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Adjoint backtracking of krill hotspots: Source water variability in the California Current

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ABSTRACT

A sequence of historical analyses (1988-2010) of the California Current System (CCS) is used to describe the variability in source water of krill hotspots which are observed during upwelling season. The Adjoint model within the Regional Ocean Modeling System (ROMS) is used to study backward trajectories of passive tracers from these hotspot locations. Backward trajectories are calculated and examined for various years which had anomalous krill abundance at these hotspots. The ecosystem response to anomalous ocean conditions is quantified using physical (depth and horizontal location) and chemical (nitrate) properties weighted by these backward trajectories of passive tracer concentrations. This method of backward trajectories of passive tracers using the ROMS Adjoint model proves useful in identifying inter-annual variability of initial conditions for more data-driven growth-advection models which will be implemented in the future.

INTRODUCTION

The importance of krill (euphausiids) in the California Current System (CCS) is immense, from an ecological standpoint as well as a commercial one. Krill are one of the most important vehicles for the movement of energy through the marine ecosystem (Field et. al., 2006). They are a key prey for many fish, marine mammals of all sizes (seals, baleen whales, etc...), and seabirds, making them a crucial component that supports the large biomass and diversity in the CCS. Without krill, many species in the CCS would loose their primary food source and populations would diminish. Krill also play a key role as forage for commercially important species such as hake, rockfish, and salmon (Field et. al., 2006). To be able to understand the foraging ecology and population biology of these important krill predators (whales, fish, seabirds, etc…) in the CCS, we need to first understand the dynamics of krill abundance in this ecosystem (Santora et. al., 2011).

A great example to the importance of krill in the marine food web is the ecological response to the delayed upwelling that occurred in 2005. In the Pacific Northwest in 2005, the spring transition was recored to be around 50 days later than usual (Kosro et. al., 2006). This led to warmer, fresher surface waters trapping upwelled waters beneath it and further delaying the surfacing of these upwelled waters. The trapping of cold, nutrient-rich water beneath an anomalously warm, fresh surface layer meant that these nutrients were not made available to the marine food web until much later than usual. This led to a significantly reduced biomass of zooplankton which persisted many months longer than the anomalous forcing conditions that started this (Mackas et. al., 2006). In response to the lower than usual krill (zooplankton) abundance, coastal seabirds had low reproductive success in 2005 and 2006, and low rates of juvenile salmon entering the ocean in 2005 resulted in 2008 being one of the worst returning salmon years (Dorman et. al., 2011). This goes to show just how important of a role krill play in the marine ecosystem. It is because of this importance that we need to make efforts to better understand krill.

The purpose of this study is to show the utility of running an adjoint model to look at back trajectories of passive tracers that are seeded at known krill hotspot locations. This model can help us understand the source water variability for these hotspots and actually allow us to quantify the differences in how the ecosystem responds to different ocean conditions.

METHODS

Numerical Model

All of the modeling efforts in this study were carried out using the Regional Ocean Modeling System (ROMS) (Shchepetkin et. al., 2005). ROMS is a hydrostatic, free-surface, terrain-following, primitive equations ocean model that is used widely in the oceanographic community.

The model domain used for this study is part of a nested configuration. The outer domain has a resolution of 1/10° (~10 km) and spans the entire CCS, while the inner domain focuses on the central California Current region, spanning from 32°N (California/ Baja border) to 44°N (Central Oregon) and 128.5°W to 116.5°W, with a resolution of approximately 1/30° (about 3km). There are 42 vertical, terrain-following levels used in the model. To improve the accuracy of the inner domain, the outer domain is run as a data-assimilative ROMS reanalysis for 1980-2010, which provides the initial, boundary, and surface forcing conditions for the inner domain (Fiechter et. al., 2018). For this study, only the years 1988-2010 were considered, because, in the model, these years were forced with the relatively high-resolution (0.25°) Cross-Calibrated Multi-Platform (CCMP) winds (Atlas et. al., 2011).

The adjoint model which will be introduced in the next section only uses physical properties, however some biological and chemical variables are used within the analysis. These variables come from a full biogeochemical model that has the exact same configuration as described above. This is a coupled model between ROMS and the North Pacific Ecosystem Model for Understanding Regional Oceanography (NEMURO; Kishi et. al., 2007). The NEMURO model contains three limiting macronutrients, two phytoplankton size-classes, three zooplankton size-classes, and three detritus pools.

