesis of Karl & Letelier (2008; Mar Ecol Prog Ser 364:257–268), Fennel (2008; Mar Ecol Prog Ser 371:301–303) presents a model and initiates an important discussion on the potential effect that widespread controlled upwelling of deep water in the North Pacific Subtropical Gyre (NPSG) may have on upper water column stratification, nitrogen (N_2) fixation, and C sequestration. Fennel concludes that the upwelling required to support the sequestration of 1Gt C yr^{-1} would deepen the mixed-layer significantly, inhibiting N_2 fixation and precluding the enhancement of the biological carbon pump. However, her model does not include the role that solar radiant heating plays in the maintenance of the upper ocean stratification, nor does she discuss observations suggesting that N_2 fixation in the NPSG is never completely suppressed. When the solar radiance absorbed by the mixed-layer is considered, the upper ocean stratification is maintained in Fennel's model. Nevertheless, and as Fennel suggests, the effects that a basin scale long-term implementation of controlled upwelling may have on the pelagic ecosystem are difficult to predict due to the complex nature of the system and our incomplete understanding of feedback mechanisms between ocean physics, biology and climate. For this reason, we contend that controlled upwelling of deep water in oligotrophic regions should be viewed as originally concluded by Karl & Letelier (2008): a tool to study the response of pelagic microbial assemblages to perturbations at different spatial and temporal scales, rather than a strategy to stabilize climate through the large-scale manipulation of poorly understood ecosystems.

KEY WORDS: Carbon sequestration · Nitrogen fixation · LNLC · Mixed-layer depth · Upwelling · North Pacific Ocean

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INTRODUCTION

In her comment regarding a potential widespread implementation of controlled upwelling in the North Pacific Subtropical Gyre (NPSG), Fennel (2008, this volume) postulates that the continuous injection of deep, cold and dense water into the surface layers of oligotrophic oceans required to support the biological sequestration of 1 Gt C per year would significantly deepen the mixed layer, thereby negating the effect of exogenous nutrient enrichment. Karl & Letelier (2008) originally suggested that artificial upwelling of deep water from specific depth strata in these regions could trigger a 2-stage bloom, initially supporting the proliferation of diatoms through the injection of nutrients, including nitrate and phosphate, followed by an increase in the abundance of diazotrophs as a result of the residual bio-available P that remains once the nitrate has been depleted; this second stage would significantly enhance C sequestration. However, Fennel (2008) contends that, because nitrogen (N_2) fixing cyanobacteria in pelagic oligotrophic regions appear

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to bloom primarily under well stratified conditions, a deepening of the mixed-layer would prevent the development of a 2-stage bloom.

We share Fennel's (2008) core concern regarding the dangers of extrapolating results from one-dimensional analyses or small scale perturbation experiments over large areas of the ocean. As she attempts to exemplify through her analysis of mixed-layer depth evolution, sustained perturbations over large oceanic regions could have significant effects on the physical, chemical, and biological state of the ocean; similar caution was expressed by Karl & Letelier (2008). We also agree with the 2 distinctions that Fennel makes between ocean iron (Fe) or phosphorus (P) fertilization and controlled upwelling: namely that some of the immediate deep water upwelling effects are to decrease upper water column stratification and increase the inorganic C concentration in surface waters. In addition, we add a third important distinction: while traditional Fe/P fertilization manipulates the ocean chemical budget by adding allochthonous nutrients into the marine system, the controlled upwelling approach corresponds to an artificial form of increasing the upward flux of nutrients from the upper thermocline into the upper euphotic zone. For this reason, controlled upwelling experiments represent a mechanism to redistribute nutrients across the thermocline and could, in principle, be used to study *in situ* the successional patterns of pelagic microbial assemblages as a function of the spatial and temporal perturbation scales without the need for dumping large quantities of nutrients into the marine environment.

MODEL FLAWS AND UNCERTAINTIES

Even though we agree with Fennel's (2008) warning regarding the extrapolation of results across scales, we contend that the argument she uses to make her point contains 2 important flaws.

(1) From a biological perspective we still do not know if there is a critical mixing depth in oligotrophic pelagic regions at which N_2 fixation is turned off. Although rates of N_2 fixation are significantly affected by the availability of light and the mixing depth, long term observations at Station ALOHA (A Long-term Oligotrophic Habitat Assessment; 22° 45′ N, 158° W) suggest that diazotrophs are always present in the euphotic zone and that their capability to fix nitrogen is never totally suppressed, even when the mixed layer reaches 100 m depth, as in February 2004 (Grabowski et al. 2008b). As long as residual P is available, once nitrate has been depleted, and N_2 fixation is not fully suppressed, we should expect diazotrophic organic matter production to take place in the euphotic zone and support the sequestration of inorganic C.

