Ichthyoplankton as cost-effective indicators of marine ecosystem change: outline of talk

- Need for indicators of marine ecosystem change around Australia
- Ichthyoplankton as proxies for fish spawning stock biomass provide community-wide indices of change related to climate/fishing
- Lessons from CalCOFI: Ichthyoplankton reveal dramatic change in fish communities off southern California
- Ichthyoplankton time series as indicators of ecosystem change along the west coast of North America, Alaska to Baja California
- Requirements for successful ichthyoplankton time series
- A model for an Australian network of ichthyoplankton time series
Need for indicators of marine ecosystem change around Australia

- Satellites, gliders, moorings provide reasonable time series of T, S, & other physical/chemical ocean parameters
- But we really want to know how ecosystems are changing!
- Australian marine fauna is highly diverse, high levels of endemism (e.g. 85% of fishes in temperate Australia are endemic (Poloczanska et al. 2007))
- Ecological time series are generally poor
- Climate change impacts are already noted (e.g. for corals, reef fishes in SE Australia) and are expected to be significant

What is needed: a low-cost but effective indicator of ecological change for a wide range of economically/ecologically/socially important fishes
Why ichthyoplankton?

- Relatively low cost, simple sampling
  - bongo net, 20 min vessel wire time/sample
- Effectively samples most of a region’s fish community
  - Most fishes (even mesopelagics) have pelagic larvae (upper 200 m)
  - Avoidance is minimal pre-flexion
- Ichthyoplankton abundance is a proxy for adult spawning stock biomass: sardine & anchovy in Calif Current (Koslow et al 2011), rockfishes (Sebastes) (Moser et al., 2000), various rocky nearshore taxa (Moser et al., 2001), and California halibut (Moser and Watson, 1990)
- Time series a potential byproduct of egg production survey assessments (e.g. CalCOFI, SA)
- Key leverage!

\[ y = 0.01x + 0.14 \]
\[ R^2 = 0.43 \]

Sardine (Hill et al. 2010)
What can we learn from ichthyoplankton time series?
Lessons from CalCOFI

• Spawning distribution & timing
• Changes in phenology (timing of spawning) related to climate change (Asch PNAS 2015)
• Changing diversity (Koslow et al. MEPS 2017)
• Changing fish distributions/community composition, relations to climate (McClatchie et al. JGR 2018, Koslow et al ICESJMS in press)
Ichthyoplankton: proxy for adult spawning stock biomass

CalCOFI (1951 – present)
Sampling monthly (1951-66) to quarterly (post 1966)
CTD & bottle sampling to 500 m at each station (T, S, chl, O2)
Oblique plankton tows to 210 m: zoo & ichthyoplankton
Physics, chemistry, biogeochemistry, ecology

Ichthyoplankton identified & enumerated to species where possible (>500 taxa)
Impacts of OMZ/oxycline variability: I: Mesopelagic fishes

PCA of CalCOFI ichthyoplankton time series, mean annual abundance, 1951-2008, of 86 common taxa (occur >50% of years)
PC 1: 21% var explained, 24/27 taxa loading >0.5

Ecosystem implications:
Mesopelagic fishes are dominant oceanic plankton consumers, prey of dolphins, squid, tunas

Mesopelagic fish biomass estimated from recent acoustic/trawl studies in CalCOFI area; past values estimated from relative abundance of total mesopelagic fish larvae
3.5-fold range in estimated biomass of mesopelagic fish, 1951-2008, closely correlated with midwater [O₂]

\[ y = 12.596x - 12.575 \]
\[ R^2 = 0.4377 \]

<table>
<thead>
<tr>
<th>PC1</th>
<th>O₂</th>
<th>PDO</th>
<th>MEI</th>
<th>NPGO</th>
<th>SST</th>
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<tbody>
<tr>
<td>R</td>
<td>0.75*</td>
<td>0.56**</td>
<td>0.47*</td>
<td>-0.23</td>
<td>0.45?</td>
</tr>
</tbody>
</table>
OMZ/oxycline variability in the CCS, 1984 - 2006
(Bograd et al. 2008)

Mean shoaling: 41 m; up to 90 m [O2] decline in SCB
(Bograd et al. 2008)

Note: Models predict a 1-7% decline in [O2] over the coming century; current declines are ~10 – 25%

Figure 3. Same as Figure 2, but percent change in DO over the period 1984–2006.