Back Trajectories of Passive Tracers

Source waters for krill hotspots along the central CCS are characterized using the adjoint of the ROMS tangent linear model (Moore et. al., 2004). Adjoint methods, including the ROMS Adjoint model, have been used for various ocean and atmospheric model sensitivity studies. These sensitivity studies use the adjoint formulation to quantify how sensitive model output is to various parameters such as remote and local surface forcing, and initial conditions (Moore et. al., 2008; Veneziani et. al., 2009). In these sensitivity study applications, the adjoint can quantify the sensitivity of a circulation metric to perturbations in initial, boundary, and surface forcing in just one model run. Contrary to tangent linear sensitivity studies, where a new run is performed for each perturbation in an initial, boundary, or forcing condition, the adjoint model integrates backwards in time, producing sensitivities to each state variable at all time steps in one run (Moore et. al., 2004). In this present study, the ROMS Adjoint model is used to a slightly different capacity. Since the adjoint model is run backwards in time, it allows us to inject a passive tracer into the final ocean state and track the water masses in that region back to their origin at an earlier time. Back trajectories based on the ROMS Adjoint model have been used to study upwelling source waters in the CCS and how they respond to various decadal-scale climate fluctuations (Song et. al., 2011; Jacox et. al., 2015). In this study, the ROMS Adjoint model will be used to study the source waters of known krill hotspots by injecting passive tracers at these hotspot locations during a time un the upwelling season that they are typically active. The details for how the passive tracer back trajectories are calculated in ROMS are given by Song et. al. (2011). These calculations ensure conservation of the passive tracer through time.

The value of the passive tracer that gets input to each cell within the seeding location for each time step during the seeding period is

$$dye\_01_{i,j,k} = \frac{dV_{i,j,k}}{Ntimes \cdot V},$$

where

$$Ntimes = Ndays \cdot outputFreq \cdot TimeStepPerDay.$$

Here, $dye\_01_{i,j,k}$ is the value of the tracer concentration for the (i, j, k) cell, $dV_{i,j,k}$ is the volume of the (i, j, k) cell, V is the total volume of all of the cells within the seeding location, $Ndays$ is the number of days that are being seeded (15 in this study), $outputFreq$ is the model output frequency in time steps, and $TimeStepPerDay$ is how many model outputs there are per day. Based on this calculation already taking into account the volume of the cells being injected and the total tracer concentration being conserved after the final seeding day, it makes analyzing results of water mass characteristics very easy.

Seeding Locations and Anomalous Years

Throughout any given upwelling season in the California Current System, there are generally five krill hotspots which are active for a given time. In the early upwelling months of May and June, the active hotspots are further south, typically one at the southern end of Big Sur (north of Point Conception), one at Monterey Bay, and one off of the Gulf of the Farallones. As the upwelling season progresses, the further south hotspots decrease and the northern hotspots become active. In July and August, the Big Sur and Monterey Bay hotspots are mostly gone, but two hotspots on either side of Cape Mendocino become active.

In order to easily capture source waters for all of these hotspots, each adjoint model run was seeded for hotspots in all five locations. Each hotspot is characterized by a different passive tracer so that during analysis, the hotspots can be viewed individually and the ones which are not usually active during a certain month can be ignored.

Each hotspot was seeded with a 0.5° latitudinal extent, from the coast to 50 kilometers offshore, and from the ocean surface to 20 meters depth. They are seeded as a 15 day average hotspot location and the model is run for 30 days prior to the start of that seeding period. This means that for the first 15 days of the backward run (last 15 days chronologically), the adjoint model is forced with passive tracer concentrations in the seeding location. After those 15 days, the passive tracer concentration is conserved. The purpose of this is so that the output back trajectories are less noisy. If you seed the hotspot for one day, then the tracers are subject to all sorts of short time scale movements and the back trajectories would be so noisy you could not do anything with them. The seeding locations are at the southern end of Big Sur (just north of Point Conception), Monterey Bay, the Gulf of the Farallones, the southern side of Cape Mendocino, and the northern side of Cape Mendocino (figure 1).

In order to have interesting results to test the usefulness of this adjoint model, I needed to find anomalous years for krill abundance. To do this, I used krill abundance values (predator zooplankton) from the full coupled ROMS-NEMURO model. Only the years 1990-2010 were used for these calculations. For each year, the krill abundance in the entire nested model domain (the 1/30° resolution domain) was temporally averaged over May through August, to get an average krill abundance for the upwelling season for each year. Then, a 20 year climatology was created by averaging these upwelling season averages for 1990

