On the Past, Present, and Future of the California Current Upwelling System

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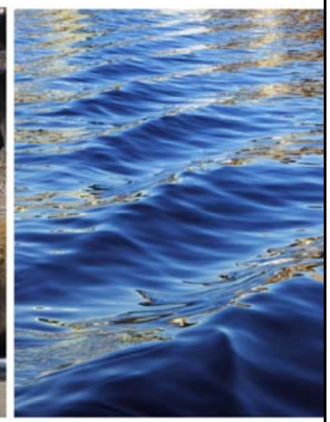
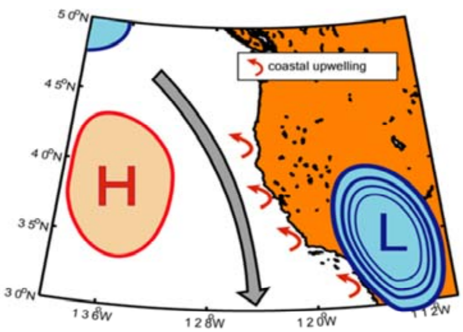
Marine Mammal Commission Annual Meeting 2018

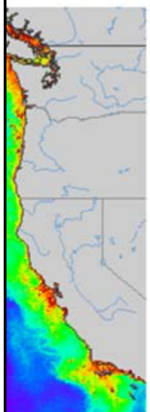


Key Topics

1. Upwelling in the California Current: Productivity, Phenology, Intensity
2. Upwelling under Climate Change?
3. Other Climate Impacts in the California Current &... **The Blob!**

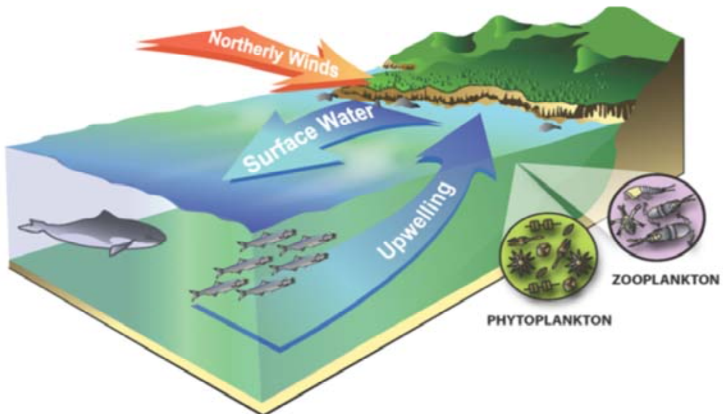


Including the Blob



1. Upwelling: Productivity, Phenology, Intensity

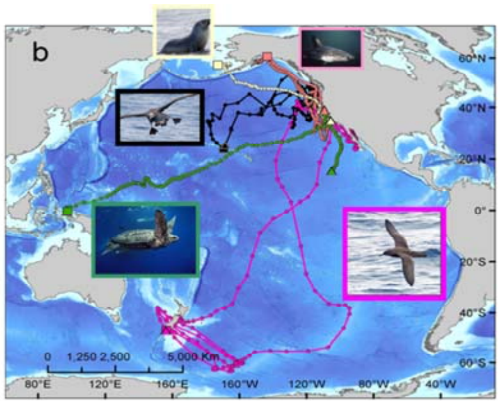
Productivity Driven by Seasonal Upwelling

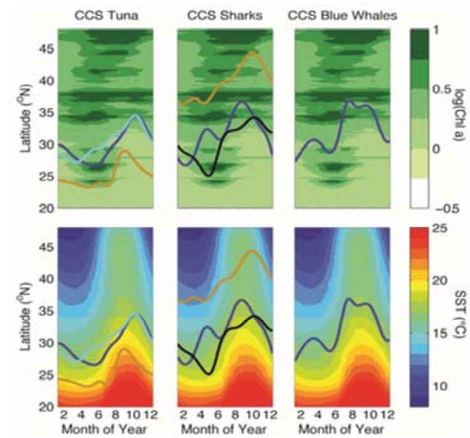


- Life cycles of many marine organisms tied to seasonal processes

Coastal upwelling in the CC is driven by spring/summer winds from the northwest that upwell cold, nutrient-rich water to the surface. Because of the high productivity driven by this seasonal upwelling, prey resources are abundant and predictable in CC, and the life cycles of many marine organisms are tied to these seasonal processes.

Productivity Driven by Seasonal Upwelling



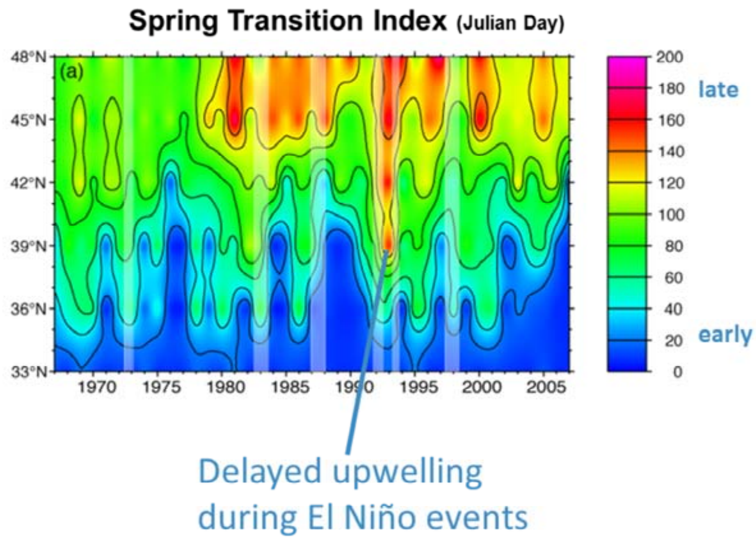


- Life cycles of many marine organisms tied to seasonal processes
- Intensity, duration, and timing (phenology) of upwelling strongly influence the ecosystem

Block et al. (2011)

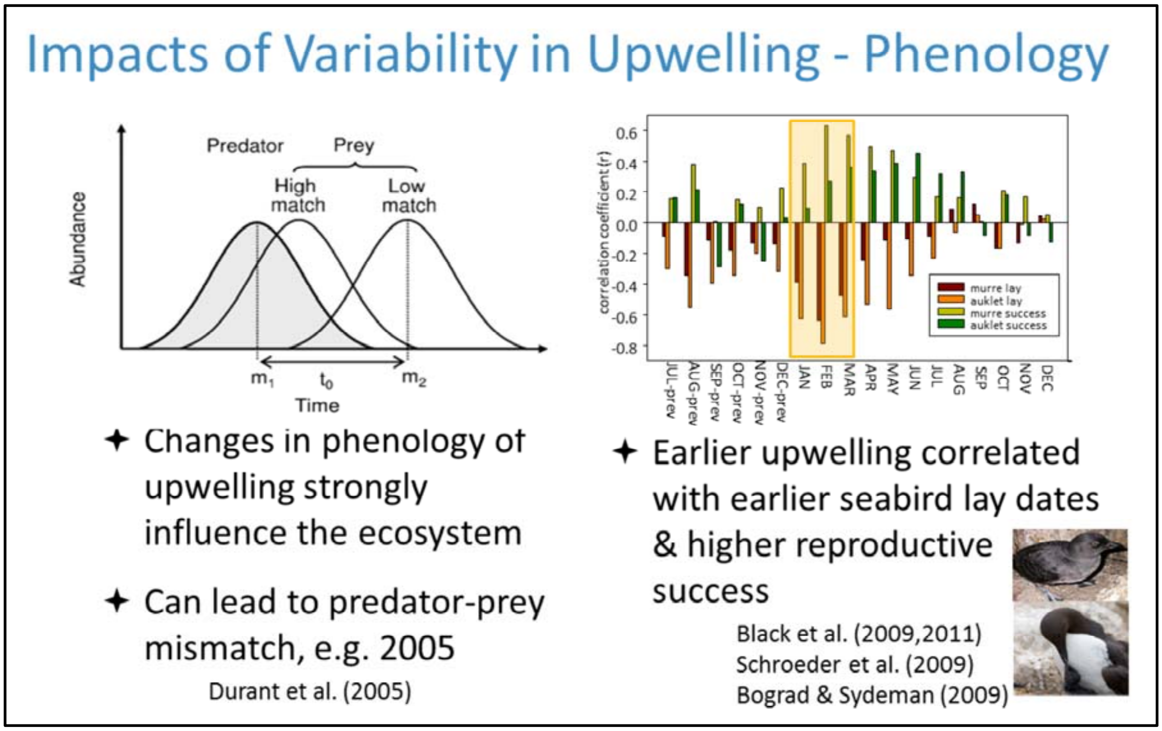
We have seen that the intensity, seasonal duration, and timing of coastal upwelling has major biological impacts in the CCS.