(2) From a physical perspective we believe that Fennel's approach to estimate the deepening of the mixed layer and potential suppression of diazotrophy is flawed because she models the evolution of the upper 1000 m of the water column as a closed system, neglecting the contribution of solar radiant heating to the maintenance of a density gradient. At Station ALOHA, where the data used by Karl & Letelier (2008) and Fennel (2008) were collected, water column stratification between 200 and 500 m is caused by a temperature gradient; salinity in this depth range decreases significantly and is lower than that observed in the mixed layer (Lukas & Santiago-Mandujano 2001). As a consequence, the injection of water from 400 or 500 m will cause a cooling and freshening of the mixed layer; only the former process will contribute to the deepening of the mixed layer by decreasing the upper water column density gradient.

In order to properly model the evolution of the mixed-layer dynamics, one needs to take into account not only the effects of deep cold water injections into surface waters, but also the solar radiant heating that enhances upper water column stratification. Taking the example used by Fennel, a widespread pumping rate of 45 $m^3\ m^{-2}\ yr^{-1}$ from 400 m depth into the mixed layer corresponds to a flux of 0.125 $m^3\ m^{-2}\ d^{-1}$. While the mean annual mixed-layer temperature at Station ALOHA is 25°C, the potential temperature at 400 m depth is 9.6°C, a differential of 15.4°C. Assuming a 45 m annual mean mixed-layer depth (Karl & Lukas 1996), the cooling effect on surface waters due to this upwelling is 0.043°C d^{-1}.

The energy required to heat 0.125 m^3 by 15.4°C is approximately 8×10^6 J or 93 W m^{-2}. Hence, in order to counteract the cooling effect of the deep water pumped into the mixed layer, this layer must absorb, on average, an equal amount of radiant energy each day. The heating resulting from radiant absorption by the mixed layer can be modeled using the approach of Strutton & Chavez (2004), which takes into account both the radiant heating due to the attenuation by water as well as the component resulting from the distribution of phytoplankton in the euphotic zone. In brief:

$$\left[\frac{\mathrm{d}T}{\mathrm{d}t}\right]_{\mathrm{rad}} = \frac{E_{d,0m^-} - E_{d,z}}{\rho_0 C_p Z_{\mathrm{MLD}}}$$

where the time rate of change of the mixed-layer temperature due to the absorbed downwelling radiation ($[\mathrm{d}T/\mathrm{d}t]_{\mathrm{rad}}$ in °C s^{-1}) is equivalent to the difference between the total downwelling shortwave irradiance flux (in W m^{-2}) measured or estimated just below the air–sea interface ($E_{d,0m^-}$) and that measured at the base of the mixed layer ($E_{d,Z}$), normalized by the density of seawater in the mixed layer (ρ_0 in kg m^{-3}), the heat capacity of seawater (C_p in J kg^{-1} °C^{-1}) and the depth of the mixed layer (Z_{MLD} in m).

Annual mean shortwave radiation at Station ALOHA, using a spectral range from 0.3 to 3 µm, is approximately 230 W m^{-2}. Based on 20 yr of Hawaii Ocean Time-series program data we consider a mixed layer with an annual mean depth of 45 m and a chlorophyll concentration of 0.13 mg m^{-3} (http://hahana.soest.hawaii.edu/hot/). In addition, we assume a 6% air–sea interface albedo (Payne 1972). Using these parameters we estimate that the mean shortwave radiation absorbed by the mixed layer at Station ALOHA is approximately 180 W m^{-2}, a value equivalent to almost twice the amount of energy required to counteract the cooling caused by the injection of 0.125 m^3 d^{-1} of water from 400 m depth into the mixed layer. In other words, our calculation suggests that the mixed layer at Station ALOHA will deepen only when the rate of cooling due to deep cold water being pumped into this layer reaches an annual mean of approximately 0.08°C d^{-1}, equaling or exceeding the solar warming of the mixed layer.

We need to be aware of some caveats resulting from our improved but still simple calculation. For example, the cooling effect due to the upwelling of deep water with constant temperature will vary as a function of mixed-layer depth and temperature. Hence, it will increase during summer, when the mixed layer shoals and the sea surface becomes warmer. However, summer is also the time of the year when the daily integrated solar downwelling irradiance is greatest, providing increased radiant energy to be absorbed within the mixed layer (Letelier et al. 2004). In addition, our present calculation neglects the role that summer blooms observed at Station ALOHA (Wilson 2003, White et al. 2007, Dore et al. 2008) have in enhancing the upper water column stratification by increasing the absorption of shortwave radiation in the mixed layer (Strutton & Chavez 2004).

Looking forward into possible climate feedback mechanisms, our current model does not include the effect of outgoing longwave radiation or that of latent and sensible heat fluxes at the air–sea interface. At Station ALOHA these fluxes generally correspond to a transfer of excess heat from the ocean surface into the atmosphere. This transfer will decrease as a result of the mixed layer cooling and may have a significant effect on cloud formation and albedo which, in turn, could affect solar radiation at the sea surface and the concomitant light availability supporting primary production and N_2 fixation in the euphotic zone.