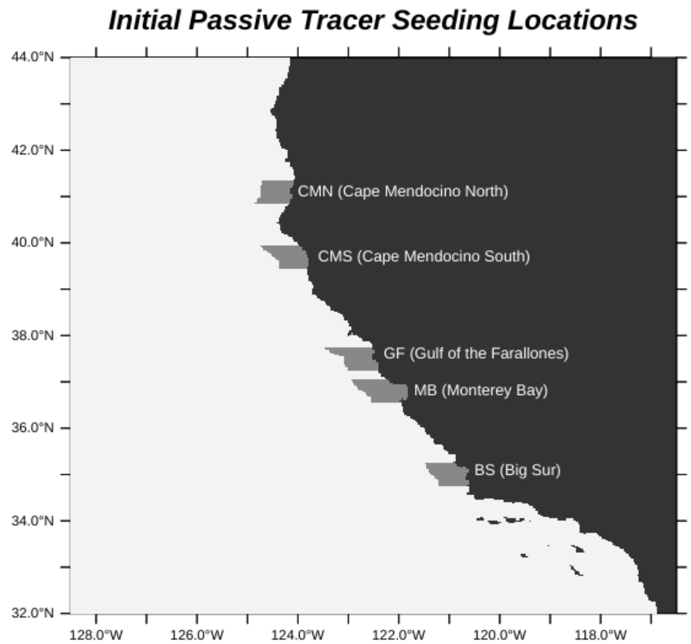

Figure 1: Passive tracer seeding locations. Representative of prominent krill hotspot locations seen during a typical upwelling season in the California Current System.

to 2010. To consider only krill that would be collocated with the hotspot seeding locations, both the climatology and the upwelling season averages were masked by the hotspot seeding locations seen in figure 1, then summed horizontally and vertically. Finally, krill anomalies for each hotspot and each year were created by subtracting the climatology values from the upwelling season averages (figure 2). With this, we wanted to pick a few years to run the adjoint model where anomalies across all hotspots were trending in the same direction. It was decided that 1991 would be our good krill year because all hotspots were peaking relative to years around then, 2000 would be an average year, and 2005 would be our bad krill year. While we could have picked other years that looked worse than 2005, we decided this year could show us some very interesting results as it is known to have been a year of delayed upwelling.

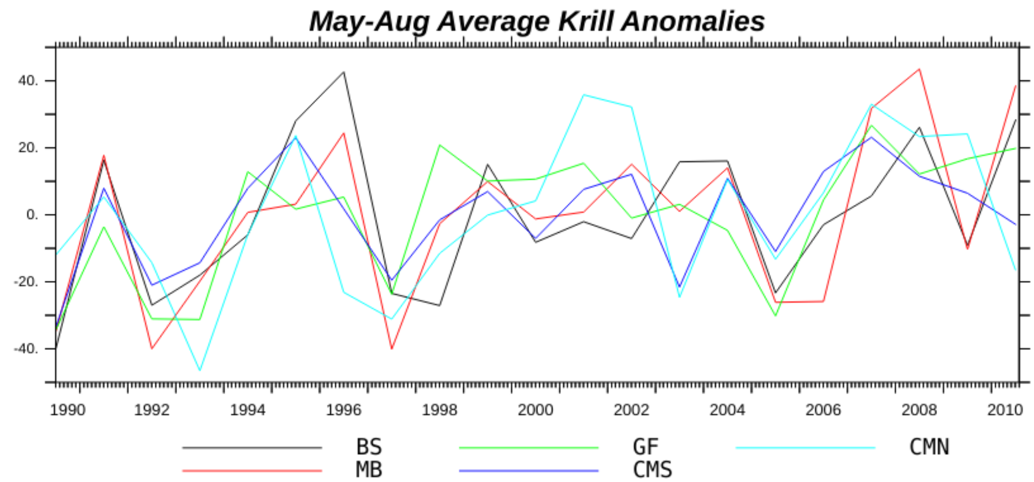

Figure 2: Upwelling season averaged krill anomalies for each hotspot seeding location.

Models were run for every month of each year we chose, but since every hotspot is not active all upwelling season, we only present results for certain active months for each hotspot. Additionally, only results for the Big Sur, Monterey Bay, and Gulf of the Farallones hotspots are discussed here. These three hotspots tell the most interesting story for the chosen years. For the Big Sur hotspot we only looked at May and for Monterey Bay and the Gulf of the Farallones we looked at May and June.

Characteristics being Analyzed

The main water mass characteristics being analyzed in this study are going to be the actual horizontal trajectories of the water mass moving into the final hotspot location, the source depth of the water mass, and the nitrate concentration of the water mass. Using these methods, in the future, we will also look at Diatom biomass in the water mass as a way of quantifying the chlorophyll content. As mentioned previously, the adjoint model only runs the physics, it has no biology or chemistry. However, since the coupled ROMS-NEMURO model has been run on the same grid, using the same forcing, for the same time periods, we can actually use our tracer concentrations to extract properties from this biogeochemical model output. This is what allows us to look at the weighted nitrate concentration of the hotspot's source waters. This is a method that has not been explored previously, but it is an invaluable opportunity to further quantify the ecosystem responses to different ocean conditions.