Interannual Variability in Upwelling - Phenology



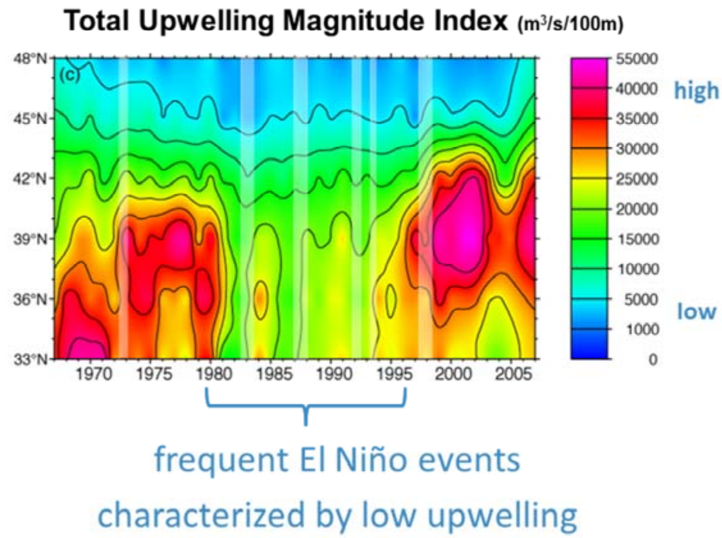
Bograd et al. (2009)

Seasonal upwelling in the CC is characterized by high interannual variability. For example, this plot shows the date of spring transition as a function of time and latitude and we can see that there's a high degree of variability in STI between years, and here I've highlighted EN years which are often associated with delayed upwelling.



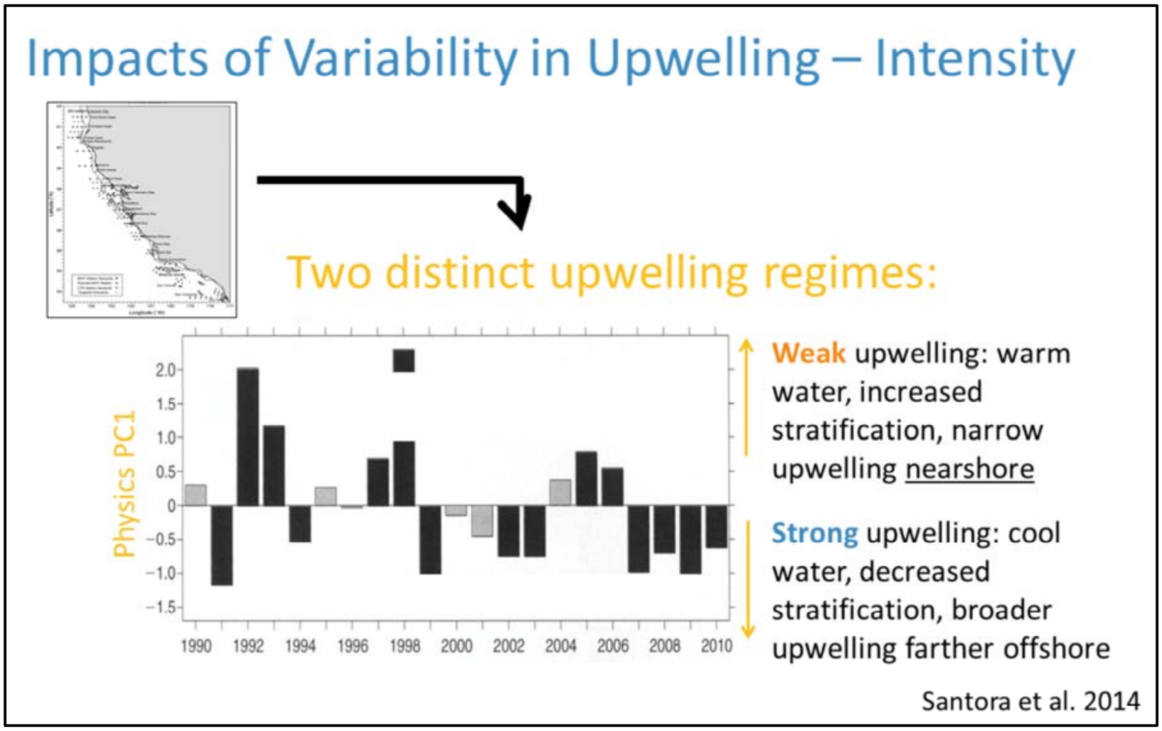
And we've also seen that early spring transition is correlated with higher reproductive success among some predator species, specifically murres and auklets. This bar chart shows the correlation between the length of the upwelling season from an earlier start and seabird lay dates, which are negatively correlated, and reproductive success, which are positively correlated. When there's earlier upwelling, there is higher productivity earlier in the season, which in turn leads to earlier seabird lay dates and more food availability to provision for chicks once they've hatched. So the phenology of the upwelling season can have significant ecosystem impacts.

Interannual Variability in Upwelling - Intensity

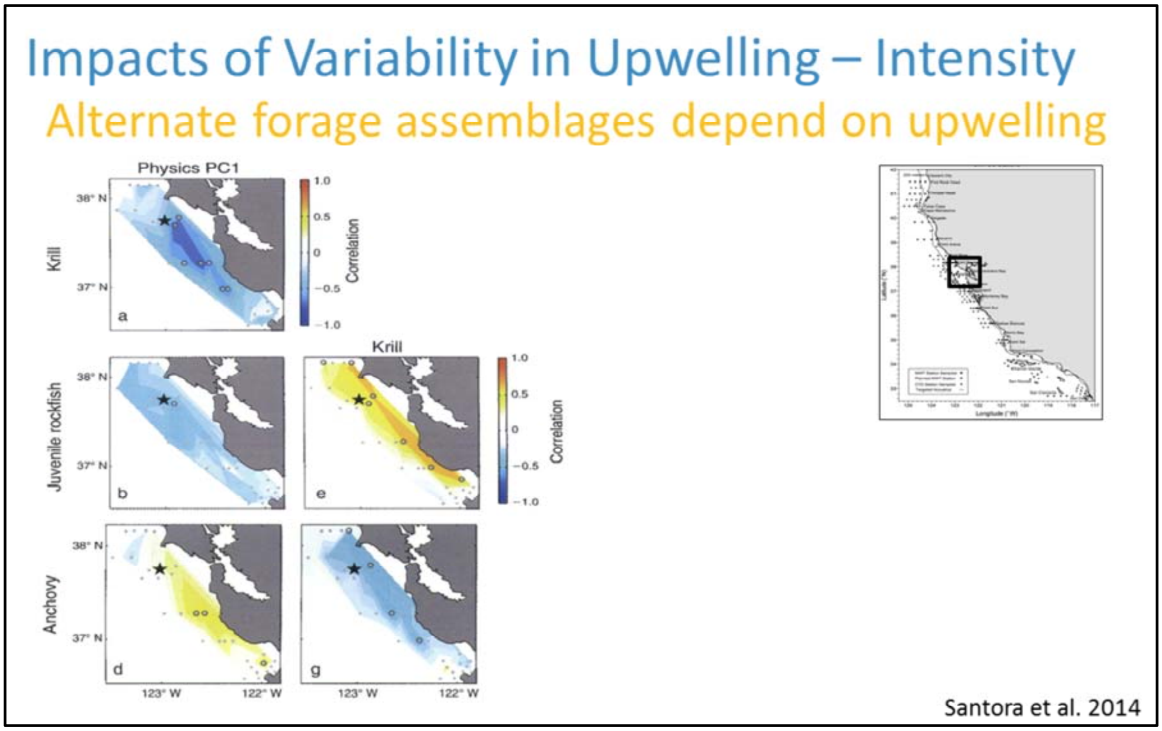


Bograd et al. (2009)

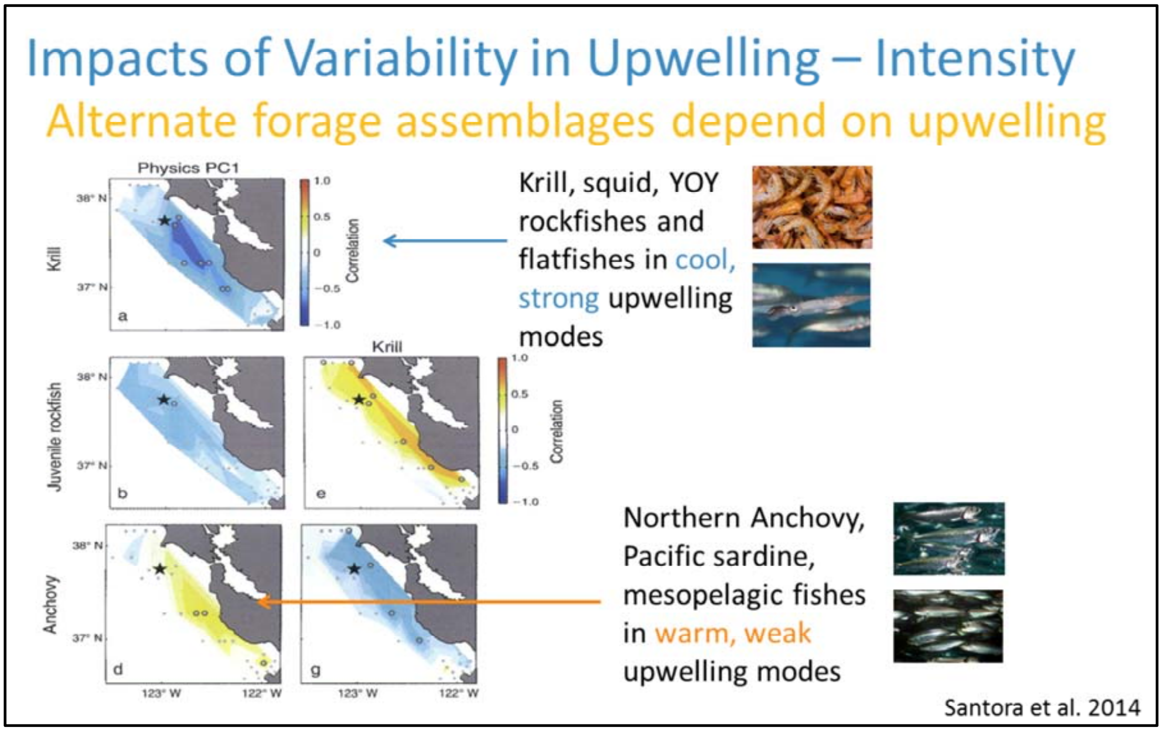
The intensity of upwelling also has major effects on the biological community, and as we can see also has a high degree of variability between years.



