Shifts in Southern Resident Killer Whale Phenology in the Salish Sea

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Target journal(s): Global change biology, Journal of Animal Ecology, Marine Ecology Progress Series, not currently written for a short-form journal but perhaps consider PNAS?

Introduction

Phenology, or the timing of biological activities such as migration, growth, and reproduction, can hgave dramatic implications for fitness (citations). When out of step with resources, phenology can cause increased mortality (cite geese migration paper) or reduced reproductive success (caribou paper). The critical nature of these "matches" or "mismatches" were originally described for fish and zooplankton (citation), and have been recieved renewed scientific interest as phenological shifts have been increasingly observed in conjuction with recent climate change (Durant et al., 2007).

Despite its importance, phenology of many organisms, even those of conservation concern, remains poorly understood and is rarely quantified, especially for marine organisms. A recent meta-analysis found that shifts in marine phenology are atleast as dramatic as those observed in terrestrial systems (e.g. XX days per decade) (Poloczanska et al., 2013). Though abundance of critical resources is more often a focus of natural resource management, the timing of resource peaks can be more important for consumers (Hipfner, 2008).

Southern resident killer whales (SRKWs) are a threatened population, and have recieved widespread scientific and public attention in recent years as their numbers have declined(e.g., seattle times articles, Lusseau et al., 2009; Larson et al., 2018; Olson et al., 2018). SRKWs differ from many orca whales in that their primary prey are salmon (*Oncorhynchus* species). Insufficient prey availability is believed to be one of the primary threats to this population, along with vessel traffic and pollutants (Krahn et al., 2007; Lusseau et al., 2009; Hanson et al., 2010). SRKWs inhabit coastal waters of the western United States and Canada and their use of the Salish Sea varies seasonally across two broad areas in the waters of Washington State. During the spring and summer, SRKWs can commonly be found in the upper Salish Sea (north of Admiralty Inlet, Figure 1), whereas during the winter they are more commonly seen in Puget Sound.

In recent decades, salmon abundance and phenology has shifted in the western United States (Weinheimer et al., 2017; Reed et al., 2011; Ford et al., 2006; Satterthwaite et al., 2014)(add Nelson for chinook hatchery release timing), though patterns vary by species and location. We would therefore expect SRKW phenology to have shifted during this time, if prey is a primary driver of their activity in the Salish Sea. SRKWs may be spending more time in Puget Sound (Olson et al., 2018). However, the details are unclear because monitoring effort has also increased duiring this time (Olson et al., 2018; Strebel et al., 2014).

Understanding how SRKW activity varies seasonally and quantifying the extent to which these seasonal patterns have shifted in recent decades will allow us to develop and test hypotheses about potential drivers of these shifts, which in turn will provide information that may be useful for management decision-making.Here, we ask:

1. Has the timing of SRKW activity (phenology) shifted in the upper Salish Sea and/or Puget Sound?
2. If there have been phenological shifts in SRKW activity, do these shifts coincide with shifts in phenology or abundance of their prey (chinook, coho, chum salmon)?

Methods

Data

SRKW: To quantify SRKW seasonal phenology over time, we used the OrcaMaster Database for Whale Sighting Data (Whale Museum), comprised of data from five main sources, including public sightings networks (e.g., OrcaNetwork), commercial whale watch data, and scientific surveys (e.g., SPOT data from satellite tracking units) (Olson et al., 2018). We used data from 1978-2017, because prior to this time there was no dedicated effort to track SRKW presence in the region (Olson et al., 2018). We used these sighting data to identify first observation day-of-year (DOY, the first date on which one or more pods of SRKWs were observed in a given region) and last observation DOY (the first date on which one or more pods of SRKWs were observed) for each sub-region (Upper Salish Sea and Puget Sound) and season (Winter– October through January; and Summer– May through September). We used these seasonal definitions because they are most aligned with mean SRKW seasonal activity patterns over time (Fig 1,Fig 2). We also quantified number of whale days (i.e. days on which which whales were observed) within a season and year for each region.