The method for examining these properties is the same for each variable:

$$\bar{z}_c = \frac{\sum_{i,j,k} \left[C(i,j,k) \cdot z_{var}(i,j,k)\right]}{\sum_{i,j,k} C(i,j,k)},$$

where $\bar{z}_c$ is the variable of interest weighted by the passive tracer concentration, z_{var} is the full variable of interest, and $C(i,j,k)$ is the value of the passive tracer in the (i,j,k) cell. The resulting weighted variable can then be plotted against time to see the evolution of that variable within the average water mass location up until the point it is at the seeding location. To calculate the weighted horizontal trajectories of the source water mass, you would use the above equation for longitude and latitude and then plot the new weighted longitude and latitude pairs.

RESULTS

Big Sur Hotspot

Examining the properties of the back trajectories for the Big Sur hotspot in May (figure 3), we immediately notice that the bad year, 2005, has source depths of a little over 20 meters shallower than the good year, 1991. This difference grows even more and we see that around day 15 (15 days prior to the beginning of the hotspot seeding period), the source waters for both 1991 and 2000 are about 40 meters deeper than for 2005. Typically deeper source waters result in higher nitrate concentration being upwelled, and we can see that this is indeed what is happening here as well. At day zero, a full month before the initial seeding time, the nitrate concentration for the source waters in 2005 were only slightly lower than in 1991 or 2000, but we see that the nitrate depletes very quickly in 2005

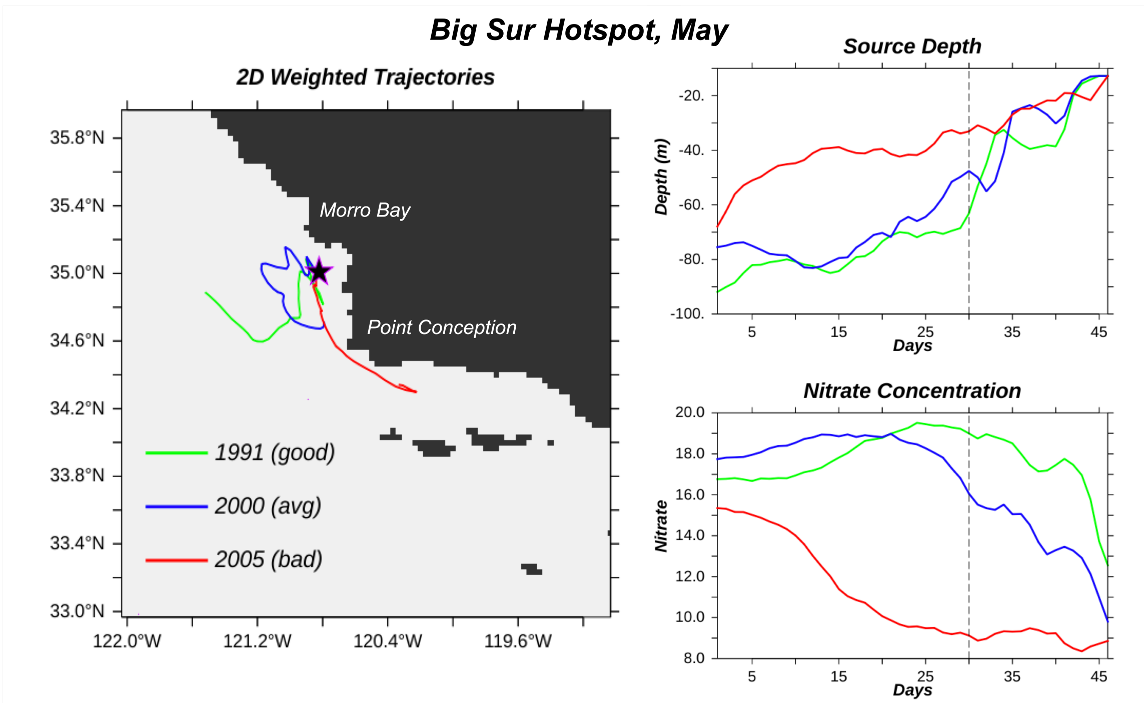

Figure 3: Weighted trajectory, depth, and nitrate concentration of the water masses which ended up at the Big Sur hotspot in May. For source depth and nitrate concentration, the seeding period (mid May) is from the vertical dotted line and to the right.

whereas in 1991 and 2000, the nitrate concentration actually increases for 20 to 25 days before depleting slightly. All of this agrees with the fact that 2005 was a poor krill abundance year according to the upwelling season average krill anomalies in figure 2. It is also interesting to note that in the 2D weighted trajectories in figure 3, the source water for the bad year, 2005, is actually coming from within the Southern California Bight, whereas the more productive years have source waters coming from more straight offshore and north of Point Conception.

