Humboldt squid as an agent of climate-driven ecosystem interactions in the California Current

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Project Summary

Since 2002 the typically subtropical Humboldt squid (*Dosidicus gigas*) has been undergoing a range expansion and is now regularly encountered in large numbers throughout the California Current System (CCS). *Dosidicus* clearly has the potential to impact coastal pelagic ecosystems and fisheries, but neither the abundance of these predators nor the optimal ocean conditions in which they flourish are known with confidence. Concerns by scientists, stakeholders and the public with respect to potential impacts on commercial and recreational fisheries have led to a need to evaluate the magnitude, causes, and consequences of the presence of these animals in the CCS. We propose to develop an index of relative abundance for the Humboldt squid population with a unique, fisheries-independent dataset. This index will be developed both to be used as an ecosystem indicator for status assessments of trends and conditions in the California Current and as a relative abundance time series for use in single species (stock assessment) and multispecies models. Specifically, this index will be directly incorporated into existing single species models for important stocks on the West Coast, such as those for Pacific hake (*Merluccius productus*) and shortbelly rockfish (*Sebastes jordani*). We will also investigate the climate-forcing mechanisms that appear to be linked to both abundance and seasonality of squid migrations throughout the CCS, providing a foundation for understanding the proximate causes of the range expansion.

Background and Context

Dosidicus gigas is a highly migratory, oceanic species that also inhabits continental shelf environments of the eastern Pacific, and both historical and contemporary range extensions have transiently reached mid-latitudes in both hemispheres (Zeidberg and Robison 2007, Field *et al.* 2007a, Alarcón-Muñoz *et al.* 2008). A reappearance of this species off Monterey after the 1997/98 El Niño has resulted in an unusually persistent residence, with Humboldt squid regularly encountered in resource surveys and fisheries throughout the CCS. Food habits data for Humboldt squid have now been evaluated throughout the entire CCS, from Baja California to the Pacific Northwest (Markaida *et al.* 2006, Bazzino *et al.* 2010, Field *et al.* 2007a, J. Field, unpublished data). Small squid and mesopelagic fishes are typically the most important prey, however Pacific hake are commonly encountered throughout the CCS, particularly in northern regions (Figure 1). Other commonly encountered prey in U.S. waters include Pacific sardine, Pacific herring, market squid, and several species of rockfish (*Sebastes spp*), while infrequently encountered prey include several species of flatfish, salmon, lingcod and sablefish.

As these range expansions do not appear to be incremental, but rather episodic (and concurrent) in both hemispheres, a climate-related mechanism is the most likely explanation for these range expansions and contractions. Climate has already driven poleward range expansions in many marine species, and animals with the highest turnover rates show the most rapid distributional responses to warming (Perry *et al.* 2005). Although a broad thermal tolerance of

Dosidicus is likely to underlie the range variability and expansion (Gilly *et al.* 2006), it is likely that other factors are also important. Current evidence suggests an ongoing expansion of the oxygen minimum zone (OMZ) throughout the Eastern Tropical Pacific, the CCS, and the North Pacific (Stramma *et al.* 2008; Bograd *et al.* 2008; Whitney *et al.* 2007, respectively), and this could be another driving factor. Tagging studies off Mexico and central California (conducted as part of a comprehensive effort funded by Sea Grant to evaluate habitat utilization and food habits) have demonstrated that *Dosidicus* utilizes the upper boundary of this unique habitat (Gilly *et al.* 2006, Bazzino *et al.* 2010, J. Stewart, unpublished data), and it is possible that the shoaling of the OMZ may act to "compress" the mesopelagic food web closer to the surface where light intensity for visual foragers is greater (Koslow *et al.* 2011). If such shoaling results in greater overlap between the location the mesopelagic forage base with the bottom of the photic zone, this could greatly favor Humboldt squid over other pelagic predators, because they are physiologically adapted to tolerate cold, hypoxic conditions (Rosa and Seibel, 2010). Over the past decade, some of the "strongest" squid years were those in which ocean conditions were anomalously warm, often due to delayed upwelling (e.g., 2005, 2006, Bograd *et al.* 2009), and transient warm-water anomalies may be associated with pulses of range extension (Gilly, 2006). Changes in the frequency and intensity of El Niño events, as well as changes in upwelling intensity and persistence are also expected to be impacted by climate change, but precisely how these phenomena impact *Dosidicus* remains unclear.