124°W 122°W 120°W 118°W 116°W
36°N 34°N 32°N 30°N

%O₂ change

-35 -30 -25 -20 -15 -10 -5 0 5 10
Declining \( [O_2] \) a regional & global trend

OWS P (Subarctic/Gulf of Alaska): 22% decline in \( [O_2] \), 1956-2006, oxycline shoaled 100 m (Whitney et al 2007)

Expanding OMZ/shoaling oxycline in ETP (Stramma et al 2008)

\[O_2\] declining globally due to climate warming (decreases solubility & increases stratification)

Impacts of PDO
Hypothesis: Decline of mesopelagics linked to shoaling of the oxycline, which enhances their vulnerability to visual predators.

Oxycline depth key factor linked to depth of the DSL (Bianchi et al 2013, Netburn & Koslow 2015)

The light available for predatory feeding has increased 2.5-fold, if the DSL has shoaled 41 m with the mean shoaling of the oxycline; 7.2-fold with the 91 m shoaling of the OMZ in parts of the CCS.

Habitat compression enhances predation risk by increasing prey density/predator encounter rate.
PC 2 (CalCOFI-core): trend of dominant fishes

72% decline in total CalCOFI-core (So Cal) larval fish abundance since 1969
• PC 2 (CalCOFI-core) explains 12.4% var
• 6 of the 7 most abundant species in ichthyoplankton time series loaded highly (> 0.5), 76% decline since ~1970
  – (+) loadings: Pacific hake, northern anchovy, rockfish (*Sebastes* spp.), 2 cool-water mesopelagics (*myctophid* (*Stenobrachius leucopsarus*) & *bathylagid* (*Leuroglossus stilbius*))
  – Pacific sardine (-) (Koslow et al 2013)

Close match with power plant intake time series enhances confidence in the time series
And shows the pattern extends from inshore across the CC
Decline of dominant fish assemblage correlated with proxies for strength & EKE of the California Current (CC)

<table>
<thead>
<tr>
<th></th>
<th>T₁₀</th>
<th>Spiciness</th>
<th>Log Zoo</th>
<th>EKE</th>
<th>H</th>
<th>W</th>
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<tbody>
<tr>
<td></td>
<td>DV</td>
<td>EOF 1</td>
<td>EOF 1</td>
<td>EOF 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC_fish</td>
<td>0.57***</td>
<td>-0.53***</td>
<td>0.70***</td>
<td>0.40*</td>
<td>-0.42*</td>
<td>0.67***</td>
</tr>
</tbody>
</table>

Declining fish assemblage (PC2) correlated with declining zooplankton and declining trend in EKE/transport & offshore wind-stress curl-driven upwelling related to CC transport.

CC EKE/transport primary mechanism for regulating productivity & providing suitable habitat for cool-water CC endemic taxa (Siegelman-Charbit et al. 2018)

Key conclusion: Multivariate analysis of ichthyoplankton data indicates massive change across fish communities (e.g. mesopelagics, cool-water affinity fishes)

Multi-species signal facilitates detection of change
Significant implications for ecosystem-based vs single-species management
North America west coast current systems

All national fishery labs in North America (USA, Canada, Mexico) adopted the CalCOFI protocol: remove, identify & enumerate ALL ichthyoplankton

Large-scale regional studies therefore possible

West coast ichthyoplankton time series
- Alaska, Shelikof shelf 1983 – (AFSC)
- Vancouver Is, 2001 - (DFO)
- Newport Line, shelf & deep 1980s, 1998 – (NWFSC)
- CalCOFI North (Spring) 1951-84, ‘91,’98, 2003 –
- CalCOFI 1951 – (every 3\textsuperscript{rd} yr, 1966-84) (SWFSC)
- Baja 1951-81, 1998 – (IMECOCAL/CalCOFI)
Analysis of Baja California ichthyoplankton

34 years: (1951-81 with gaps, 1998-2011)