Monterey Bay Hotspot

Now, looking at the back trajectories for the Monterey Bay hotspot in May (figure 4), we see a very similar story as the Big Sur hotspot in may (figure 3). The source waters in 1991 are over 25 meters deeper than the source waters for 2005. Our average year, 2000, has source waters at a depth in between these other two years. This again agrees with the nitrate concentrations as well. At day zero, a

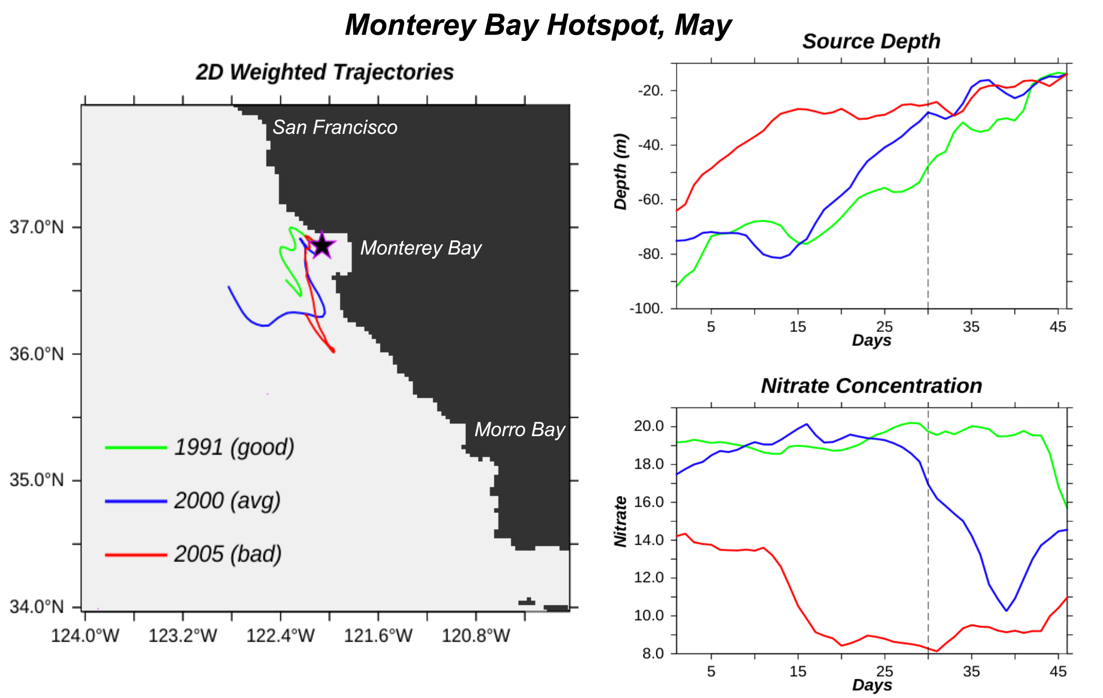

Figure 4: Weighted trajectory, depth, and nitrate concentration of the water masses which ended up at the Monterey Bay hotspot in May. For source depth and nitrate concentration, the seeding period (mid May) is from the vertical dotted line and to the right.

month before the beginning of the seeding period, 2005 has a nitrate concentration of about 14 mmol/m^3, but by day 15, this depletes to almost half that level. Whereas, in 1991 and 2000, the nitrate concentration stays around 18-20 mmol/m^3 until the beginning of the seeding period. At this time, the nitrate concentration begins depleting for 2000, but not to the same level as it did in 2005. The trajectories are not as different for this hotspot in May. The one note is that the water mass started and reached further south in 2005 than either of the other years, but not to a significant difference.