Salmon: WDFW adult salmon return data for coho, chum, chinook in XX streams OR WDFW recreational fishing data (in progress) for timning AND abundance

Need to add Frasier river timing and abundance from test fishery. Not sure if other Canadian data are reasonable

Analysis

SRKW:

To identify trends over time in phenology for SRKWs in the Upper Salish Sea and in Puget Sound, we used linear regression on first and last observation dates from 1978 through 2017. We also compared first and last observation dates across time periods (1978-1997 versus 1998-2018), using t-tests (Fig 3 and 4), because relationships over time did not look linear and linear regression provided poor fit (Fig 6). Could also break this into 4 decade-long time periods- this might capture the recent trend of later arrival to San Juan Island.

To estimate effects of increased effort (i.e., increased numbers of sightings over time) on trends in phenology, we simulated datasets of whale presence during two seasons equivalent to those in our dataset (summer, which was 1 May through 31 Sept, or 153 days, and fall, which was 1 October through 1 Feb, or 123 days). We used whale presence probabilities of 0.85 for the Upper Salish Sea and 0.6 for Puget Sound (the means in our dataset for each region) and kept it constant over 40 simulated years. We then created an observation dataset, in which effort (the number of observations), varied. During the low effort time period (years 1-20), the number of observations had a mean of 15 per year for Puget Sound and 104 per year in the Upper Salish Sea (matching the means for these reagions from 1978-1997 in the OrcaMaster database). During the high effort time period (years 21-40 in our simulated dataset), the number of annual observations had a mean of 39 for Puget Sound andand 133 for the Upper Salish Sea (matching those in the OrcaMAster database from 1998-2017). We then calculated first- and last- observations dates for each simulated year. We ran these simulation 100 times and calculated the difference between the low effort and high effort time periods. We compared these to the mean differences first- and last-observation daates across time periods in the OrcaMaster database, for each region, to understand whether observed changes may be due to changes in effort over time, rather than changes in orca activity (Fig 5).

Add analyses of subsets of data for which effort has not changed so dramatically: Lime Kiln observations for USS; West Seattle observations for PS.

To identify trends over time in phenology for each pod separately (J,K,L) in the Upper Salish Sea and in Puget Sound, we used linear regression on first-, last-, and peak detection dates estimated from pod-specific occupancy models. Occupancy models (MacKenzie et al. 2002) can estimate jointly species presence or abundance and detection probability (the probability to detect at least one individual present at site). We parameterized the model with annual occupancy probabilities (i.e., we did not fit a dynamic model, but a multiseason model (Royle and Kery 2007). The distribution submodel distinguishes true presence or absence of pod,p, (z, a latent state) in marine area i in year t,(add equation here). We assumed zi,t to be a Bernoulli random variable. We modelled detection probability as a function of year and date, with detectability modelled as a semi-parametric, smooth function of date using flexible thin-plate spline regression modelling (Strebel et al., 2014). Salmon:

We used linear regression to identify trends over time in first, median, and last dates of salmon adult migration timing. Will add more as this approach develops!

Results

We found that SRKW phenology has shifted over the past four decades, though not necessarily in a linear fashion. Across the full timespan, arrival dates have gotten earlier by XX days per decade in Puget Sound and by XX days per decade in the Upper Salish Sea (Fig. 6 A,B). Departure dates have gotten later by XX days in Puget Sound and by XX days per decade in the Upper Salish Sea (Fig. 6 C,D). Add trends in whale days. At least some (quantify this?) of these observed shifts are due to increased effort, however (Fig. 5).

We found that salmon abundance and phenology as also shifted, though temporal patterns varied in space. Add more!

Discussion

The timing of SRKW activity has shifted.

1. SRKWs are spending more time in Puget Sound- first dates have gotten earlier, last dates have gotten later (this is a stronger trend)
2. SRKWs are spending less time in recent years in the upper Salish Sea. Though the trend across the full time series is earlier arrival and departure dates (in part due to increased effort), in the last 5-10 years, arrival dates have gotten later in the upper Salish Sea region.

The timing of adult salmon returns has shifted.

