Non-analogue states in Gulf of Alaska salmon production

This notebook documents all the code needed to replicate results of the submitted version of the paper.

First, load the required packages

```
library(gtools)
library(ncdf4)
library(MuMIn)
library(zoo)
library(scales)
library(nlme)
library(gplots)
library(dplyr)
library(lattice)
library(maps)
library(mapdata)
library(chron)
library(fields)
library(pracma)
library(FactoMineR)
library(lmtest)
library(MuMIn)
library(broom)
library(reshape2)
```

Data accession details.

ERRST v4 data were obtained from https://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.v4.html on 2 February 2017.

NOAA-CIRES 20th Century Reanalysis v2c data were obtained from https://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2c.html on 2 February 2017.

SODA v. 2.2.4 wind stress data for Fig. 1 were obtained from https://coastwatch.pfeg.noaa.gov/erddap/index.html on 10 May, 2018.

The PDO index was obtained from http://research.jisao.washington.edu/pdo/PDO.latest.txt on 3 March 2018.

The NPGO index was obtained from http://www.o3d.org/npgo/npgo.php on 14 February 2018.

Fig. 1

Test the hypothesis that prominence of PDO and NPGO changed around 1988/89.

```
# load ERSST data
nc <- nc_open("/Users/MikeLitzow 1/Documents/R/NSF-GOA/sst.mnmean.v4.nc")
```

```r
# assign dates (Days since January 1, 1800)
d <- dates(ncvar_get(nc, "time"), origin=c(1,15,1800))

# Extract SST data for desired period and locations:
# Pick start and end dates (January 1950-December 2012):
d1 <- d[1153:1908]

# Select latitude and longitude: 20-66 deg. N, 132-250 deg. E:
x <- ncvar_get(nc, "lon", start=67, count=60)
y <- ncvar_get(nc, "lat", start=12, count=24)

SST1 <- ncvar_get(nc, "sst", start=c(67,12,1153), count=c(60,24,length(d1)))

# process
SST1 <- aperm(SST1, 3:1)  # First, reverse order of dimensions - "transpose" array
SST1 <- SST1[,24:1,]  # Reverse order of latitudes to be increasing for convenience in later plotting
y <- rev(y)  # Also reverse corresponding vector of lattidues
SST1 <- matrix(SST1, nrow=dim(SST1)[1], ncol=prod(dim(SST1)[2:3]))  # Change to matrix with column for

# Keep track of corresponding latitudes and longitudes of each column:
lat <- rep(y, length(x))   # Vector of latitudes
lon <- rep(x, each = length(y))   # Vector of longitudes
dimnames(SST1)  <- list(as.character(d1), paste("N", lat, "E", lon, sep=""))

# identify columns in SST matrix corresponding to land
land <- is.na(colMeans(SST1))

# For analysis, we only use the columns of the matrix with non-missing values:
X1 <- SST1[,!land]

# To remove seasonal trend we compute long-term means for each month and substract them:
m1 <- months(d1)  # Extracts months from the date vector

f <- function(x) tapply(x, m1, mean)  # function to compute monthly means for a single time series
mu1 <- apply(X1, 2, f)  # compute monthly means for each time series (cell)
mu1 <- mu1[rep(1:12, length(d1)/12),]  # replicate means matrix for each year at each location
X1.anom <- X1 - mu1   # compute matrix of anomalies

# now detrend
X1.anom.detr <- detrend(X1.anom)

# and load the pdo and npgo
pdo <- read.csv("pdo.csv")
npgo <- read.csv("npgo.csv")

# the file version of the PDO that I used requires some processing
# drop winter mean and change pdo to long form data

pdo <- pdo[,-2]
pdo <- melt(pdo, id.vars = "YEAR")
pdo <- pdo[order(pdo$YEAR),]
rownames(pdo) <- 1:nrow(pdo)
```

```
# creat an indicator object ("ind.weighted.21") to hold the rolling window results for climate indices a
ind.weighted.21 <- data.frame(year=rep(1950:2012, each=12), month=rep(1:12, length.out=756), pdo=pdo$val

# create columns to hold the rolling correlations
ind.weighted.21$pdo.pc1.cor <- ind.weighted.21$pdo.pc2.cor <- ind.weighted.21$npgo.pc1.cor <- ind.weight

# get a vector of weights (square root of the cosine of latitude)
lat.weights <- lat[!land]
weight <- sqrt(cos(lat.weights*pi/180))

# now loop through the 21-year windows and calculate relevant values
# note that I am using 253-month (21 year + 1 month) windows to ease plotting at window centers

for(i in 127:(nrow(ind.weighted.21)-126)){

  temp.sst <- X1.anom.detr[(i-126):(i+126),] # using anomalies here, NOT scaled, in order to capture imp
  temp.pca <- svd.triplet(cov(temp.sst), col.w=weight) #weighting the columns
  pc1 <- temp.sst %*% temp.pca$U[,1]
  pc2 <- temp.sst %*% temp.pca$U[,2]

  ind.weighted.21$pdo.pc1.cor[i] <- cor(pc1, ind.weighted.21$pdo[(i-126):(i+126)])
  ind.weighted.21$pdo.pc2.cor[i] <- cor(pc2, ind.weighted.21$pdo[(i-126):(i+126)])

  ind.weighted.21$npgo.pc1.cor[i] <- cor(pc1, ind.weighted.21$npgo[(i-126):(i+126)])
  ind.weighted.21$npgo.pc2.cor[i] <- cor(pc2, ind.weighted.21$npgo[(i-126):(i+126)])

  }

  # create decimal year column for plotting
ind.weighted.21$dec.yr <- ind.weighted.21$year + (ind.weighted.21$month-0.5)/12
```