Looking at the back trajectory and source water characteristics for the Monterey Bay hotspot in June (figure 5) is a completely different story. Recall that 2005 was an anomalously bad krill year based on the upwelling season averaged anomalies. However, the source depth for the water mass that makes up this hotspot observed in June is about 20 meters deeper in 2005 than 1991, our good year. Even though the source waters are significantly deeper for 2005, the

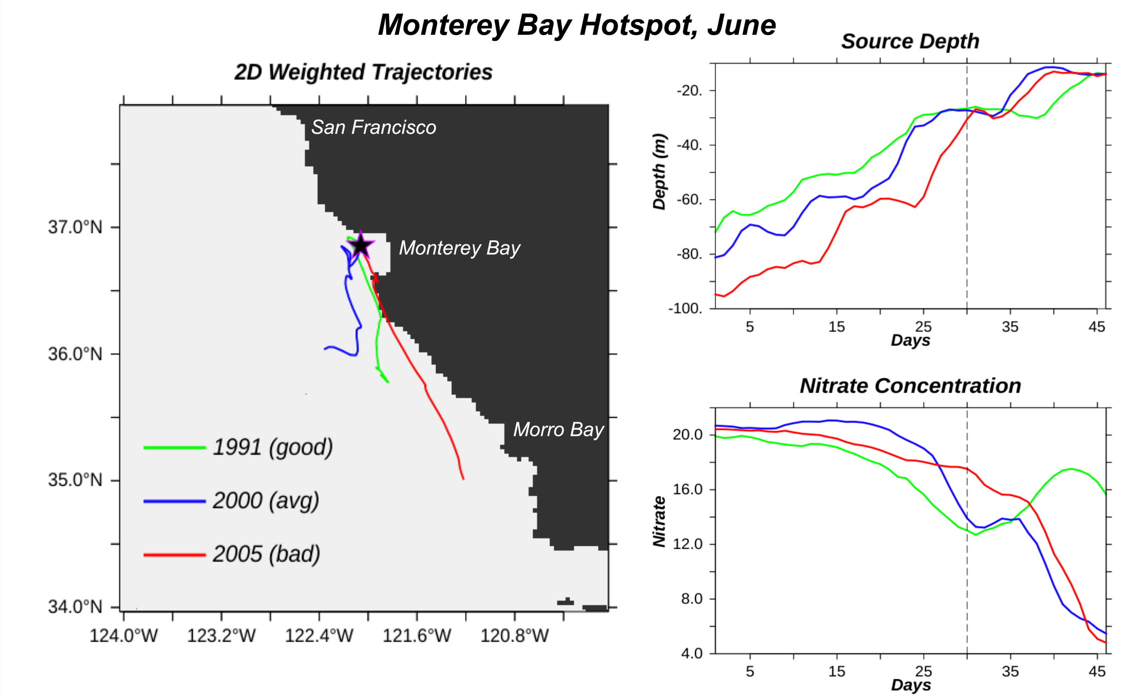

Figure 5: Weighted trajectory, depth, and nitrate concentration of the water masses which ended up at the Monterey Bay hotspot in June. For source depth and nitrate concentration, the seeding period (mid June) is from the vertical dotted line and to the right.

nitrate concentrations are relatively consistent among all three years. On days 35-45, there is more nitrate depletion in 2000 and 2005, possibly meaning that there is more persistent upwelling in 1991, but before then there are very little differences.

One would think that since the source depth for 2005 is 20 meters deeper than in 1991, that the nitrate concentration would be significantly higher for 2005 than 1991, similar to how we see higher nitrate for 1991 in May. However, this is likely not the case due the extremely low amounts of nitrate being supplied to this area in May. So, even though it appears that the upwelling at the Monterey Bay hotspot is stronger in June 2005 than June 1991, the nitrate contents are about the same because of how deplete of nitrate it was in May 2005 versus May 1991. This picture of May versus June for the Monterey Bay hotspot does indeed match up with the reason that 2005 was a bad year for krill availability, and that is due to the delayed upwelling. May 2005 is significantly worse than May 1991 because upwelling had not kicked in yet, but by June, 2005 had started upwelling pretty significantly, and this is clearly seen in our results (figures 4 versus 5).