Moreover, recently Humboldt squid have been complicating monitoring, and consequently management for Pacific hake, the largest fishery (by volume) on the U.S. West Coast. In 2009, high squid abundance created difficulty in interpreting the results of the fishery-independent hydroacoustic survey that is a key component of the Pacific hake stock assessment. Specifically, the presence of squid appears to alter the distribution and dispersal of hake, complicating target identification (Holmes *et al.* 2008; Stewart and Forrest 2011). Further, in 2009, squid and hake accounted for approximately 47% and 50% of the total trawl catch, respectively, making accurate differentiation of echo-signs critically important (Stewart and Hamel 2010, Stewart and Forrest 2011). Such concerns led to an increased relative uncertainty in the 2009 hake acoustic survey data, adding ~50% more variance to the survey point estimates as attributed to sampling variability and patchiness (Stewart and Forrest 2011).

Impacts on Pacific hake may be also be occurring directly on population dynamics (e.g., increased predation mortality), and the magnitude of this effect could be considerable as ongoing research suggests squid biomass levels on the order of 800,000 to 1,500,000 tons in 2009 (Figure 2, R. Thomas, unpublished data). Combined with the observation that hake may comprise 10 to 30% of the diet by volume in various times and places in the CCS (Figure 1), there is some concern that the current *Dosidicus* population may have a significant influence on the mortality rate of hake and other important species. These potential effects cannot be directly investigated in current stock assessment models without a coherent time-series of relative squid abundance.

Although Humboldt squid have been uncommon in the California Current for the past two years, they have been present (as of this writing, occurring in high recent abundance in the Southern California Bight) and we anticipate that their low relative abundance is a temporary phenomena. The reason for the recent reduced abundance is unclear, but may have been in response to an unusually strong El Niño Modoki (sensu Yeh *et al.* 2009) event in 2009-2010 that led to major changes in distribution, diet and reproductive strategy of squid in the Gulf of California. Specifically, squid abandoned their normal coastal-shelf habitats in early 2010 and appeared en masse in areas of the Gulf of California where productivity was less dependent on wind-driven upwelling (W. Gilly, unpublished data).

We have three main objectives: First, we will develop of a robust index of relative abundance of *Dosidicus* in the CCS using fisheries-independent data from ROV surveys in Monterey Bay, and complement this index using fisheries-dependent data from the hake fishery off Washington and Canada. Second, we will integrate this index into existing stock assessment models for Pacific hake and other species, to evaluate whether this index can help explain observed patterns in abundance and age structure through variable predation mortality. Finally, we will design an oceanographic habitat model using an ensemble modeling approach.

Objective 1. Develop an index of relative abundance for *Dosidicus* in the CCS.

In this project we will be working with unique, fisheries-independent time-series data of *Dosidicus* abundance in Monterey Bay, California. The Monterey Bay Aquarium Research Institute (MBARI) has been monitoring deep-sea and midwater environments using remotely operated vehicles (ROVs) since 1989, documenting marine life as well as oceanographic data. *Dosidicus* has been observed and quantified in the Monterey Canyon system by MBARI during this entire period (Zeidberg and Robison 2007). We are in the process of refining "sightings per unit effort" (SPUE), analogous to catch per unit effort (CPUE), from this database (Figure 3). This will be done using generalized linear models (GLMs) with the optimized sightings per unit effort (SPUE) time-series data to remove the effects of seasonality, ROV location, ROV depth and other variables to be explored. The GLM is intended to account for non-uniform effort throughout different time frames, particularly because of strong seasonal patterns suggested by these data. GLMs are commonly used for standardizing catch rate or other survey data into usable indices for assessments (Maunder and Punt 2004, Dick 2004).

The MBARI ROV data is regularly collected in a centrally located region of seasonally high squid abundance, and will effectively sample the *Dosidicus* population throughout the year. Although the Pacific hake fishery itself is typically prosecuted northward of this region (in the Pacific Northwest), the hake population itself is highly migratory, and transverses the Central California region during a northward (feeding) migration in the spring, and the southward (spawning) migration in the late fall or early winter (Dorn et al. 1995, Stewart and Forrest 2011). Our incomplete but growing understanding of the seasonal movement pattern of Humboldt squid suggests a comparable migration, as *Dosidicus* are typically most abundant in the Pacific Northwest during late summer and fall, and off of central California in winter. We will complement our sightings index by exploring relative catch rates from bycatch data from the Pacific hake fishery and other sources.[1] These two sources of data are considered by this team to hold the greatest potential based on our assessment of the duration of the time series and the relative frequency of positive observations, which is approximately over an order of magnitude greater with the ROV survey relative to any other readily available data source.