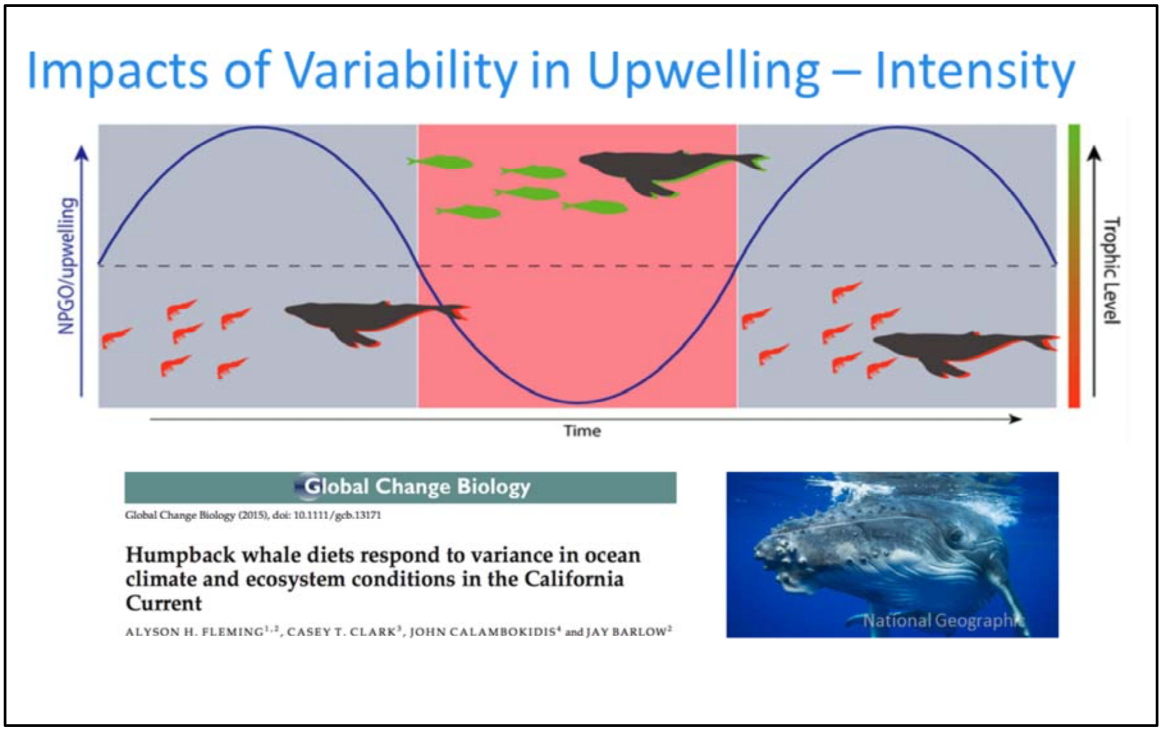
To understand the impacts of upwelling intensity on forage assemblages, Santora and colleagues ran a Principal Components Analysis on a suite of physical variables from sampling stations along the California coast, and found two distinct upwelling modes: a warm, weak upwelling regime in which upwelling is concentrated in a narrow band nearshore, and a strong, cool upwelling regime in which upwelling occurs in a much wider area from the coast to farther offshore.



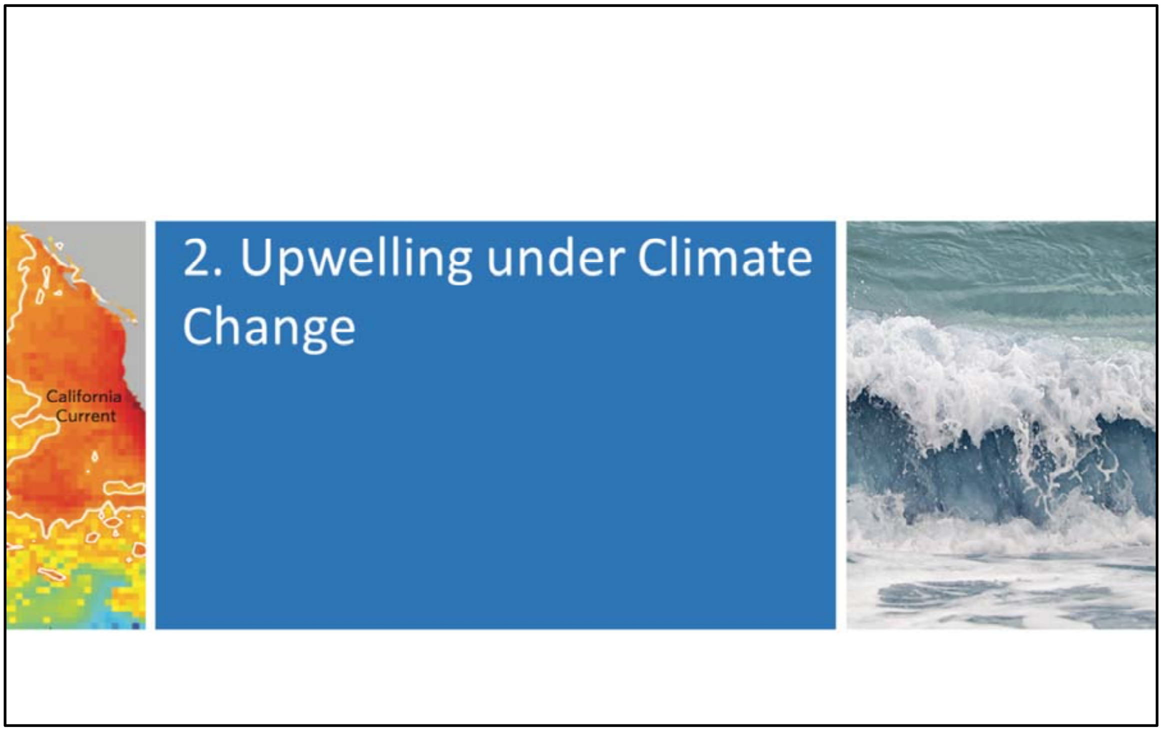
They then correlated that Principal Component with long-term biological time series,



Conversely, a weak upwelling mode results in a forage assemblage dominated by species from farther south and/or off-shore including adult northern anchovy and Pacific sardine



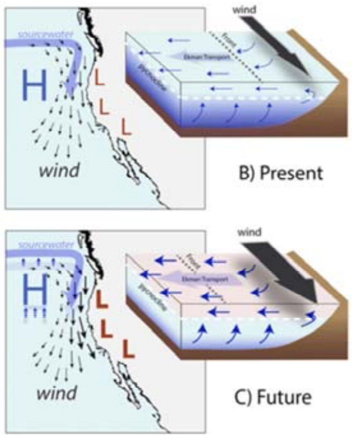
And we also know that these ecosystem shifts are reflected in the ecology of top predators– for example, Fleming et al. found that humpback whale diets switch between being dominated by krill and forage fish depending on the upwelling regime.



So now that we see how integral upwelling is to the California Current Ecosystem, how might coastal upwelling respond to climate change?