Gulf of the Farallones Hotspot

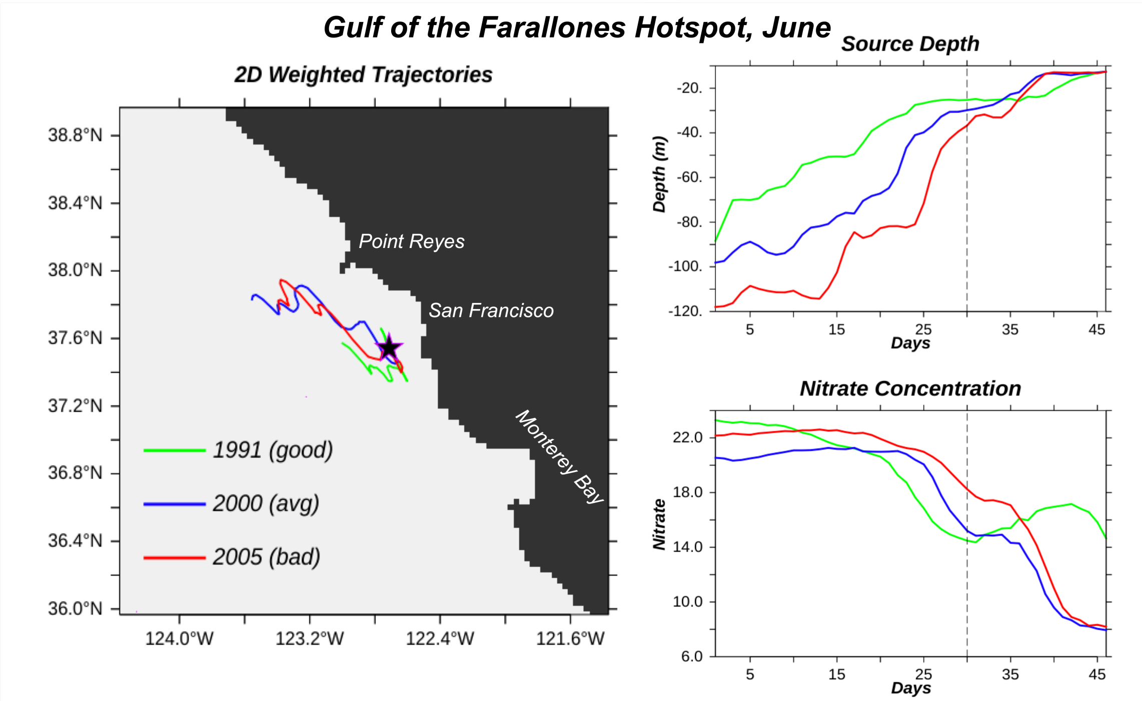

Figure 6: Weighted trajectory, depth, and nitrate concentration of the water masses which ended up at the Gulf of the Farallones hotspot in June. For source depth and nitrate concentration, the seeding period (mid June) is from the vertical dotted line and to the right.

The overall results for the back trajectories leading up to the Gulf of the Farallones hotspot that is observed in June (figure 6) are fairly consistent with the Monterey Bay hotspot in June (figure 5). We see that, even though 2005 was on average a poor year for krill availability, the source depths for the hotspot observed here during June are significantly deeper (~30 meters) in 2005 than they are in 1991 or even 2000 (by ~10 meters). The nitrate concentrations are once again fairly even across all three years, with the same depletion over the last 5-10 days in 2000 and 2005 as observed in figure 5. Again, while it appears the upwelling around the Gulf of the Farallones hotspot was stronger in June 2005 than in June 200 or 1991, the nitrate concentrations were about the same each year.

If one were to only observe these passive tracer trajectories for the Gulf of the Farallones hotspot during it's peak month, June, then there would be no reason to believe that 2005 was a less productive year in terms of krill availability and hence productivity of the California Current Ecosystem. However, since we know that 2005 was a delayed upwelling year, we can gain insights by looking at the source waters that led up towards this hotspot in May (still within its peak window), to see how the state of the ocean was around that area before upwelling finally caught back up in June 2005.