Since 1999 PC1 (Baja) has increased while PC1 (CalCOFI) declined

PC 1: 32% var explained; 19/21 taxa, loadings > 0.5 mesopelagic

$R = 0.60$
$P < 0.001$
Baja California: Changing relationships with ocean forcing post-1998

Baja PC 1 (mesopelagics): changed relationship with O2

PC 1 – Deep $[O_2]$ correlation pre-1999: $r = 0.62$, $p < 0.01$
No significant correlation post-1998

Baja PC 1: regime shift in relation with PDO

R$^2 = 0.42$, $p < 0.05$

R$^2 = 0.18$, $p = 0.054$
A shift off Southern California as well.... but lagged & staged

CalCOFI PCA updated from 2008 to 2015 based on spring data
Relationship of mesopelagics (PC 1) with O2 shifted ~2004, then again ~2011

But still correlated with MEI, PDO: (p < 0.01)

<table>
<thead>
<tr>
<th></th>
<th>MEI</th>
<th>PDO</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC 1 (CalCOFI spr)</td>
<td>0.35**</td>
<td>0.43**</td>
</tr>
</tbody>
</table>
## Comparison of mean abundance 1951-2004 vs 2011-2015

<table>
<thead>
<tr>
<th></th>
<th>1951 – 2004</th>
<th>2011 - 2015</th>
<th>% change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total larvae</td>
<td>59.3</td>
<td>30.0</td>
<td>-49%</td>
</tr>
<tr>
<td>All mesopelagics</td>
<td>12.6</td>
<td>13.3</td>
<td>6%</td>
</tr>
<tr>
<td>Warm mesopelagics</td>
<td>1.5</td>
<td>2.6</td>
<td>+73%</td>
</tr>
</tbody>
</table>

Warm-water mesopelagics, adapted to low [O2], shallow OMZ conditions of southern Baja and the ETP, are taking on increasing importance off southern California.

Species richness: relation to water mass/biogeographic affinity

Changes in S closely linked to changes in warm-water affinity taxa

No significant change in #s of CC endemics or cool-water affinity taxa

Hypothesis: CalCOFI region is an ecotone
S sensitive to influx of warm-water affinity taxa during warmer periods: + PDO/MEI/SST and their decline during cool-water periods
Community dominance in high PC2/low evenness years (blue) and low PC2/high evenness years (red)

10 of the 11 most abundant ichthyoplankton loaded significantly on PC 2, including northern anchovy, Pacific hake, rockfishes (*Sebastes* spp), *Leuroglossus stilbius*, *Stenobrachius leucopsarus*. Their decline significantly altered the dominance structure of the fish assemblage.
Comparison of fish community dynamics between N, S California Current & Alaska Current


Hypotheses:
• Taxa will respond coherently in N & S CCE but oppositely between CCE & Alaska:
  • Declining [O2] observed throughout the CCE, with evidence of coherent ecological responses to other drivers, e.g. El Nino, PDO (Chelton et al 1982, Hare & Mantua 2000) but opposite trends between CCE & Alaska (Hollowed et al 1987, Hare & Mantua 1999, Mantua 2004, etc)
• Taxa in N & S CCE will respond oppositely
  • If response is driven by changing SST, taxa may respond oppositely at the N & S portions of their range
Newport + GoA common-species joint PCA