Climate Change and Coastal Upwelling

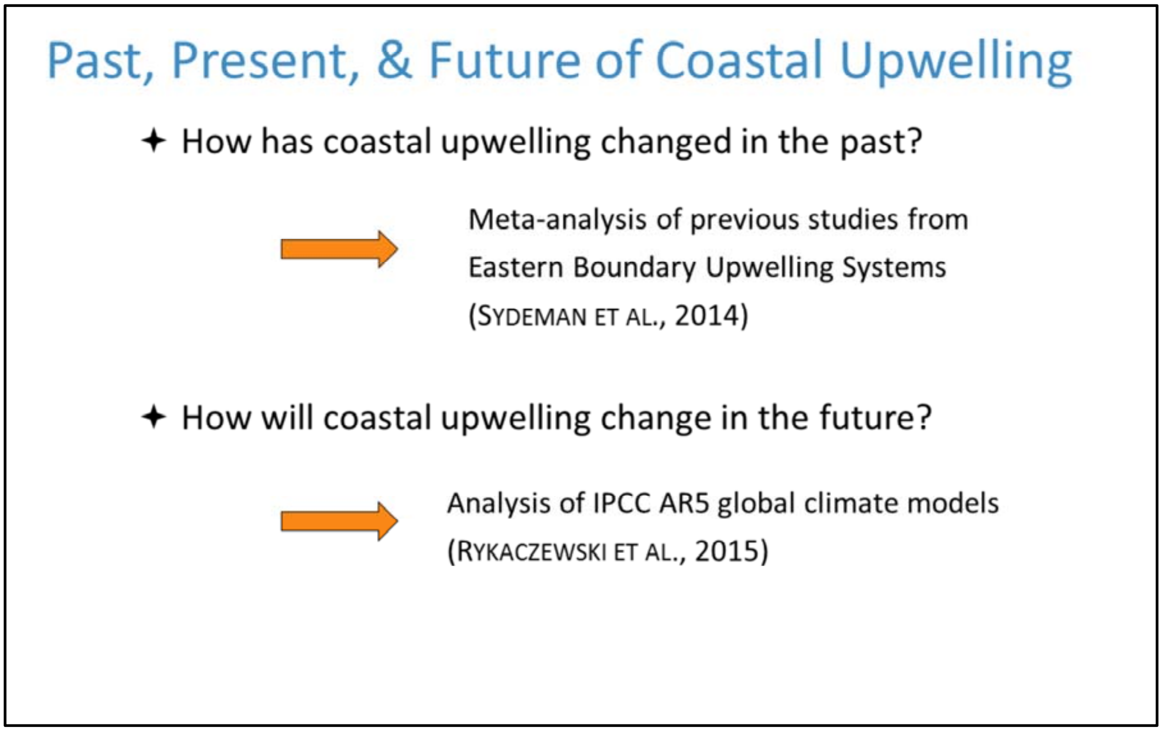
Bakun (1990) suggested that global warming would intensify coastal upwelling in eastern boundary currents.



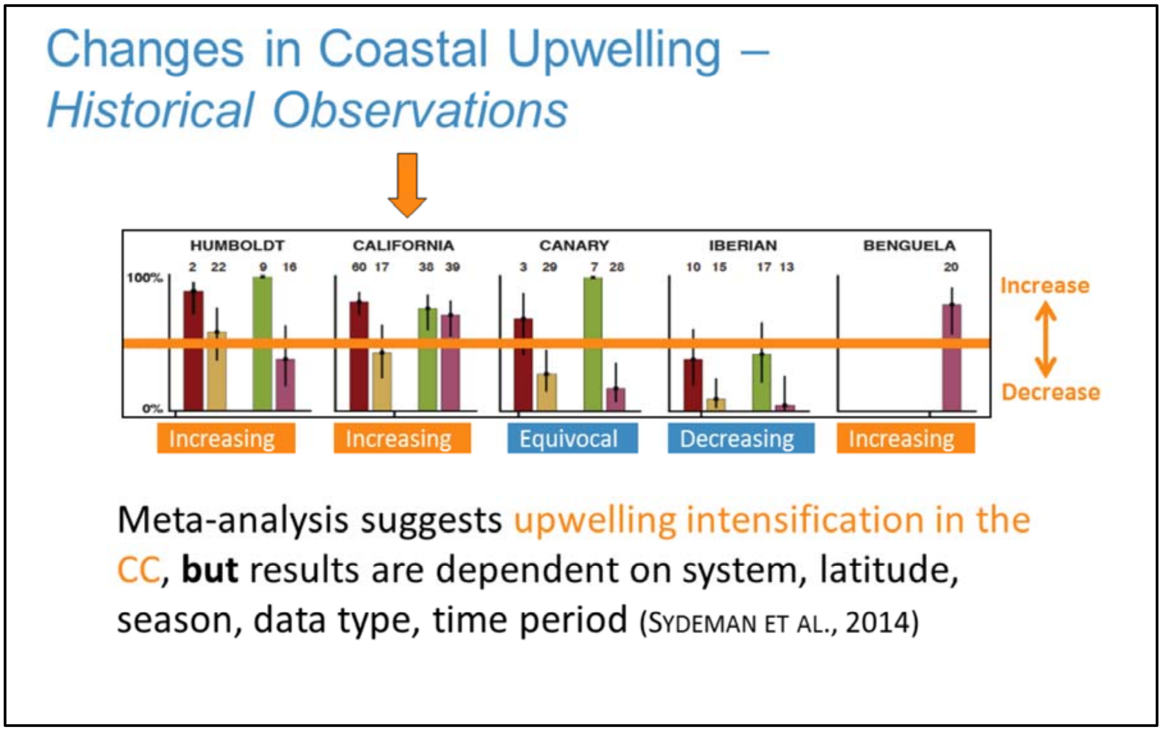
Differential heating of the surface air over the landmass relative to the ocean…

…will result in intensification of the thermal Low, generating a stronger pressure gradient.

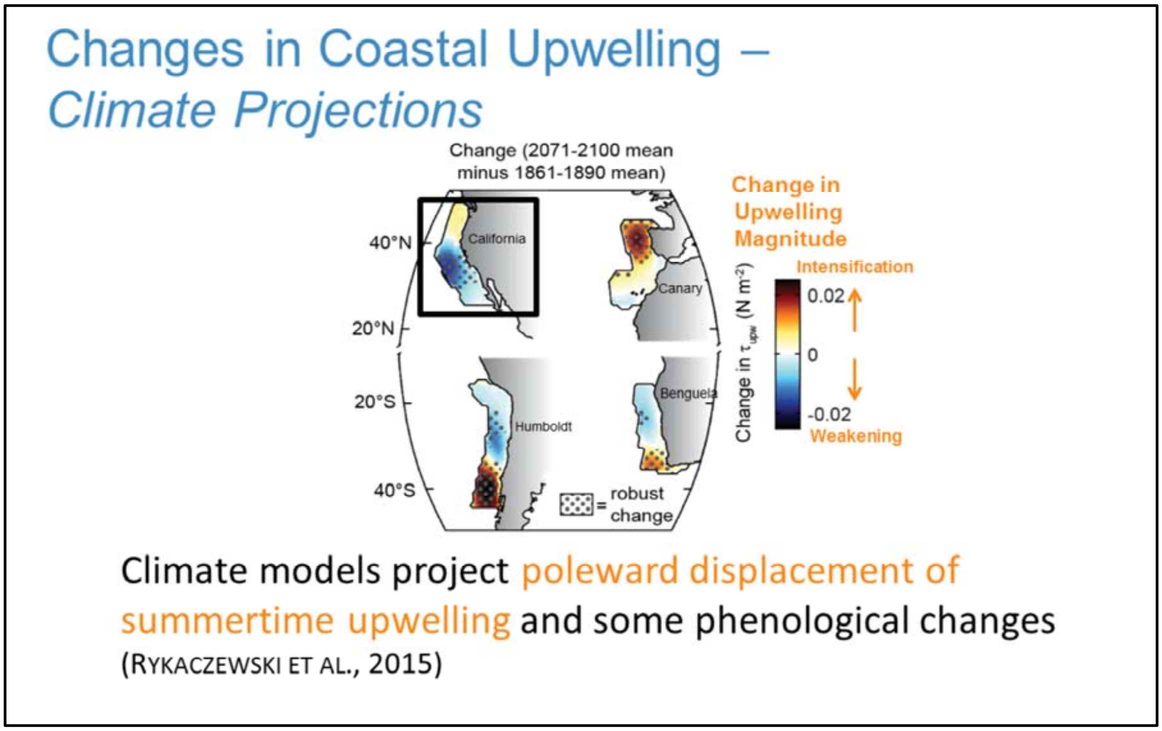
…and cause increased cross-shore pressure gradients that drive upwelling favorable winds.



For this, I will show results from a paper that looked at the upwelling response in an ensemble of global climate models out to the end of the century .

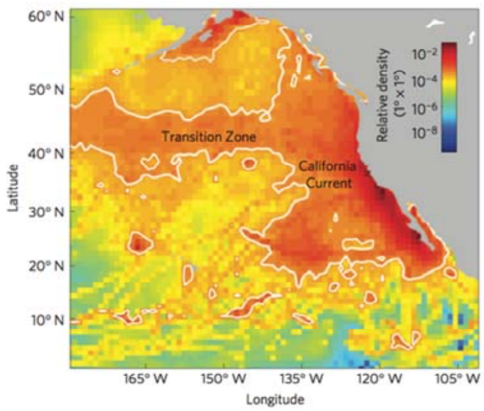


Histograms show number of studies that were consistent or inconsistent with Bakun hypothesis, i.e. increasing or decreasing trends in upwelling-favorable winds. The different colored bars show break down of the datasets in various ways (annual vs. only one season, modeled vs. observed. The metaanalysis showed most studies were consistent with the Bakun hypothesis, including the California Current, but with a big caveat that the results were highly dependent on a number of factors. In particular, most of the studies showing increased upwelling were at higher latitudes.