1. If using stream data: Hatchery fish are returning earlier, for the most part (Need to divide up by region) (Fig. 10)

2. If using rec data: discuss trends by region in timing and abundance

If using rec data, synthesis of timing versus abundance of SRKW prey in terms of how they coincide with SRKW shifts.

Observer effort has shifted over time.

1. Its great that so many people are outside looking for whales!
2. Recommend collecting absence data too. This would allow for more robust analyses of whale distributions. Challenge is increased time/money required for database maintenance with this extra data.

Conclusion

Figures

Add the following:

1. A figure that is a 3-paneled figure with the following panels:
   (a) Map of Salish Sea showing 2 seasons and habitat use areas.
   (b) Observations in Puget Sound (fall/winter) (rough versions are Fig. 1 and 2
   (c) Observations in the upper salish sea (spring/summer)
2. A figure comparing SRKW to salmon abundance and phenology: could be SRKW vs salmon, or plot with effect sizes for all over time (i.e. change in days/propriton per decade)

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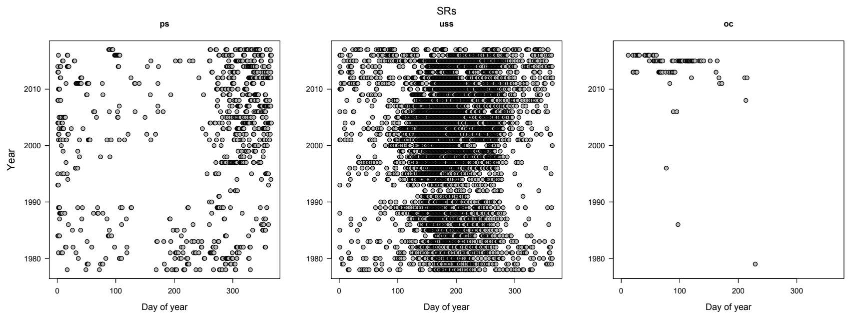

Figure 1: **Southern resident killer whale activity in the Upper Salish Sea and Puget Sound varies by season**. Need to add a map of where observations are, and make this look prettier...

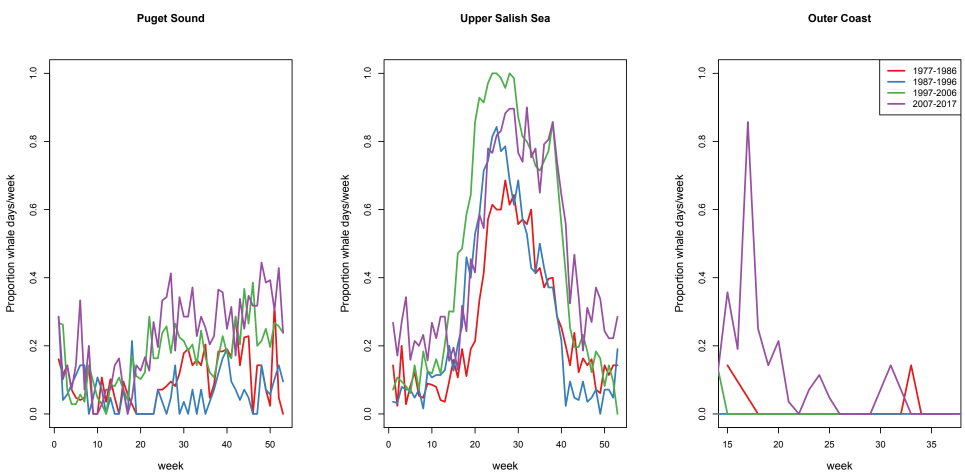

Figure 2: **Southern resident killer whale activity varies by season and region**. Lines show proportion of days per week (1 Jan= week 1) in which whales were observed in the region.