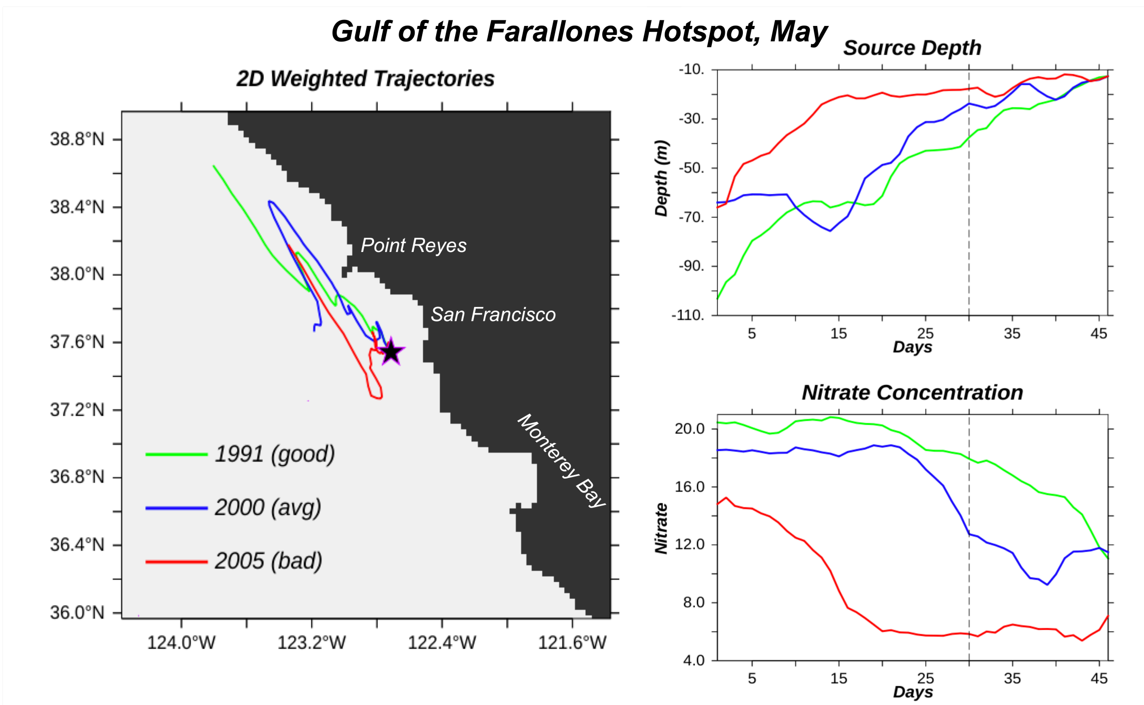

Figure 7: Weighted trajectory, depth, and nitrate concentration of the water masses which ended up at the Gulf of the Farallones hotspot in May. For source depth and nitrate concentration, the seeding period (mid May) is from the vertical dotted line and to the right.

Now that we are looking at the source waters leading up to the Gulf of the Farralones hotspot that would be observed in May (figure 7), we again see exactly why 2005 was a poor year for krill availability. Similarly to the other hotspots observed in May (figures 3 and 4), we see that significant upwelling has yet to kick in. The source waters for the Gulf of the Farallones hotspot in May are over 30 meters deeper in 1991 than in 2005 and the nitrate concentration 10 days prior to the beginning of the hotspot seeding period is about three times as high in 1991 as it is in 2005. 2000 also sees high nitrate concentrations, though not quite as high as in 1991. When looking at the 2-dimensional trajectories, we see that water masses for the 1991 hotspot are coming from closer to the enhanced upwelling that is typical in the lee of Point Arena, with the source water masses for 2000 being second farthest north, and source water for 2005 being the furthest south. This could play into the enhanced nitrate concentrations seen in 1991 and 2000 as well.

DISCUSSION

We have presented a method of using back trajectories of passive tracers within the Adjoint ROMS model to examine and quantify the differences in how the ecosystem responded to different anomalous ocean conditions. By picking a year that was considered to be a good year for krill availability in the CCS (1991), an average year (2000), and a year that was widely considered a bad year due to delayed upwelling (2005), we have verified that this method can indeed quantify these differences. It was also shown that by simply looking at the ocean conditions during just the peak month of a hotspot (i.e. June for the Gulf of the Farallones), one could easily miss what could actually lead to an incredible unproductive year. This was evident for the Gulf of the Farallones hotspot in 2005. By looking just at the passive tracer back trajectories and state variables for the peak month of June, 2005 looked to be a completely normal year. When in reality, the poor krill availability in 2005 let to massive declines in seabird populations in the short term and big hits to the number of returning mature salmon in the long-term (historically 2008 was a very bad year for returning adult salmon). By also looking at the passive tracer back trajectories for May at this hotspot however, we do in fact see that 2005 was very unproductive.

This goes to show that this type of adjoint backtracking model can be useful in examining the ecosystem responses to different ocean conditions. This would become extremely useful when run for several years covering a wide variety of ocean conditions. It could also be beneficial in determining initial trajectory locations and initial conditions for the data driven models which are highly dependent on using correct initial conditions. The ideal scenario would be to have a real time model that predicts krill hotspots using satellite data. Models like this would be highly dependent on initial conditions though, and there is no way, at least currently, to get accurate initial conditions from satellites, because these initial conditions are values at depth. This is where the utility of this adjoint model could come in. It could provide better initial conditions for these satellite data models.

As work on this project progresses, we will also look at diatom biomass weighted by the passive tracers within the water masses throughout time. This would give us an estimate of chlorophyll content and further enable to usefulness of this model with satellite data models, since satellites can pick up chlorophyll data. Additionally, I will also quantify the variability of the transport along these back trajectories. Since we are weighting all of the state variables with the passive tracer and summing together, we loose some information on the variability of the water mass. It could even be that there are two distinct water masses which combine at some point at the hotspot, but come with different characteristics. So, quantifying the variability of these trajectories can aid in the interpretation of the ecosystem response as well.

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