The results of climate projections were generally consistent with the meta-analysis but were more nuanced. There was significant variation between EBC systems, but most showed a consistent intensification in upwelling only in the poleward portion of the systems, and weaker upwelling farther from the poles. This suggests that EBC systems may <u>shift poleward</u> in the future.

Potential Ecosystem Impacts of Changes in Coastal Upwelling



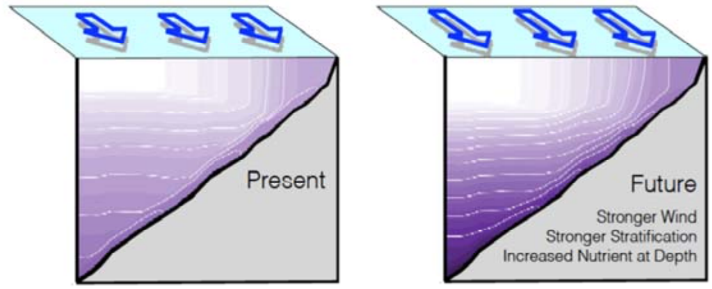
(Hazen et al., 2013)

- Poleward shift in coastal productivity & thermal habitat
- Poleward shift of oceanic features (e.g., TZCF) and corresponding biodiversity (see Polovina et al., 2011; Hazen et al., 2013)
- Spatial and temporal mismatches of preyscape

So what might be the impacts of such shifts in upwelling? We are likely to see poleward shifts in habitat and oceanic features like the Transition Zone Clorophyll Front, and corresponding shifts in biodiversity. For that I'll refer you to Hazen et al.'s 2013 Nature Climate Change paper which examined shifts in top predator distributions in response to climate change. We can also expect there to be more mismatches between predators and prey. And of course, we will need to consider the adaptive plasticity of various species to get a fuller appreciation of the potential climate-driven impacts in the California Current.

But there are many other things to consider when trying to project changes in upwelling ecosystems.

Other Climate Impacts in the California Current



Jacox *et al.* (2015)

- Changes in stratification …?
- Changes in nutrient content of source waters …?
- Increased hypoxia and ocean acidification …?

This is just a brief overview, but we anticipate changes in water column structure, including increased stratification and changes in the nutrient and oxygen content of source waters, such as oxygen depletion and increased hypoxia.

Spotlight on: The Blob

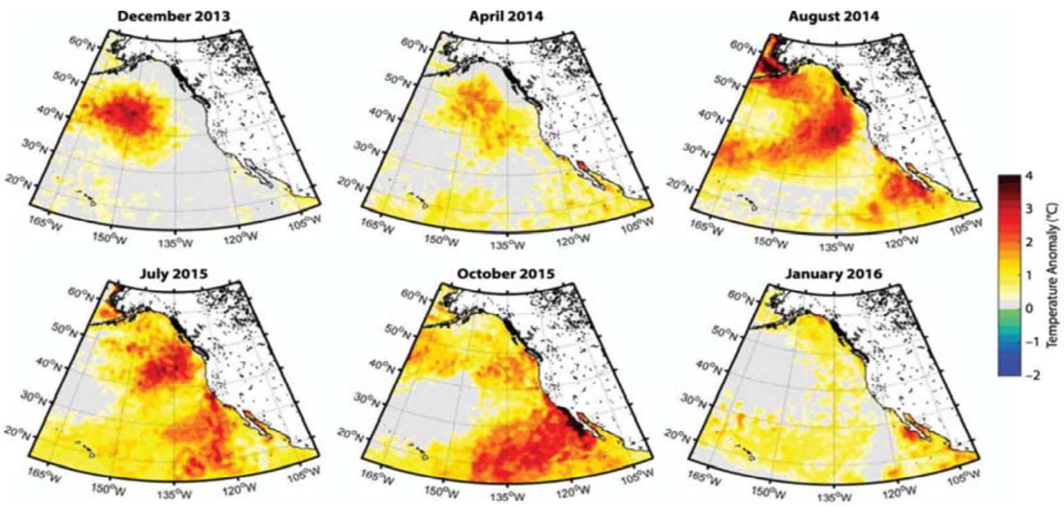


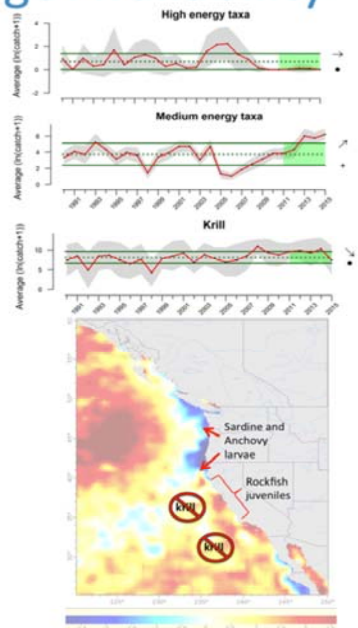
FIGURE 1. Sea surface temperature (SST) anomalies showing the progression of the warm water anomaly (WWA) from December 2013 through January 2016 in the northeastern Pacific Ocean. Temperature data were obtained from the National Oceanic and Atmospheric Administration (NOAA, 2016b).

Cavole et al. (2016)

And as Nick highlighted, we can look to the recent warm water anomaly to help predict ecosystem impacts. Warm water anomalies might be the type of thing we see more of in the future, therefore can consider the Blob a climate stress test.

The Blob: Impacts on Forage Availability

- High-energy forage fish (sardine & anchovy) low abundance, shifted N & inshore
- Medium-energy forage very high, esp. squid and rockfish
- Krill declining
- Poor forage availability in southern CC



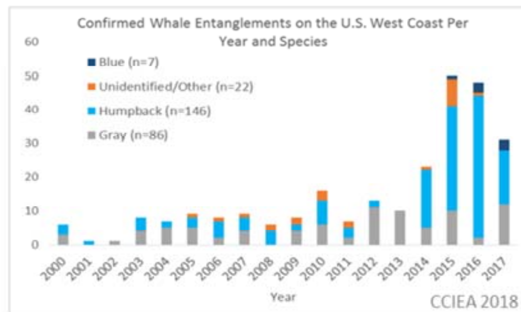
Sea surface temperature anomaly June 2015

CCIEA 2016

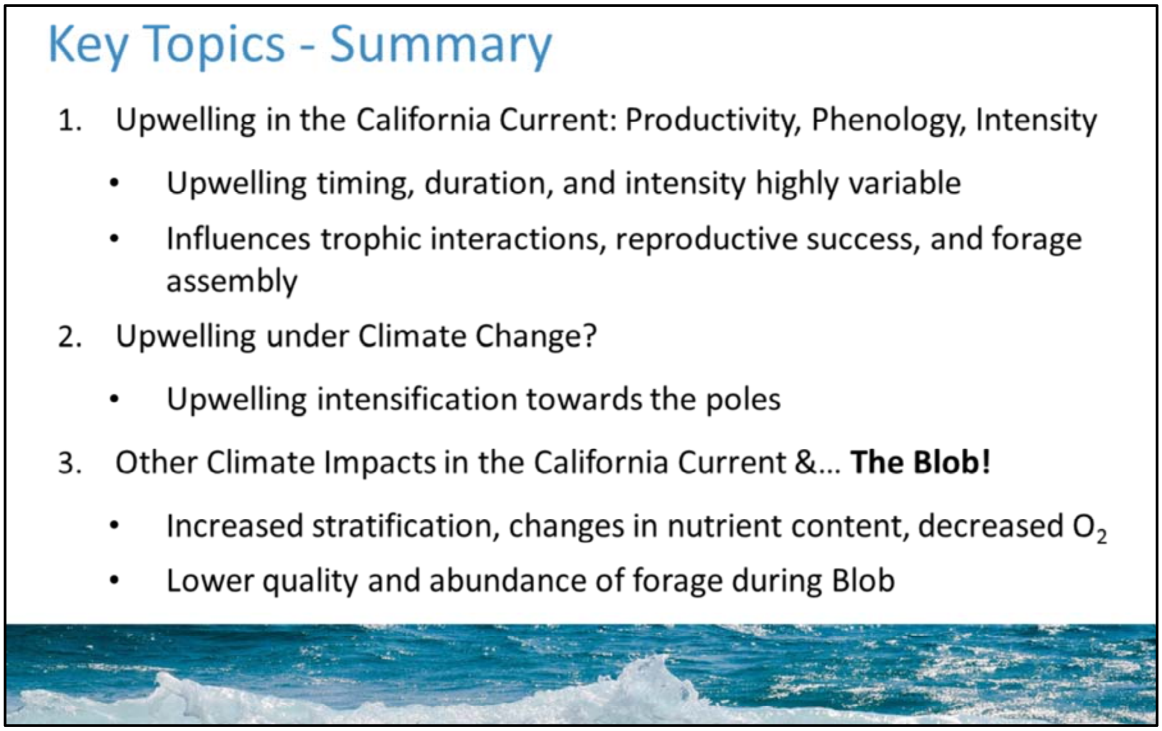
And in general forage was higher in the northern California Current than in the southern region.