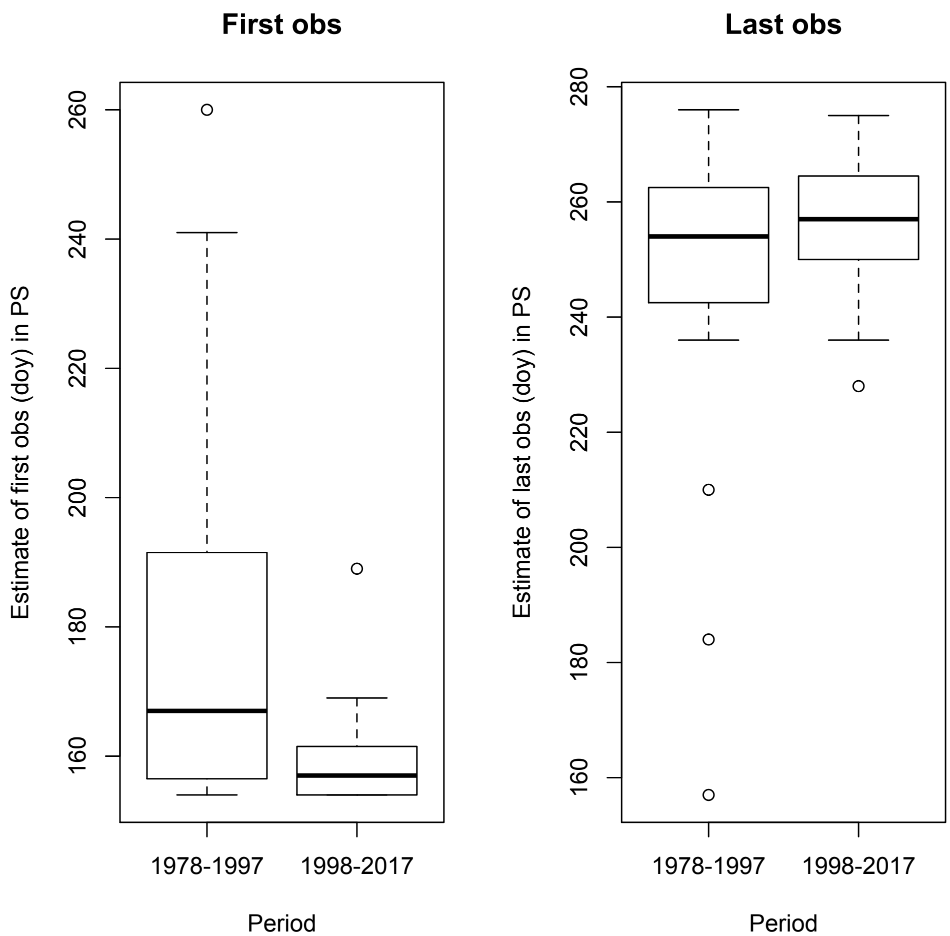

Figure 3: **Change in in first and last observation dates of SRKW in Puget Sound.**