Objective 2. Integrate relative abundance index into existing stock assessment models for Pacific hake and other species.

Our index of relative abundance can be directly evaluated in single-species stock-assessment models (and potentially in future multispecies models). Our collaborators at the NWFSC (I. Stewart and R. Thomas) will play a key role in developing the index, and

[1] Dosidicus have been identified to the species level since 2006 in the At-sea fishery, thus such an index would have limited duration. We intend to work with the observer program to explore these data, noting that any analysis will be done solely by NOAA FTE's due to confidentiality issues. We will also explore abundance information from the NWFSC Pacific hake acoustic and bottom trawl surveys, both of which are also of a more limited duration.

investigating the statistical support for a link between squid abundance and Pacific hake population dynamics or observation processes. This index can serve as a direct covariate for temporal changes in natural mortality in the current assessment software (Stock Synthesis III, Methot 2009), or for additional process-error variance of the observed hydroacoustic survey estimates (high squid abundance would be positively correlated with uncertainty about acoustic point estimates of hake abundance). This approach is not unprecedented; predation by *Dosidicus* has been directly incorporated into an assessment model of hake in Chile (CHASAW, in press). In that example, predation mortality of squid on hake was found to be important in accounting for a decline in hake abundance during a period in which *Dosidicus* catch-rates (and relative abundance) rose from trace levels to several hundred thousands tons. We also will explore statistical support for inclusion of the squid index in stock assessments of other potentially important prey species, including chilipepper and shortbelly rockfish, two species with markedly different exploitation histories (Field *et al.* 2007b, Field 2008).

Objective 3. Create a model to provide a parsimonious explanation for variability in *Dosidicus* abundance.

We will develop a model that relates ocean conditions to abundance based on upwelling, temperature, dissolved oxygen, and other physical variables impacting the CCS. Our habitat models will be based on an ensemble modeling approach (Araùjo and New 2008), which means we will combine a suite of models in an attempt to best describe the system. Our efforts will include a combination of structural equation modeling (SEM), binomial distribution, generalized additive models (GAMs), maximum entropy models and mixed models. We will create these models at midwater depths (~200-600m), which is the daytime habitat for *Dosidicus* in the CCS (Zeidberg & Robison 2007; our unpublished data). Projections of future climate suggest that an increase in warmer, more stratified water masses with lower oxygen content at depth are expected under most global change scenarios (Whitney *et al.* 2007), and the eastern Pacific region (including the CCS) is particularly vulnerable to this impact (Deutsch *et al.* 2011). This index could thus prove to be a meaningful metric regarding the effects of global change on marine communities and fisheries (Doney *et al*. in press).

We will use structural equation models (SEMS) to evaluate the relationships among environmental covariates (e.g. depth, temperature, oxygen, salinity, light) and between these covariates and squid abundance in order to assess habitat use and the proximate causes of the ongoing range expansion (e.g., Wells *et al.* 2008). From presence/absence data, we will use a binomial distribution to model the oceanographic variables that structure *Dosidicus* distribution and abundance. GAMs and maximum entropy models may provide additional approaches for working with non-normally distributed data and can examine the effect of each physical variable on potential habitat. Mixed models that incorporate each fishing vessel or ROV trip as a random effect and a first order correlation function in the error term (Wood 2006) will be used to examine individual variability and account for spatial autocorrelation in the error term.