The Blob: Other Biological Impacts

- Massive coastwide harmful algal bloom (HAB), leading to domoic acid toxicity
- Record number of baleen whales entangled in nearshore crab gear
- Mass mortalities of CA sea lions, Guadalupe fur seals & murres



There were also a number of anomalous events during the blob, including huge harmful algal blooms that led to fishery delays and closures, which Vera will speak about later, record entanglements of baleen whales in nearshore fishing gear attributed in part because they followed their forage fish prey further inshore, and mass mortalities of other predator species because of poor forage conditions.



Upwelling timing, duration, and intensity highly variable

Influences predator-prey interactions, reproductive success, and forage assembly

Predictions on upwelling intensification are equivocal, but consensus around intensification towards the poles
Increased stratification, changes in nutrient content, decreased O_2
Lower abundance and more northerly/inshore distribution of high quality forage fish during the Blob, & other anomalous events


THANK YOU!
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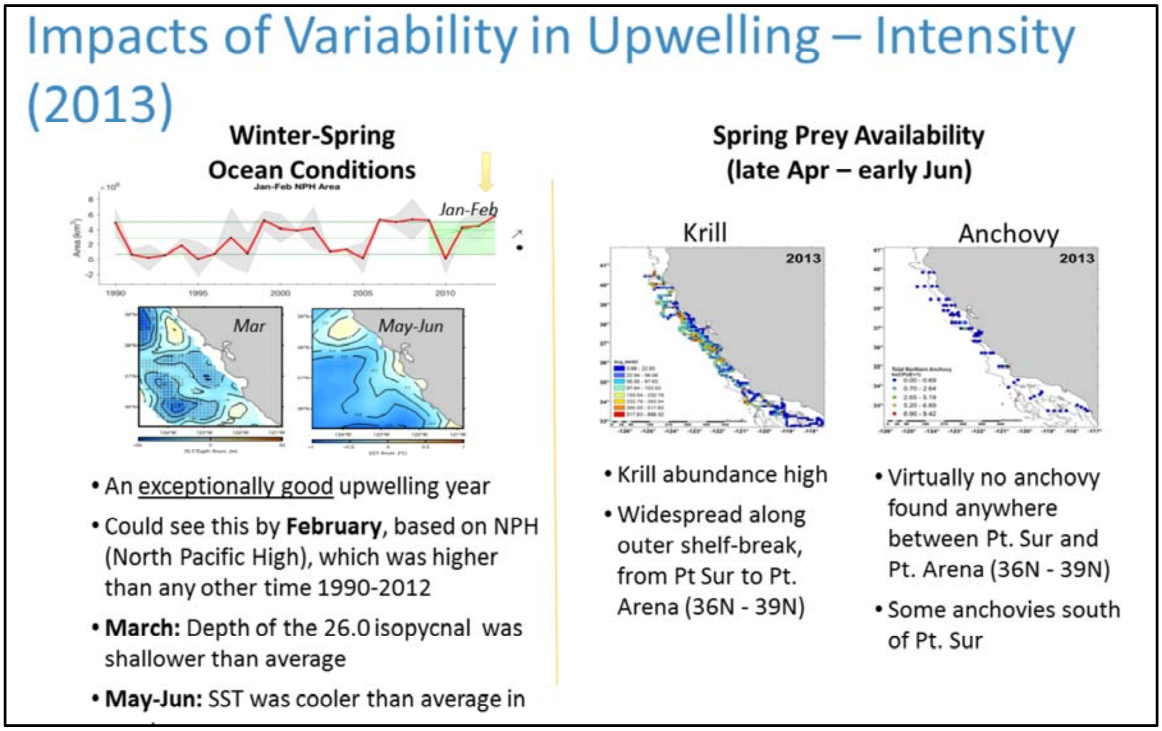
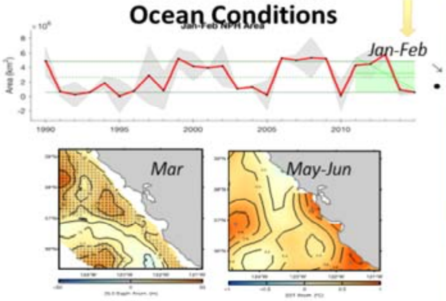
Extra Slides



The intensity of upwelling can have significant impacts on the dominant forage community. 2013 – strong upwelling > high krill abundance

Impacts of Variability in Upwelling – Intensity (2015)

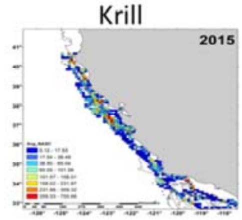
Winter-Spring Ocean Conditions



- A <u>weak</u> upwelling year
- By **February** the NPH (North Pacific High Index) had dropped to lowest level since 2010
- **March:** depth of the 26.0 isopycnal was deeper than average
- **May-Jun:** SST was warmer than average, and the

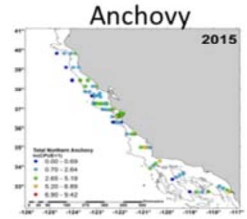
Spring Prey Availability (late Apr – early Jun)

Krill



- Krill abundance was low/moderate
- Concentrated offshore along shelf break in a few patches off San Mateo, Sonoma, and Mendocino Counties

Anchovy

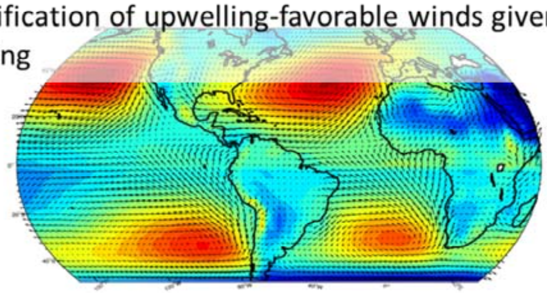


- Anchovy very abundant
- Distributed throughout the region, with high concentration patches off central and southern California

2015 – low upwelling > high anchovy abundance, low krill

Changes in Upwelling Ecosystems:
Historical Observations

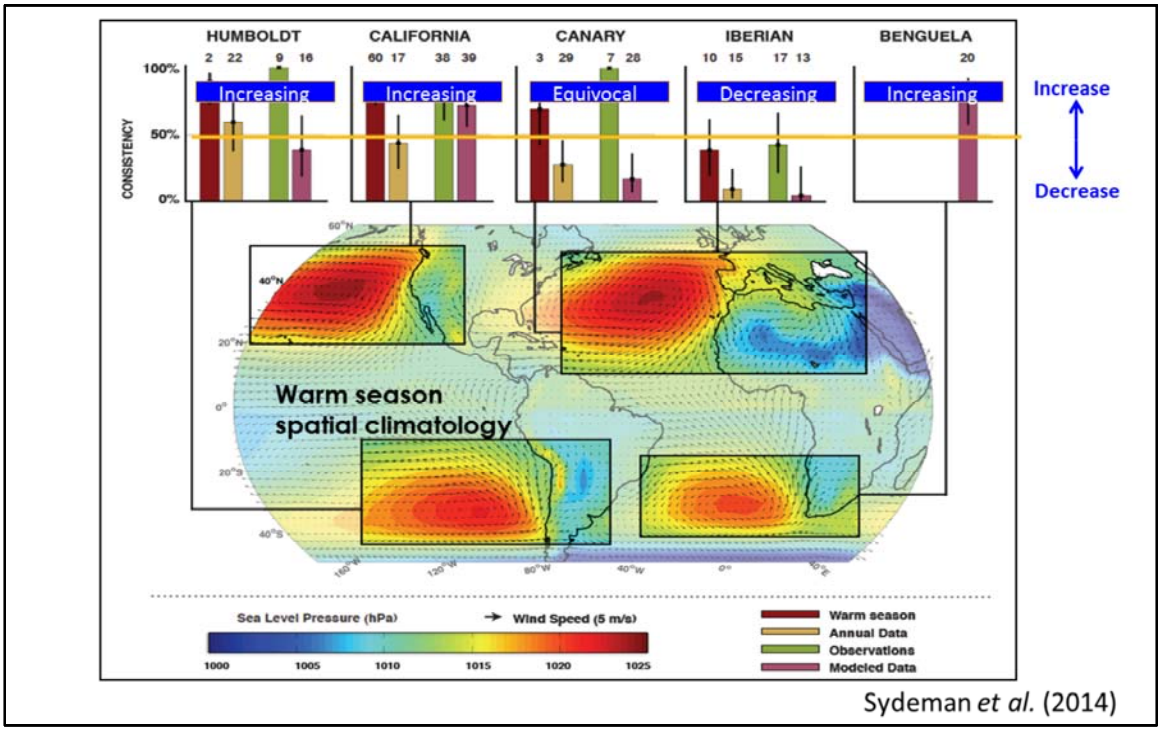
- Synthesized results from 22 published studies
  - Represented analyses of 128 time series from 1950-2010
  - California Current, Humboldt Current, Canary-Iberian Current, Benguela Current
- H: Results 'consistent' with Bakun hypothesis:
  - Intensification of upwelling-favorable winds given global warming



Sydeman *et al.* (2014)

What we were looking for was published reports of long-term trends in upwelling-favorable winds, with our hypothesis being that these studies would support the Bakun upwelling intensification hypothesis.