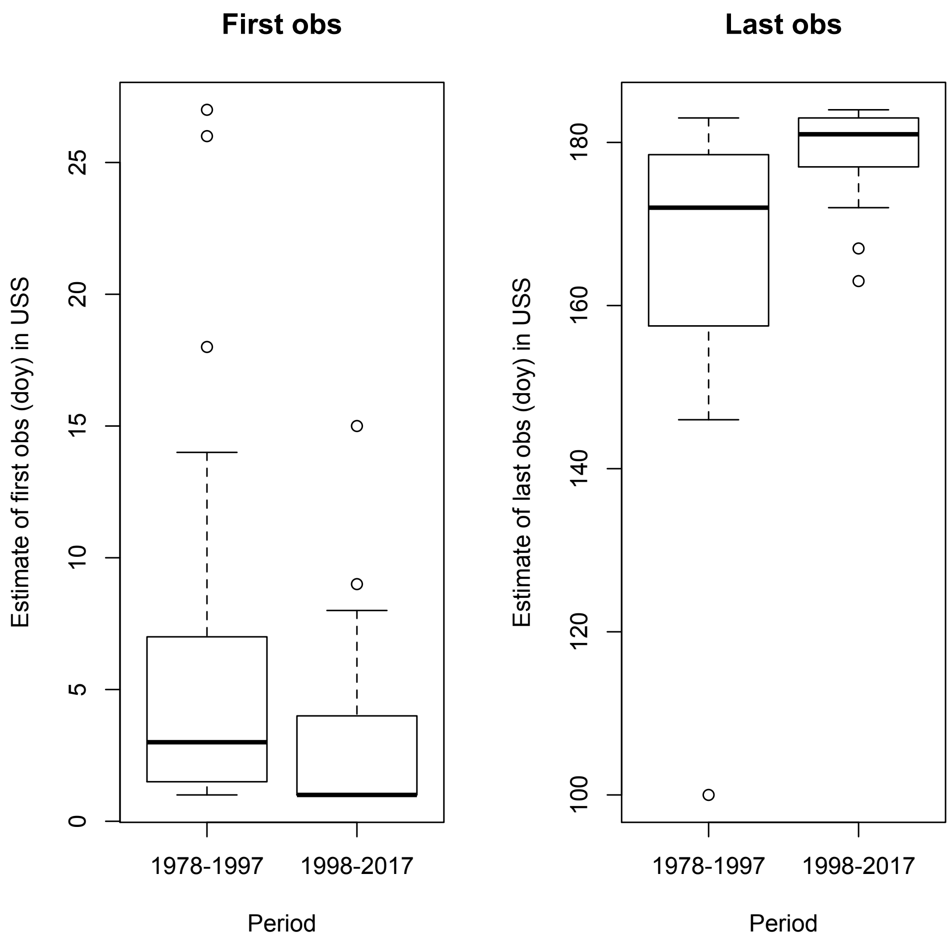

Figure 4: **Change in in first and last observation dates of SRKW in the Upper Salish Sea.**

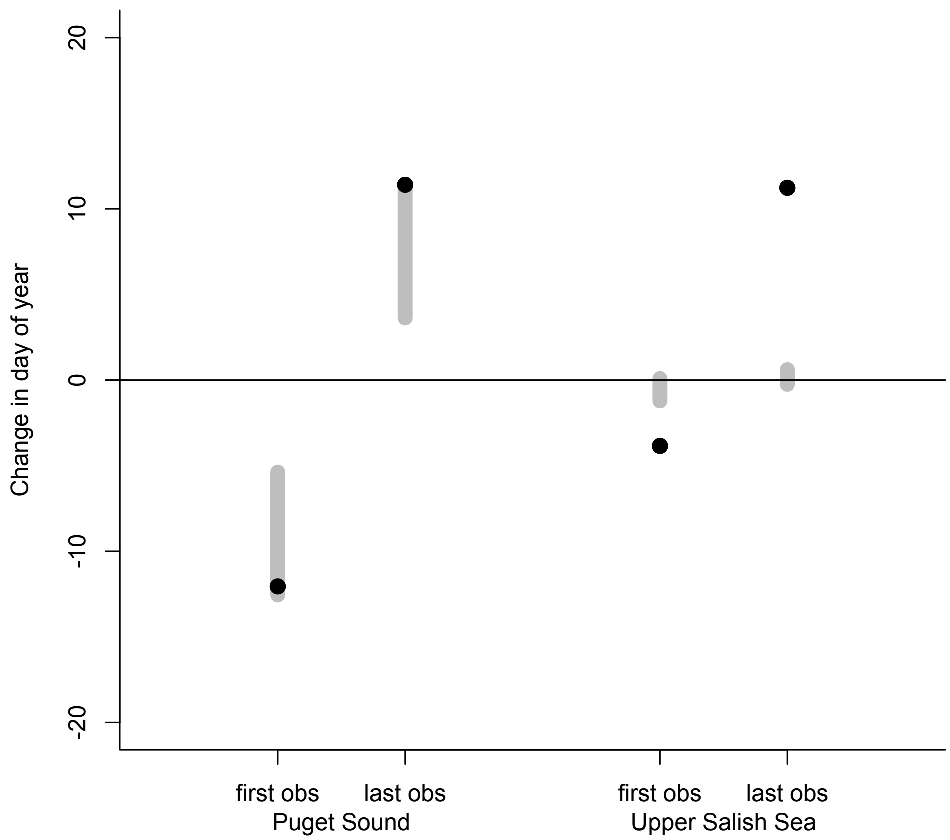

Figure 5: **Change in first and last observation dates in Puget Sound and the Upper Salish Sea.** Observed changes (black dots) are compared with expected changes due to shifts in effort alone (gray lines show 90 quantiles of from a simulated dataset resulting from shifts in effort, with the probability of SRKW presence was kept constant across time).