Benefits

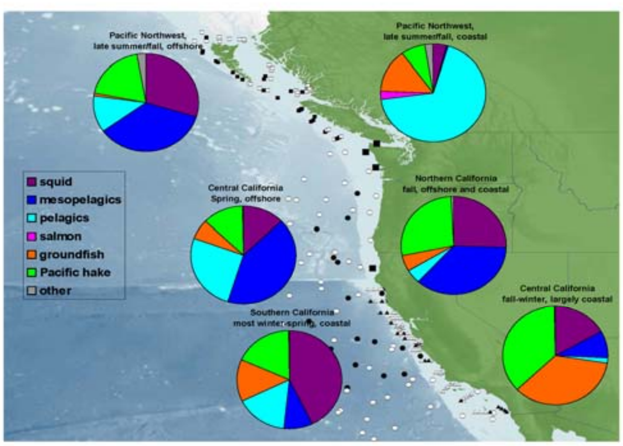
Based on documented impacts of *Dosidicus* on the Pacific hake population and on hake monitoring efforts, and the potential for future interactions, a relative abundance index for squid is critically needed to better understand and predict the consequences of this highly influential new member of the CCS. This proposal includes experts in *Dosidicus* ecology (W. Gilly, B. Robison, J. Stewart) as well as stock assessment scientists (including the lead for the Pacific hake assessment, I. Stewart, as well as the lead for several assessments of central California rockfish, J. Field) and climatologists experienced with linking oceanographic data to ecological data (S. Bograd, E. Hazen). Moreover, our index will also provide a rigorous, quantitative alternative to the largely qualitative accounts of *Dosidicus* abundance in relation to physical and biological conditions in the CCS (e.g., Bjorkstedt *et al.* 2010, Levin and Schwing. 2011, http://www.pacoos.org). Ultimately, these efforts will help to inform fisheries managers on ongoing impacts of Humboldt squid on fisheries resources and to help elucidate the subtle nature of interactions among ecosystem processes that will be impacted by future changes in climate.

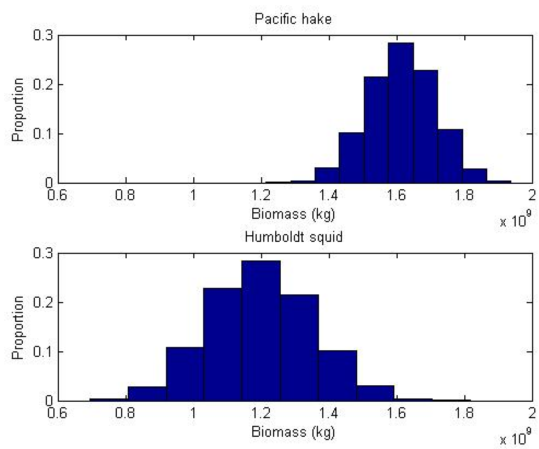
Deliverables

1. A statistically rigorous index of relative abundance of Humboldt squid in the CCS for the period 1997/98-present, and comparison of this index with other sources of information about squid abundance. A publication is expected, and the result will also be made available to CCS indicator reports and other relevant stock assessments and models.

2. An evaluation of the utility of this index (deliverable #1) in the stock assessments for Pacific hake, chilipepper and shortbelly rockfish. Regardless of outcome, these efforts are likely to be referenced (if not included) in future assessments. Synthesis of results could form the basis for future publications depending on the strength of the relationships.

3. An assessment of the suite of physical variables that are associated with changes in the relative abundance based on a structural equation model, including an evaluation of how future climate change may relate to habitat suitability. This should lead to a significant publication.





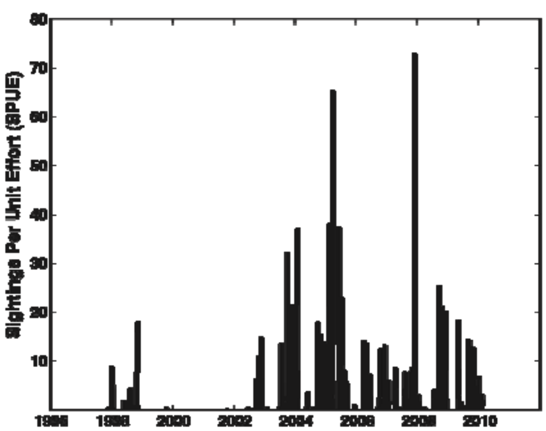


Figure 1 (top left): Observed proportion of Pacific hake in Humboldt squid diets throughout the CCS, 2007-2009. Shown are estimates for the fraction of Pacific hake as a percentage of mass of fish and cephalopods only, excluding approximately 20% of diet accounted for by crustaceans and pteropods). Points show areas where squid were sampled (black) and where sampling was attempted but squid were not encountered (white). Figure 2 (top right): Bootstrap estimates of the absolute abundance of Humboldt squid from the 2009 NWFSC Pacific Hake Hydroacoustic survey (R. Thomas and I. Stewart, unpublished data). Figure 3 (left): Mean monthly sightings per unit effort (SPUE) for MBARI ROV-observed Humboldt squid since 1995.