We determined whether the wind series were consistent (i.e. increasing) or inconsistent (i.e. decreasing) with the Bakun hypothesis, taking account of the statistical significance of the observed trends (down-weighted non-significant trends OR counted those as inconsistent).



To summarize the results …

Map shows climatological warm-season SLP and winds, showing each of the EBCs.

Histograms show number of studies that were consistent or inconsistent with Bakun hypothesis, i.e. increasing or decreasing trends, respectively.

Consistency in more than 50% of the studies indicates support for the Bakun hypothesis, i.e. that upwelling has intensified.

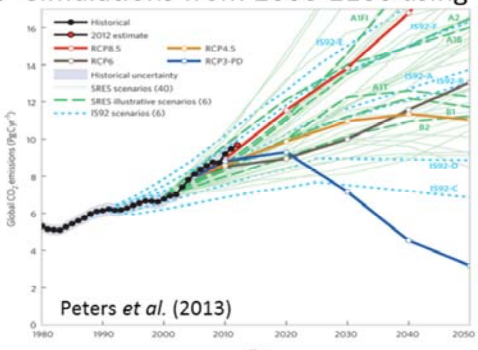
The different colored bars show break down of the studies in various ways: warm season vs. annual data, observed vs. modeled data.

CAVEAT: The results are highly dependent on season, data type, time period and latitude. Most of the studies showing increased upwelling were at higher latitudes.

Net result – a preponderance of studies suggest that there is upwelling intensification in the observational record in 3 of 5 systems; the studies are equivocal or even opposed to the Bakun hypothesis in the North Atlantic.

Changes in Upwelling Ecosystems: *Climate Models*

- IPCC AR5 models that capture 'historical' (1850-2005) conditions
- Surface air temperature, sea level pressure, surface wind stress available at monthly resolution
- Simulations from 2006-2100 using RCP 8.5



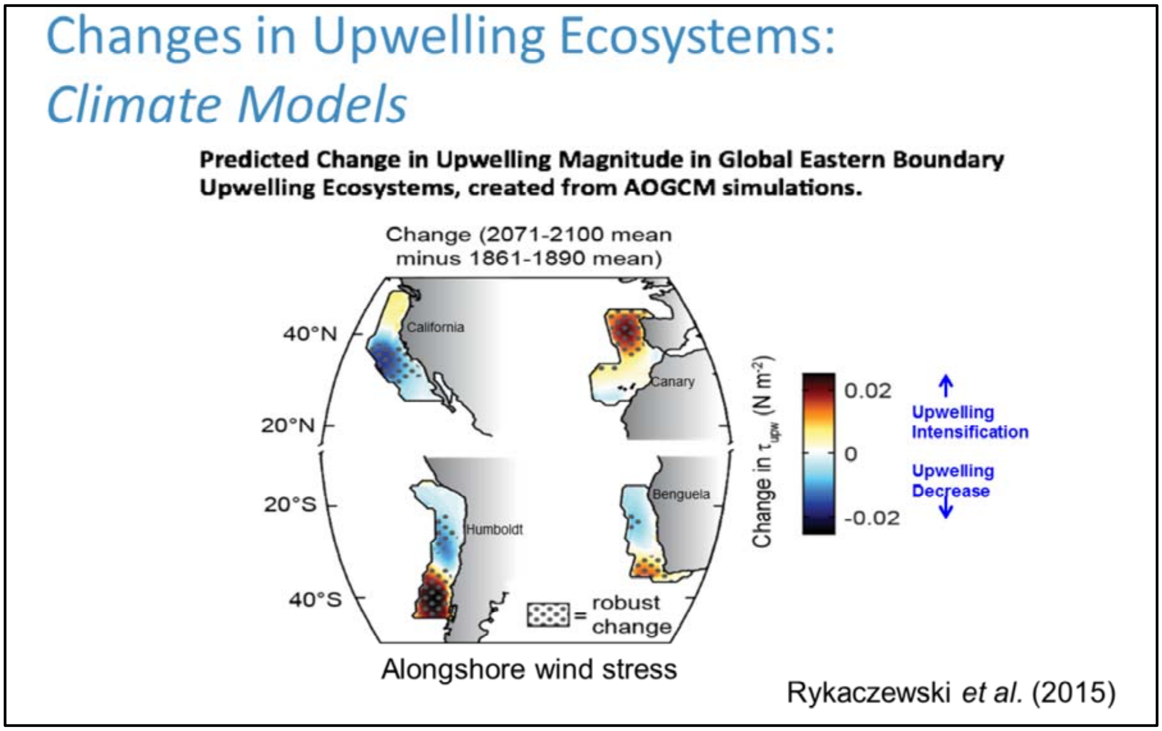
Peters *et al.* (2013)

IPCC Models Included		
Modeling Center	**Model (# of versions)**	**Country**
CCCma	CanESM2	Canada
CMCC	CMCC (3)	Europe
CNRM-CERFACS	CNRM-CM5	France
CSIRO-BOM	ACCESS1 (2)	Australia
CSIRO-QCCCE	CSIRO-Mk3.6.0	Australia
IPSL	IPSL-CM5 (3)	France
MOHC	HadGEM2-A	UK
NCAR	CCSM4	USA
NCC	NorESM1 (2)	Norway
NOAA GFDL	GFDL (4)	USA
NSF-DOE-NCAR	CESM1 (5)	USA

Rykaczewski *et al.* (2015)

Let's now look at changes in upwelling as projected by global climate models.

Ryan used an ensemble of IPCC-class climate models; looked at several variables at monthly resolution; looked at simulations out to the end of the century

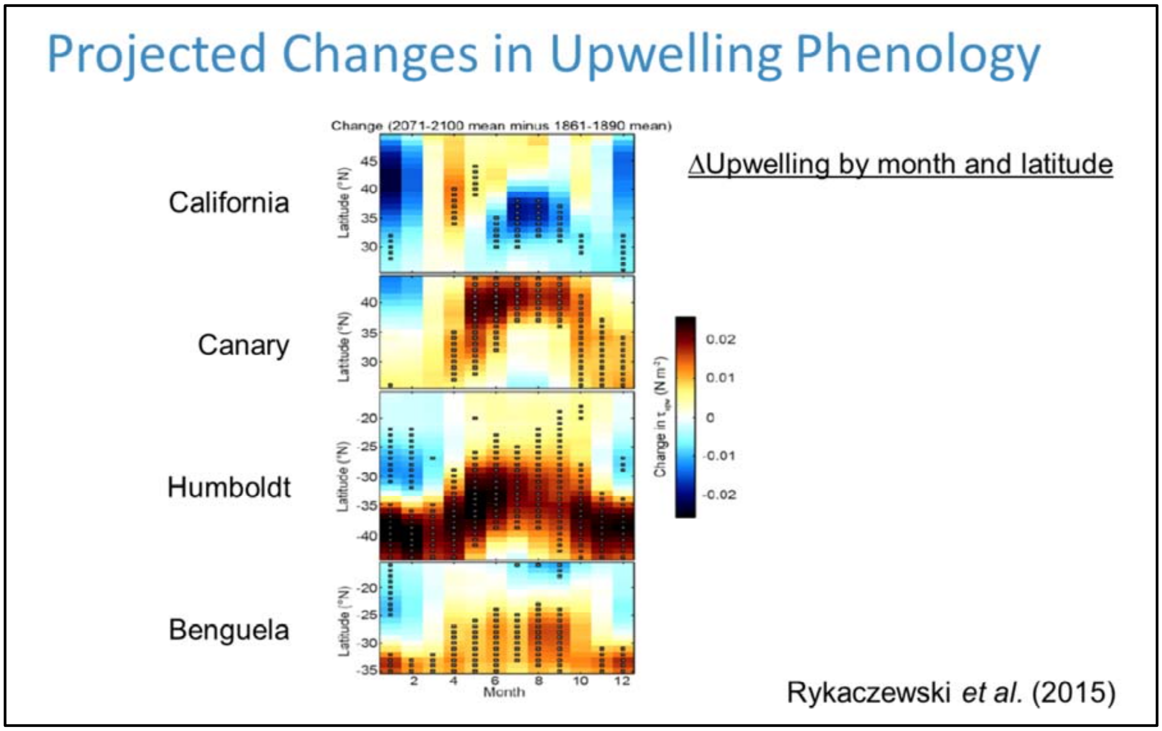


Looking at projected CHANGES in alongshore wind stress (i.e. upwelling) between the end of this century and a historical control period.