**PC1 loadings**

22% variance explained by PC1

<table>
<thead>
<tr>
<th>species</th>
<th>R</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snailfish</td>
<td>0.886</td>
<td>0.000</td>
</tr>
<tr>
<td>Rex sole</td>
<td>0.785</td>
<td>0.000</td>
</tr>
<tr>
<td>Butter sole</td>
<td>0.736</td>
<td>0.001</td>
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<tr>
<td>Cockscomb 1</td>
<td>0.525</td>
<td>0.037</td>
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<tr>
<td>Sand lance</td>
<td>0.352</td>
<td>0.182</td>
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<tr>
<td>Lingcod</td>
<td>0.322</td>
<td>0.223</td>
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<tr>
<td>VM myctophid</td>
<td>0.268</td>
<td>0.315</td>
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<tr>
<td>Lingcod</td>
<td>0.184</td>
<td>0.495</td>
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<tr>
<td>Sand lance</td>
<td>0.062</td>
<td>0.819</td>
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<tr>
<td>Rockfishes</td>
<td>-0.255</td>
<td>0.340</td>
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<tr>
<td>VM myctophid</td>
<td>-0.295</td>
<td>0.267</td>
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<tr>
<td>Cockscomb</td>
<td>-0.297</td>
<td>0.265</td>
</tr>
<tr>
<td>Rockfishes</td>
<td>-0.328</td>
<td>0.215</td>
</tr>
<tr>
<td>Snailfish</td>
<td>-0.332</td>
<td>0.209</td>
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<tr>
<td>Cockscomb 2</td>
<td>-0.355</td>
<td>0.177</td>
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<tr>
<td>Butter sole</td>
<td>-0.450</td>
<td>0.081</td>
</tr>
<tr>
<td>Rex sole</td>
<td>-0.562</td>
<td>0.023</td>
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</table>

Regions load oppositely.
CalCOFI core + Newport common-species joint PCA

PC1 loadings
26% variance explained by PC1

<table>
<thead>
<tr>
<th>Species</th>
<th>R</th>
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<tbody>
<tr>
<td>Rockfishes</td>
<td>0.729</td>
<td>0.001</td>
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<tr>
<td>sanddabs</td>
<td>0.593</td>
<td>0.010</td>
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<tr>
<td>VM myctophid</td>
<td>0.545</td>
<td>0.019</td>
</tr>
<tr>
<td>English sole</td>
<td>0.504</td>
<td>0.033</td>
</tr>
<tr>
<td>sanddabs</td>
<td>0.497</td>
<td>0.036</td>
</tr>
<tr>
<td>Rockfishes</td>
<td>0.484</td>
<td>0.042</td>
</tr>
<tr>
<td>English sole</td>
<td>0.348</td>
<td>0.157</td>
</tr>
<tr>
<td>VM myctophid</td>
<td>0.072</td>
<td>0.776</td>
</tr>
</tbody>
</table>

Regions load together (trend)
### Regional PC1 cross-correlations

<table>
<thead>
<tr>
<th></th>
<th>GoA PC1</th>
<th>OR PC1</th>
<th>CN PC1</th>
<th>CC PC1</th>
</tr>
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<tbody>
<tr>
<td>OR PC1</td>
<td>0.089</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>CN PC1</td>
<td>-0.115</td>
<td>0.266</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC PC1</td>
<td>0.162</td>
<td>0.419**</td>
<td>0.588*</td>
<td></td>
</tr>
<tr>
<td>BC PC1</td>
<td>0.334</td>
<td>-0.218</td>
<td>0.447*</td>
<td>0.646*</td>
</tr>
</tbody>
</table>

- **Newport**
- **CalCOFI north**
- **CalCOFI core**
- **Baja CA**

- n=14 smallest sample sizes
- GoA not correlated with any other region
- Many correlations within CCS
Time series requirements: how many, how often?

Reduced sampling (single transect) captures patterns in abundance of key taxa & dominant multivariate patterns (Koslow & Wright, Mar Pol 2016)

With reduced stations, a longer time series is required to capture main patterns
Proposed network of ichthyoplankton time series for Australia

Australian egg production surveys

NRS: Oblique bongo-net sampling at NRSs, single transects linked with egg production surveys where possible. (Leverage!)
Minimum: 4-5 stn (monthly)
6-10 stn (qtrly)
Bongo tows -> 200m (or >bottom)
Consistent sampling design, long-term commitment!

Polish sorting center option?

From Smith et al ms
Summary

• Critical need for ocean ecological time series in an era of accelerating climate change
• Ichthyoplankton provide quantitative cost-effective ecological time series for a key marine group
• Ichthyoplankton time series off southern California (and elsewhere) indicate massive change in key species groups: mesopelagics, cool-water affinity complex linked to changing ocean conditions: deepwater [O2], temperature/circulation/water mass structure (reflected in PDO, SST, etc)
• Changes in diversity, phenology, spawning distributions can be analysed
• Effective time series for key marine provinces around Australia can be based on limited transects at NRS, linked with periodic egg production surveys
  – But without a minimum commitment, results will be limited and disappointing!