References

Alarcón-Muñoz, R., L. Cubillos and C. Gatica. 2008. Humboldt squid (*Dosidicus gigas*) biomass off central Chile: Effects on Chilean hake (*Merluccius gayi*). CalCOFI Reports 49: 157-166.

Araújo M.B. and M. New. 2007. Ensemble forecasting of species distribution. Trends Ecology and Evolution 22: 42–47.

Bazzino, G., W.F. Gilly, U. Markaida, C.A. Salinas-Zavala, J. Ramos-Castillejos. 2010. Horizontal movements, vertical-habitat utilization and diet of the Humboldt squid (*Dosidicus gigas*) in the Pacific Ocean off Baja California Sur, Mexico. Progress in Oceanography 86:1-2: 59-71.

Bjorkstedt, E., R. Goericke and 37 co-authors. 2010. State of the California Current 2009-2010: regional variation persists through transition from La Niña to El Niño (and back?). CalCOFI Reports 51:39-68.

Bograd, S.J., C.G. Castro, E. Di Lorenzo, D.M. Palacios, H. Bailey, W. Gilly, and F.P. Chavez. 2008. Oxygen declines and the shoaling of the hypoxic boundary in the California Current. Geophysical Research Letters 35: L12607.

Bograd, S.J., I. Schroeder, N. Sarkar, X. Qiu, W.J. Sydeman and F.B. Schwing. 2009 The phenology of coastal upwelling in the California Current. Geophysical Research Letters 36, L01602, doi:10.1029/ 2008GL035933.

CHASAW (Chilean Hake Stock Assessment Workshop). In Press. Draft of Final Report of Chilean Hake Stock Assessment Workshop. Instituto de Fomento Pesquero, Chile.

Deutsch, C., H. Brix, T. Ito, H. Frenzel and L. Thompson. 2011. Climate forced variability of ocean hypoxia. Science 333: 336- 339.

Dick, E.J. 2004. Beyond 'lognormal versus gamma': discrimination among error distributions for generalized linear models. Fisheries Research 70:351-366.

Doney, S.C., M. Ruckelshaus, J. Emmett Duffy, J.P. Barry, F. Chan, C.A. English, H.M. Galindo, J.M. Grebmeier, A.B. Hollowed, N. Knowlton, J. Polovina, N.N. Rabalais, W.J. Sydeman, and L.D. Talley. In press. Climate Change Impacts on Marine Ecosystems. Annual Review of Marine Science.

Dorn, M.W. 1995a. The effects of age composition and oceanographic conditions on the annual migration of Pacific whiting, *Merluccius productus*. CalCOFI Reports 36:97-105.

Field, J.C., K. Baltz, A.J. Phillips, and W.A. Walker. 2007a. Range expansion and trophic interactions of the Humboldt squid, *Dosidicus gigas*, in the California Current. CalCOFI Reports 48: 131-146.

Field, J.C., E.J. Dick, M. Key, M. Lowry, Y. Lucero, A. MacCall, D. Pearson, S. Ralston, W. Sydeman, and J. Thayer. 2007b. Population dynamics of an unexploited rockfish, *Sebastes jordani*, in the California Current. pp 451-472 in J. Heifetz, J. Dicosimo, A.J. Gharrett, M.S. Love, V. M. O'connell and R.D. Stanley (editors) Proceedings of the Lowell-Wakefield Symposium on the Biology, Assessment and Management of North Pacific Rockfish. University of Alaska Sea Grant: Anchorage, Alaska.

Field, J.C. 2008. Status of the Chilipepper rockfish, Sebastes goodei, in 2007. In: Status of the Pacific Coast Groundfish Fishery Through 2007, Stock Assessment and Fishery Evaluation: Stock Assessments and Rebuilding Analyses Portland, OR: Pacific Fishery Management Council.

