California Fish and Game 103(4): 177-182; 2017

Impacts of El Niño on Adult Chinook Salmon (*Oncorhynchus tshawytscha*) Weight in the Gulf of the Farallones from 1983 to 2015

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Key words: Chinook, El Niño, Farallones, reduction in weight, *Oncorhynchus tshawytscha*

Chinook salmon (*Oncorhynchus tshawytscha;* hereafter, Chinook*)*, is a species that has evolved to cope with the highly variable oceanic and freshwater environments of the Pacific Northwest, and responds to large changes in those environments in equally dramatic fashion. Here, some of the effects of El Niño on Chinook as they migrate through the Gulf of the Farallones (GoF), central California Current System, are examined. The southernmost portions of Chinook are those that spawn in the Sacramento-San Joaquin River system (Central Valley of California). They pass through the GoF as adults returning to spawn; their progeny out-migrate through the system as juveniles. Chinook in this system have four distinct runs: fall, late-fall, winter, and spring (Boydstun et al. 2001). While all the runs were probably abundant historically, large-scale habitat changes have reduced populations almost entirely to fall fish, facilitated by production in hatcheries. Natural spawning runs have fallen to such low levels that winter Chinook are listed as Endangered and spring Chinook as Threatened under both the U. S. Endangered Species Act (ESA) and the California Endangered Species Act (CESA). Also fall and late fall Chinook are considered a species of concern by the National Marine Fisheries Service. Herein, we analyze annual variation in body weight of returning adult Chinook, and its relation to the food web in the GoF as affected by El Niño-Southern Oscillation (ENSO), a major driver of California Current System variability (Checkley et al. 2015). El Niño is the positive phase of ENSO, an irregularly occurring change in oceanic conditions affecting the equatorial Pacific region, and leading to the appearance of unusually warm, nutrient-poor water and increased precipitation along the western coast of North and South America (NOAA 2017; Wang et al. 2017). The changes in water temperature and nutrients have a marked effect on a number of important anadromous and marine fishes, especially through reduced forage (Glantz and Thompson 1981; Ainley et al. 2014, 2015). Among the effects are increased mortality and changes in migratory patterns of fishes such as salmon, albacore (*Thunnus alalunga*), and bluefin tuna (*T. orientalis*) (CDFW 2017, PMEL 2017, Kilduff et al. 2015,

Dufour et al. 2010). Southern species are found much farther north, especially market squid, Pacific jack mackerel (*Trachurus symmetricus*), and California barracuda (*Sphyraena argentea*) (PMEL 2017). Marine mammals and seabirds also experience dramatic reductions in reproduction and increases in mortality (Benson et al. 2002, Parrish et al. 2007, Ainley et al. 2018, CDFW 2017).

We tested the hypotheses that the strength and occurrence of an El Niño event would be linked with (1) Chinook seasonal dressed mean weights from the commercial fishery from May to June between Bodega Bay and Monterey (PFMC 2017), and (2) the Sacramento Index (O'Farrell et al. 2013), which is an index of Sacramento River fall Chinook adult ocean abundance that includes both catch and escapement using correlation matrices. El Niño events were defined by use of the Oceanic El Niño Index (NCAR 2017) reflecting the winter of *t*-1 through *t* (which we assign to year *t* for correlation analysis). Chinook dressed weights (fish that are landed with their viscera removed) were obtained from commercial fishery landings, from the nearest statistical area between Bodega Bay and Monterey (PFMC 2017), and were compared to El Niño indices. Dressed weights were not available during the season closures, 2008 to 2010, when the California Fish and Game Commission took emergency action to close all California ocean salmon fisheries (i.e., Salmon Emergency). Also, dressed weights during 2005 to 2007 were not used due to local or partial seasonal closures.

Commercial landed Chinook dressed weight was lower during El Niño compared to non-El Niño years (Figure 1). During strong El Niño winters (1982-1983, 1997-1998, and 2015-2016), as well as the moderate El Niño winter (1991-1992), Chinook dressed weight was 69% of mean weights from other years. These El Niño salmon are known as "snakes" due to their substantially reduced body mass relative to length. The Chinook live weight reduction due to El Niño may actually be larger since the gonads, which should be increasing during May and June and would be expected to be smaller during El Niño, have already been removed before the dressed weights are measured.