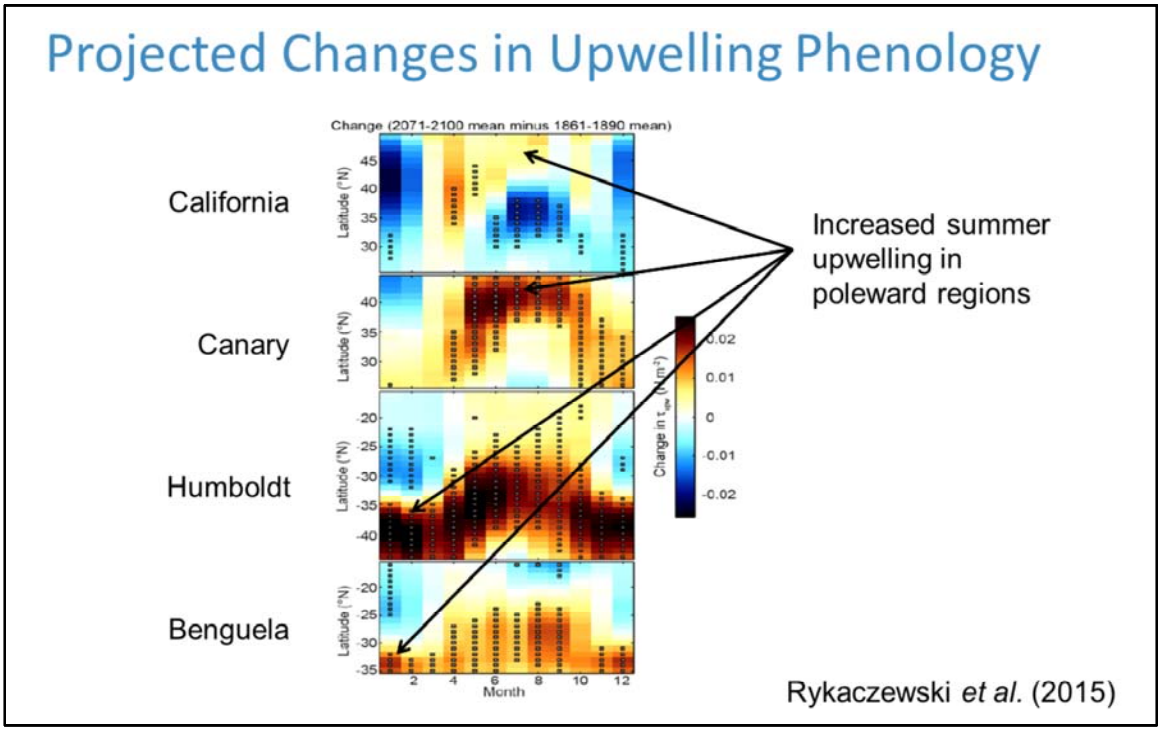
Reds = increases in upwelling favorable winds; Blues = decreases; stipples = significant.

Take-home: There was significant variation between EBC systems, but most showed a consistent intensification in upwelling only in the poleward portion of the systems, in response to the poleward shift of the oceanic Highs, and declines in the equatorward regions. This suggests that EBUEs may shift poleward.

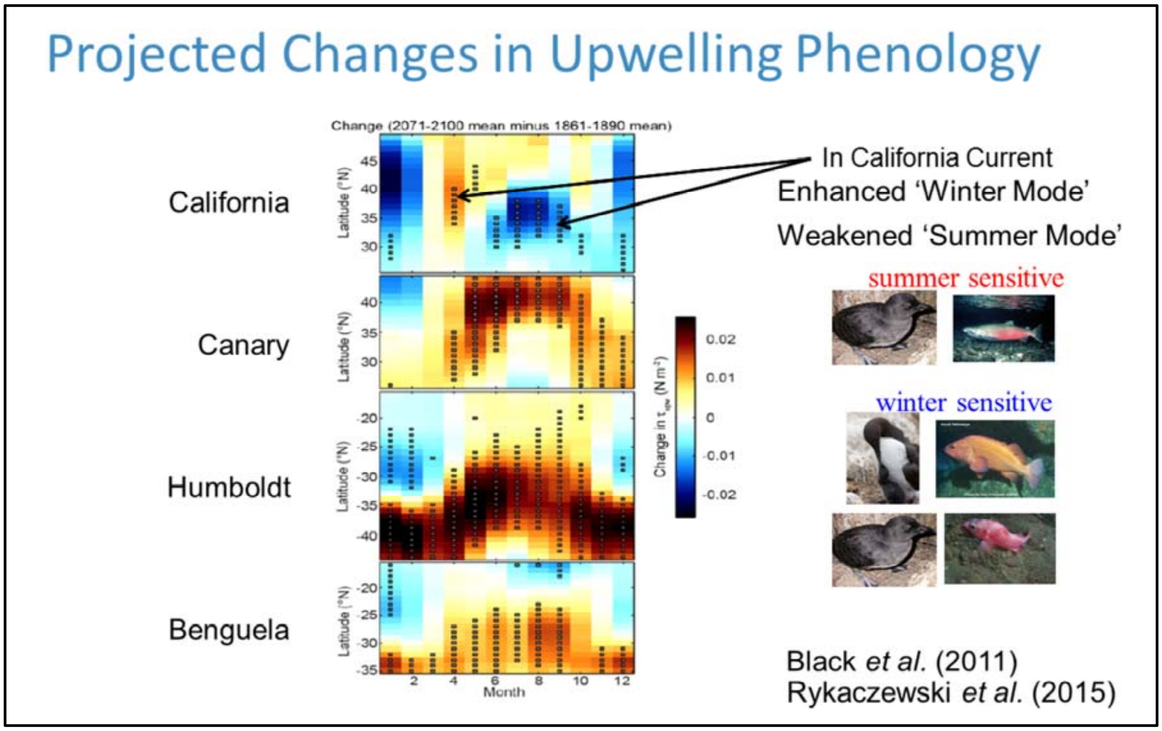
This is generally consistent with the meta-analysis results of Sydeman et al.



Now looking at changes in upwelling phenology … this is the century-scale change in alongshore wind stress by latitude and month for each EBC system.



We clearly see the increase in summertime upwelling in poleward portions.

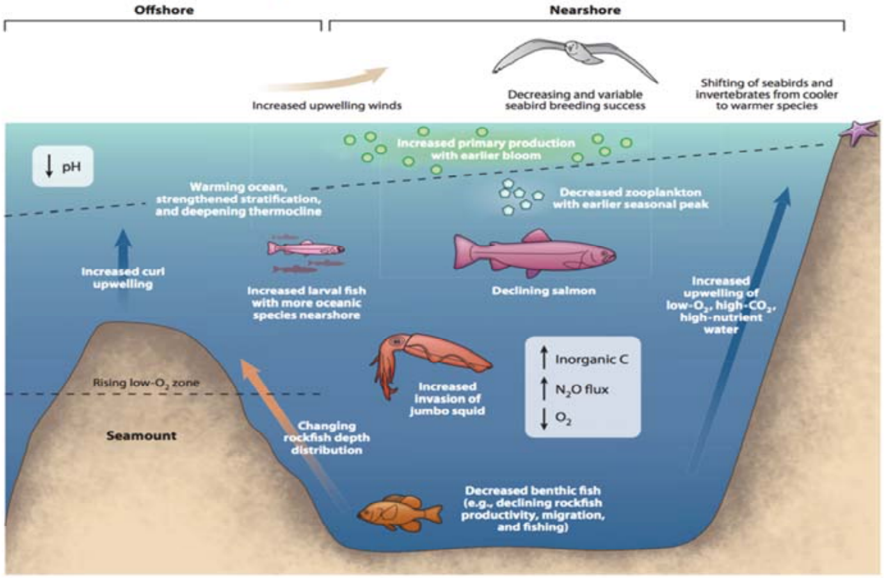


IN THE CC …we have found independent 'winter' and 'summer' modes of upwelling, with biological components of the ecosystem differentially sensitive to these modes.

And we see important projected phenological changes in the CC, with an increase in the 'winter' mode and decrease in the 'summer' mode, with likely subsequent impacts on species that are attuned to either of these modes of upwelling.

And an overall lengthening of the upwelling season in the CC! These phenological changes, in fact, may be the most significant ecosystem impacts from climate change.

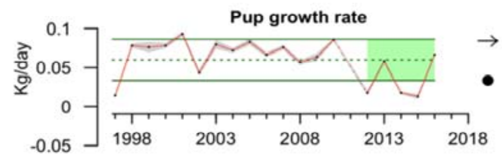
Other Climate Impacts in the California Current



Doney et al. (2012)

…Life after The Blob?

- Basin-scale climate indices returning to averages
- Forage: some increases in central, southern CCE
  - *Central: more krill and squid in 2017; juv. rockfish high for 5th year*
  - *South: anchovy increasing, along with shortbelly rockfish (but squid decreasing)*
- Sea lion pup growth implies better feeding conditions



CCIEA 2018

Where we're at after The Blob: Basin-scale climate indices are returning to averages, so for example the Pacific Decadal Oscillation Index was strongly positive from 2014-2016, but Returned to neutral in July 2016 and Was neutral in nearly all of 2017. We're also seeing some recovery in forage species particularly in the central and southern California Current, which may be reflected in the fact that pup growth rates were strong in winter 2017, suggesting improved foraging conditions for nursing mothers.