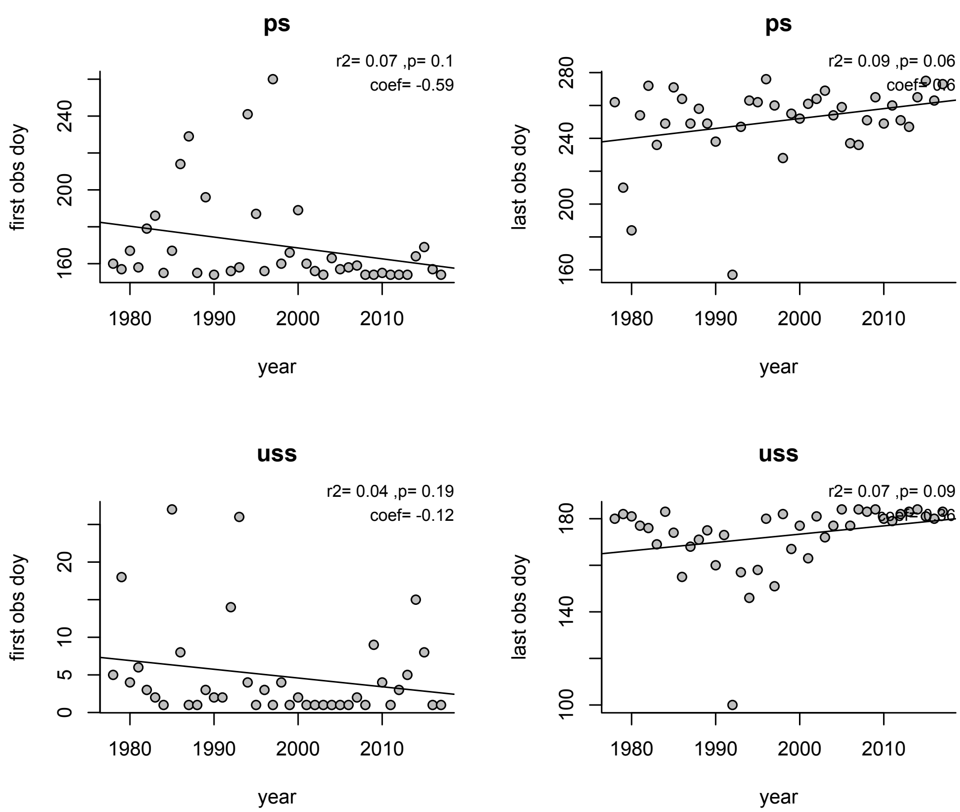

Figure 6: **Time series and linear regression of first and last observation dates of all SRKW pods.** observed in Puget Sound (upper panels) versus the upper Salish Sea (lower panels). Explanatory power of pod-specific models is generally greater (e.g. Fig. 7, Fig. 8)