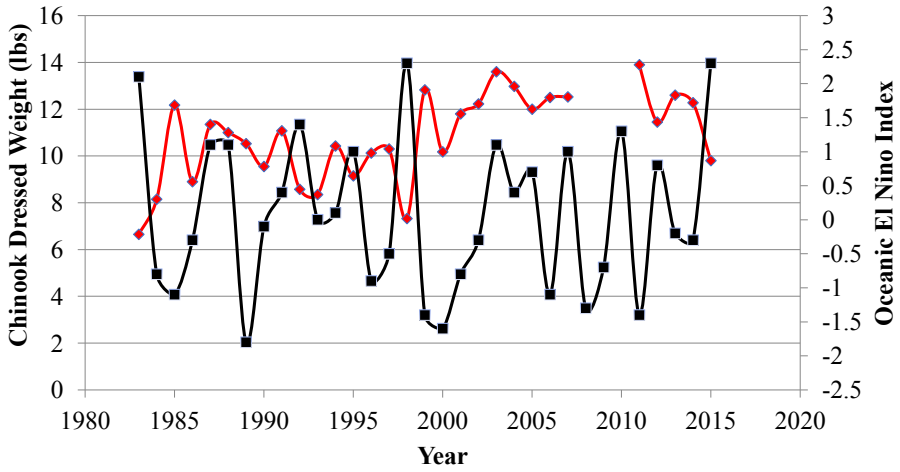

FIGURE 1.—Chinook dressed weight (red) and the Oceanic El Niño Index (black), by calendar year. Note low dressed weights during the strong El Niño winters of 1982-1983, 1997-1998, and 2015-2016 and the moderate El Niño winter of 1991-1992.

Chinook dressed weight from the GoF and the Sacramento Index are correlated at a probability greater than 0.99 until 2004 (correlation between normalized values, r=0.54, df=18; Figure 2). After 2004, the Sacramento Index was forecast at such low levels that fishing seasons were either completely or partially closed and therefore dressed weights were not available. The cause of the these low Sacramento Index numbers was thought to be the result of freshwater and ocean conditions present when these year-classes were entering the ocean as juveniles rather than due to adult conditions at sea (Lindley et al. 2009). These years were not included in our analyses due to fishery closures. After these season closures, the relationship between Chinook dressed weight and the Sacramento Index changed. The dressed weights became high (including the highest and two of the four highest in the series) while the Sacramento Index numbers were very low. It is unclear whether this change is a rebuilding situation from the very low Sacramento Index numbers or a change to a different relationship between Chinook numbers and dressed weight.

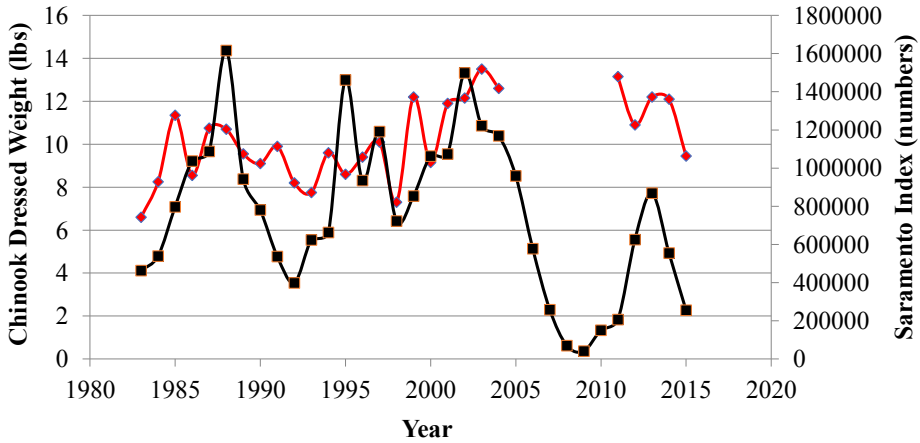

FIGURE 2.—Chinook dressed weight (red) and the Sacramento Index (black), by calendar year. Low values occur in association with the strong El Niño winters of 1982-1983, 1997-1998, and 2015-2016 and the moderate El Niño winter of 1991-1992.