Gilly, W.F., U. Markaida, C.H. Baxter, B.A. Block, A. Boustany, L. Zeidberg, K. Reisenbichler, B. Robison, G. Bazzino and C. Salinas. 2006. Vertical and horizontal migrations by the Humboldt squid *Dosidicus gigas* revealed by electronic tagging. Mar. Eco. Prog. Ser. 324: 1-17.

Gilly, W.F. 2006. Spreading and stranding of jumbo squid. Ecosystems Observations for the Monterey Bay National Marine Sanctuary 2005: 25-26.

Holmes, J., K. Cooke, and G. Cronkite. 2007. Interactions between Humboldt squid (*Dosidicus gigas*) and Pacific hake (*Merluccius productus*) in the northern California Current in 2007. CalCOFI Reports 49: 129-141.

Ibañez, C.M., H. Arancibia and L. Cubillos. 2008. Biases in determining the diet of Humboldt squid *Dosidicus gigas* (D'Orbigny 1835) (Cephalopoda: Ommastrephidae) off southern-central Chile (34S-40S). Helgoland Marine Research 62:331–338.

Koslow, J.A., R. Goericke1, A. Lara-Lopez and W. Watson. Impact of declining intermediate-water oxygen on deepwater fishes in the California Current. Marine Ecology Progress Series 436: 207–218.

Levin, P. S., F. B. Schwing. (Eds.) 2011. Technical background for an integrated ecosystem assessment of the California Current: Groundfish, salmon, green sturgeon, and ecosystem health. U.S. Dept. of Commerce, NOAA Tech. Memo., NMFS-NWFSC-109, 330 p.

Markaida, U. 2006. Food and feeding of Humboldt squid *Dosidicus gigas* in the Gulf of California and adjacent waters after the 1997–98 El Niño event. Fisheries Research 79:16–27.

Maunder, M.N. and A.E. Punt. 2004. Standardizing catch and effort data: a review of recent approaches. Fisheries Research 70:141-159.

Methot, R.D. 2009. Stock assessment: operational models in support of fisheries management. In R.J. Beamish and B.J. Rothschild (editors) The Future of Fisheries Science in North America, 137 Fish & Fisheries Series. Springer Science and Business Media

Perry, A.L., P.J. Low, J.R. Ellis and J.D. Reynolds. 2005. Climate change and distribution shifts in marine fishes. Science 308: 1912-1915.

Stramma, L., G.C. Johnson, J. Sprintall, V. Mohrholz. 2008. Expanding Oxygen-Minimum Zones in the Tropical Oceans. Science 320: 655-658.

Stewart, I.E. and R.E. Forrest. 2011. Status of the Pacific Hake (Whiting) stock in U.S. and Canadian waters in 2011. Pacific Fishery Management Council Stock Assessment and Fishery Evaluation. Available online at http://www.pcouncil.org/wp-content/uploads/2011_Pacific_hake_assessment_final_withAppendices.pdf

Stewart, I.J. and O.S. Hamel. 2010. Stock Assessment of Pacific Hake, *Merluccius productus*, (a.k.a. Whiting) in U.S. and Canadian Waters in 2010. Pacific Fishery Management Council Stock Assessment and Fishery Evaluation. http://www.pcouncil.org/wp-content/uploads/E3a_ATT2_HAKE_USCAN_NWFSC_MARCH_2010_BB.pdf

Wells, B.K., J. Field, J. Thayer, C. Grimes, S. Bograd, W. Sydeman, F. Schwing and R. Hewitt. 2008. Untangling the relationships between climate, prey, and top predators in an ocean ecosystem. Marine Ecology Progress Series 364: 15-29.

Whitney, F.A., H.J. Freeland, and M. Robert. 2007. Persistently declining oxygen levels in the interior waters of the eastern subarctic Pacific. Progress in Oceanography 75: 179-199.

Wood, S.N. 2006 Generalized additive models: an introduction with R. CRC Press. 391pgs.

Yeh, S.-W., J.-S. Kug, B. Dewiktte, M.-H. Kwan, B.P. Kirtman and F.-F. Jin. 2009. El Niño in a changing climate. Nature 461: 511- 515.

Zeidberg, L.D. and B.H. Robison. 2007. Invasive range expansion by the Humboldt squid, *Dosidicus gigas*, in the eastern North Pacific. Proceedings of the National Academy of Sciences 104: 12948-12950.