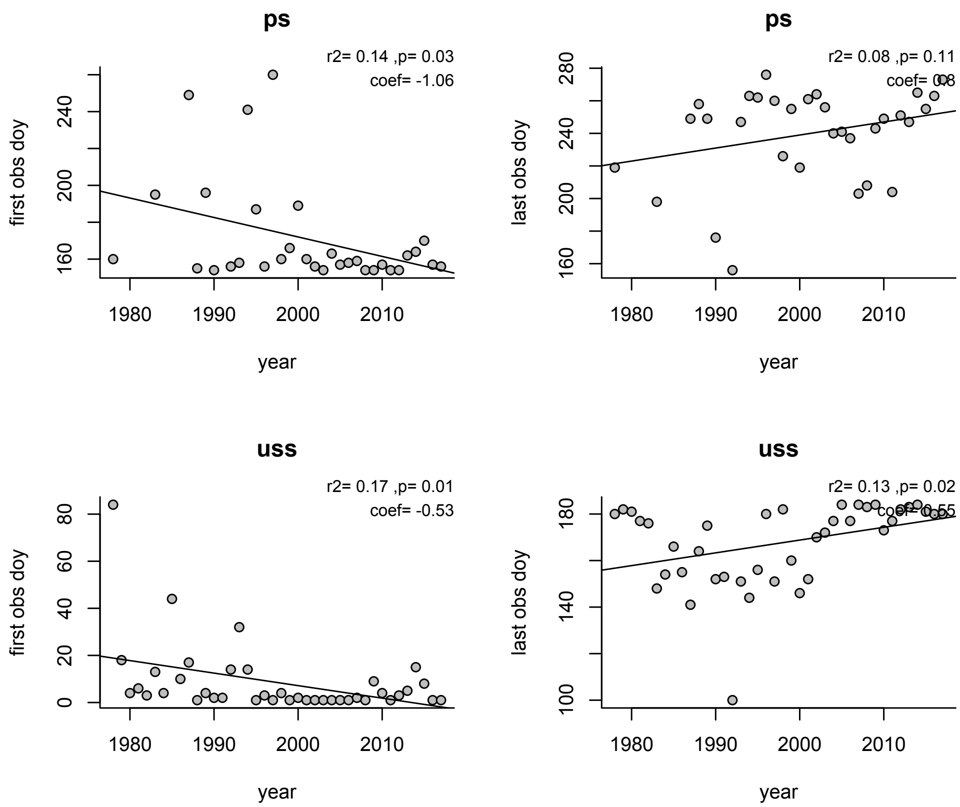

Figure 7: **Time series and linear regression of first and last observation dates of J pod.**- not with occupancy models