The reduced Chinook dressed weight during El Niño was likely due to a disruption in their normal feeding cycle in the GoF. In non-El Niño years, Chinook move into the GoF beginning in February and March, at which time they are found in waters from Bolinas Point in the north to Pillar Point in the south (Merkel 1957, Adams 2001). They feed almost equally on Pacific herring (*Clupea pallasii*) and northern anchovies (*Engraulis mordax*) in this area (Ainley et al. 2014). April is a time of transition between the earlier nearshore feeding and the offshore feeding that occurs in May and June. Chinook are then found from north of the Golden Gate, i.e., Point Reyes, and offshore to the Farallon Islands. In May and June, Chinook feed on juvenile rockfish (*Sebastes* spp.) and euphausiids offshore along the Farallon Ridge. Sometime between mid-June and mid-July, the Chinook abruptly move shoreward and position directly in front of the Golden Gate, known as the "middle grounds." Here, Chinook feed exclusively on anchovies until they move through San Francisco Bay

and into the river system. They stop feeding during their freshwater spawning migration (Boydstun et al. 2001).

Disruption of this feeding cycle appears to have a significant impact, and during El Niño the prey complexes that normally sustain these fish do not form and there is little to feed on (Ainley et al. 2014; Wells et al. 2017). Juvenile rockfish, euphausiids, and herring virtually disappear and anchovies are more dispersed and do not form their usual large aggregations. Juvenile rockfish and anchovies are probably the most important prey because of their high caloric values (Roth et al. 2008). One potential hypothesis is that the disruption of these prey complexes results in the low Chinook dressed weight, and this leads to the reduced condition and fecundity. How this connects to low numbers of Chinook in the Sacramento Index is not understood, but clearly fishing was poor in these years.

For Central Valley fall Chinook, the vast majority of Chinook in the GoF, the impact of reduced weight and Index numbers related to El Niño on the overall long-term population dynamics is small since fall Chinook reproduction occurs largely in hatcheries. That is, hatchery production is maintained at a fairly consistent level across years unless the number of returning fall Chinook adults is very low. In addition, Chinook harvest management tightly controls the ocean fishery to meet a number of objectives (besides Central Valley Chinook escapement, escapement in other systems and ESA concerns). This means that even small numbers of returning adult fall Chinook can maintain average levels of out-migrant juvenile production. The most severe example of this was the complete season closures of 2008-2010. In this way, the fishery has been managed to maintain Chinook populations to meet the various objectives.

However, the situation with ESA and CESA-listed spring and winter Chinook is different since these two runs rely more heavily on natural production of juveniles, even though there are conservation hatchery programs. Therefore, these two Chinook runs may be more vulnerable to El Niño, possibly leading to significantly reduced juvenile production. Spring Chinook, originally the most abundant run in the California Central Valley, now rely on natural production in the upper Sacramento River Valley, with Feather River Hatchery spring Chinook included in the ESA listing unit but not considered in abundance trends (Good et al. 2005). Winter Chinook of the Sacramento River also rely on natural production in the area below Keswick Dam. Both of these runs, spring and winter, have dedicated conservation hatchery programs that produce small numbers of juvenile fishes. These two populations, which are under 10,000 adult fish, but at times dipping into the hundreds of fish (PFMC 2017), are vulnerable to even slight alterations in spawning populations and reduced reproductive capacity. Spawning habitat and freshwater conditions have always been the major concerns as specific risk factors for Central Valley Chinook when considering actions with the long term viability of these ESA and CESA-listed populations. Our analysis suggests that management agencies also need to give more importance to ocean conditions as risk factors in recovery planning.

Acknowledgements

The data analysis and writing of this paper was provided by a Saltonstall- Kennedy Grant from NOAA (NA15NMF4270308, Grant 2014/15 S-K) through H. T. Harvey & Associates. A review by Michael Mohr substantially improved this manuscript.

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Received: 30 May 2017
Accepted: 17 November 2017
Associated Editor was R. Bellmer