There are other physical processes that should be implemented when trying to model the introduction of a cold water plume into a warm layer. For example, one must consider how deep a cold plume will sink before reaching a neutral density layer. Preliminary numerical simulations by Isaac Ginis from the University of Rhode Island (unpubl. data) suggest that the sinking dynamics of a plume prior to reaching a neutral density layer will strongly depend on the background turbulence and the characteristics of the plume (i.e. discrete versus continuous flow, plume volume and dilution rates). In addition, since Karl & Letelier (2008) presented the idea of controlled upwelling as a testable hypothesis, a field experiment has been conducted in the vicinity of Station ALOHA to investigate the feasibility of using wave energy to pump 315 m deep water into the mixed layer (Grabowski et al. 2008a, A. E. White unpubl.). Although this initial experiment was only partially successful, thermistors deployed inside the pump at different depths (315 m, 165 m and 15 m) documented a significant conductive heat exchange across the pump walls during the upwelling process; the temperature of water being upwelled from 315 m depth had warmed from 11.2 to 16°C by the time it crossed the 165 m depth horizon and to 24°C by the time it reached the upper opening of the pump in the mixed layer. The warming of deep water en route to the surface will vary as a function of the pump pipe diameter and upwelling rate and, as our direct observations suggest, it could further reduce the convective mixing caused by the injection of a deep water plume into the mixed layer.

CONCLUSIONS

Beyond any uncertainty inherent to the 2-stage phytoplankton bloom hypothesis suggested by Karl & Letelier (2008), the fact remains that we may never be able to predict the physical, ecological and climate consequences of long-term large-scale perturbations in oceanic regions. Planktonic assemblages are complex adaptive systems with emergent properties that may vary as a result of the spatial and temporal perturbation scale (Cullen et al. 2002, Leibold & Norberg 2004). We believe that the prospect of developing *in situ* controlled upwelling perturbations at different spatial and temporal scales opens the possibility to study the successional response of these pelagic ecosystems and provides us with an experimental approach to test and refine hypotheses on the evolution of pelagic microbial assemblages under a climate change scenario. However, we also believe that any proposed strategy to intentionally modify or restore large marine ecosystems using a controlled upwelling approach is premature and should be avoided unless we can first identify and characterize potential outcome scenarios and constrain their uncertainties through multidisciplinary empirical and modeling research efforts.

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LITERATURE CITED

Cullen JJ, Franks PJS, Karl DM, Longhurst A (2002) Physical influences on marine ecosystem dynamics. In: Robinson AR, McCarthy JJ and Rothschild BJ (eds) The sea, Vol 12. John Wiley & Sons, New York, p 297–336

Dore JE, Letelier RM, Church MJ, Lukas R, Karl DM (2008) Summer phytoplankton blooms in the oligotrophic North Pacific Subtropical Gyre: historical perspective and recent observations. Prog Oceanogr 76:2–38

Fennel K (2008) Widespread implementation of controlled upwelling in the North Pacific Subtropical Gyre would counteract diazotrophic N_2 fixation. Mar Ecol Prog Ser 371:301–303

Grabowski E, Karl DM, Watkins B, Poulos S, Björkman K, Letelier RM, White AE (2008a) Ocean Productivity Perturbation Experiment: final report. http://hahana.soest.hawaii.edu/oppex/

Grabowski MNW, Church MJ, Karl DM (2008b) Nitrogen fixation rates and controls at Stn ALOHA. Aquat Microb Ecol 52:175–183

Karl DM, Letelier RM (2008) Nitrogen fixation-enhanced carbon sequestration in low nitrate, low chlorophyll seascapes. Mar Ecol Prog Ser 364:257–268

Karl DM, Lukas R (1996) The Hawaii Ocean Time-series (HOT) program: background, rationale and field implementation. Deep-Sea Res 43:129–156

Leibold MA, Norberg J (2004) Biodiversity in metacommunities: plankton as complex adaptive systems. Limnol Oceanogr 49:1278–1289

Letelier RM, Karl DM, Abbott MR, Bidigare RR (2004) Light driven seasonal patterns of chlorophyll and nitrate in the lower euphotic zone of the North Pacific Subtropical Gyre. Limnol Oceanogr 49:508–519

Lukas R, Santiago-Mandujano F (2001) Extreme water mass anomaly observed in the Hawaii Ocean Time-series. Geophys Res Lett 28:2931–2934

Payne RE (1972) Albedo of the sea surface. J Atmos Sci 29: 959–970

Strutton PG, Chavez FP (2004) Biological heating in the Equatorial Pacific: observed variability and potential for real-time calculation. J Clim 17:1097–1109

White AE, Spitz YH, Letelier RM (2007) What factors are driving summer phytoplankton blooms in the North Pacific Subtropical Gyre? J Geophys Res 112:C12006

Wilson C (2003) Late summer chlorophyll blooms in the oligotrophic North Pacific Subtropical Gyre. Geophys Res Lett 30:1942–1945

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