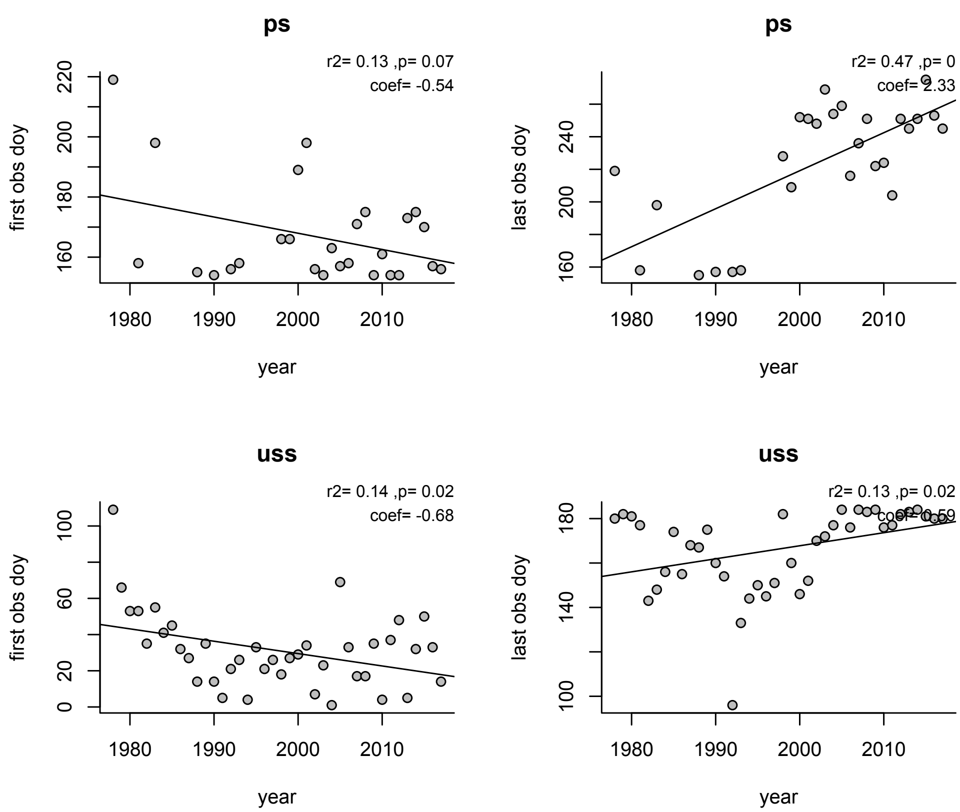

Figure 8: **Time series and linear regression of first and last observation dates of K pod.-** not with occupancy models

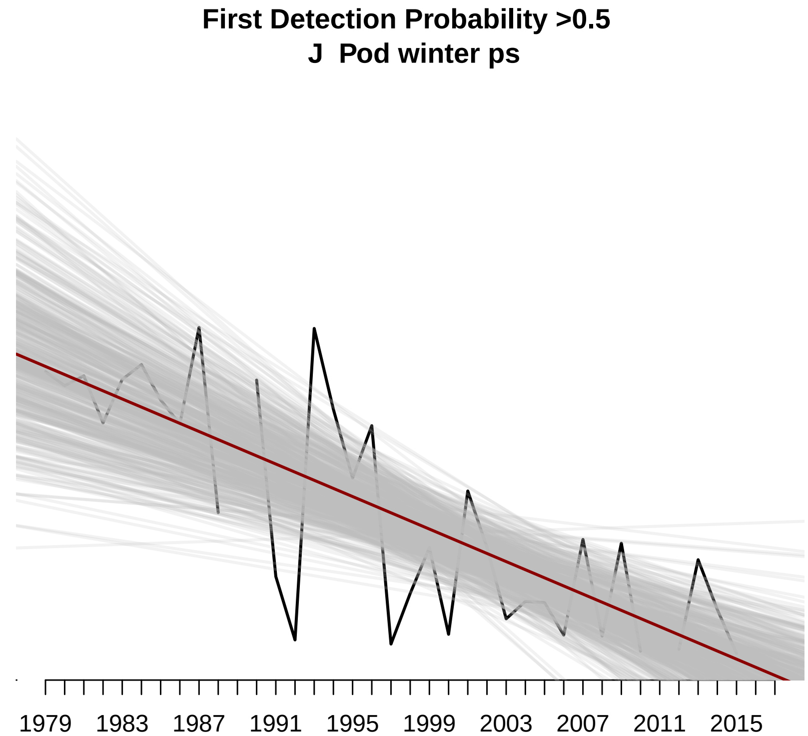

Figure 9: **Trends in first- and last- observation dates for J, K, and L pod.** Make this a 6-paneled figure

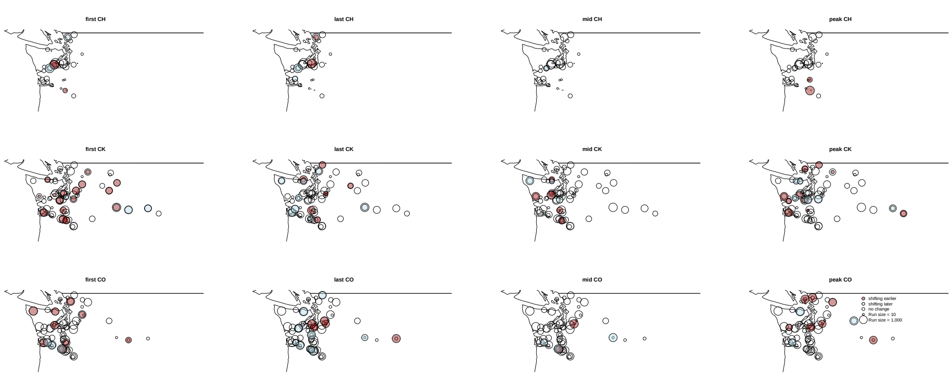

Figure 10: **Salmon return timing is shifting**, though patterns vary by stream and species.

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