Now examine the change in the spatial fields of the regression coefficients linking the PDO and SLP.

```
# load slp data
nc <- nc_open("/Users/MikeLitzow 1/Documents/R/climate data/prmsl.mon.mean.7.28.15.nc")

# get dates (hours since 1/1/1800)
raw <- ncvar_get(nc, "time")
h <- raw/24
d <- dates(h, origin = c(1,1,1800))

# Pick start and end dates (Jan 1949-Dec 2012):
d <- d[937:1704]

# Extract North Pacific SLP, 20-66 deg. N, 132-250 deg. E
# my version of the data only includes that area, so no need to subset
x.slp <- ncvar_get(nc, "lon", start=67, count=60)
y.slp <- ncvar_get(nc, "lat", start=13, count=24)

SLP <- ncvar_get(nc, "prmsl", start=c(67,13,937), count=c(60,24,length(d)), verbose = F)

# manipulate as needed
SLP <- aperm(SLP, 3:1)  # First, reverse order of dimensions ("transpose" array)
SLP <- SLP[,24:1,]  # Reverse order of latitudes to be increasing for convenience (in later plotting)
```

```r
y.slp <- rev(y.slp)

SLP <- matrix(SLP, nrow=dim(SLP)[1], ncol=prod(dim(SLP)[2:3]))  # Change to matrix

# Keep track of corresponding latitudes and longitudes of each column:
lat <- rep(y.slp, length(x.slp))   # Vector of latitudes
lon <- rep(x.slp, each = length(y.slp))   # Vector of longitudes
dimnames(SLP) <- list(as.character(d), paste("N", lat, "E", lon, sep=""))

X1 <- as.data.frame(SLP) # using data over land, too!

# remove seasonal signal
# and set up vector of winter years (identify winters by the year corresponding to Jan.)
m <- months(d)
yr <- years(d)
win.yr <- as.numeric(as.character(yr))
win.yr[m %in% c("Nov", "Dec")] <- win.yr[m %in% c("Nov", "Dec")] +1

f <- function(x) tapply(x, m, mean)
mu <- apply(X1, 2, f)   # Compute monthly means for each time series (location)
mu <- mu[rep(1:12, round(length(d)/12)),]
X1.anom <- X1 - mu   # Compute matrix of anomalies!

# restrict to relevant months
p.win <- c("Nov", "Dec", "Jan") # months for SLP data
X1.anom <- X1.anom[m %in% p.win,]
win.yr <- win.yr[m %in% p.win]

# clean up
rownames(X1.anom) <- 1:nrow(X1.anom)

# restrict PDO to relevant months
t.win <- c("FEB", "MAR", "APR")
pdo <- pdo[pdo$variable %in% t.win,]
rownames(pdo) <- 1:nrow(pdo)

r1 <- r2 <- NA # vectors to catch regression coefficients
p.val <- NA # and to catch p-values

pdo.FMA <- tapply(pdo$value, pdo$YEAR, mean) # mean values for winter year corresponding to Jan.

ff <- function(x) tapply(x, win.yr, mean)

X1.NDJ <- apply(X1.anom, 2, ff) # mean values for winter year corresponding to Jan. Note that 1949 and 
# (1 mo and 2 mo, respectively!)

for(j in 1:ncol(X1.anom)){

  # subset the data for only the cell of interest and set up the early and late eras (pre/post 1988/89)
  temp <- data.frame(slp=X1.NDJ[2:64, j], pdo=pdo.FMA[51:113], era=c(rep("early", 39), rep("late", 24)))
  mod <- gls(slp ~ pdo*era, data=temp, corAR1()) # allows autocorrelated residuals
  r1[j] <- summary(mod)$tTable[2,1]
  r2[j] <- r1[j] + summary(mod)$tTable[4,1]
```

```r
  p.val[j] <- summary(mod)$tTable[4,4]

}

# convert Pa to hPa
r1 <- r1/100
r2 <- r2/100
```

Add the regression on wind stress.

```r
# load the SODA wind stress data
nc <- nc_open("/Users/MikeLitzow 1/Documents/R/pdo-npgo paper/hawaii_3e19_7ccd_16ff_ad5d_5cb7_0e6f.nc")

# view dates (middle of month):
raw <- ncvar_get(nc, "time")
h <- raw/(24*60*60)
d <- dates(h, origin = c(1,1,1970)) # jan 1949 - dec 2010

# first, eastward wind stress!
# get all the data - they have already been subsetted by date and area in my version
tauX <- ncvar_get(nc, "taux")

x <- ncvar_get(nc, "longitude")     # view longitudes (degrees East)
y <- ncvar_get(nc, "latitude")     # view latitudes

# process!
tauX <- aperm(tauX, 3:1)  # First, reverse order of dimensions ("transpose" array)

tauX <- matrix(tauX, nrow=dim(tauX)[1], ncol=prod(dim(tauX)[2:3]))  # Change to matrix

# Keep track of corresponding latitudes and longitudes of each column:
lat <- rep(y, length(x))   # Vector of latitudes
lon <- rep(x, each = length(y))   # Vector of longitudes
dimnames(tauX) <- list(as.character(d), paste("N", lat, "E", lon, sep=""))

m1 <- months(d)
y1 <- years(d)
dec.yr1 <- as.numeric(as.character(y1)) + (as.numeric(m1)-0.5)/12

# and define the seasons for analysis
win <- c("Nov", "Dec", "Jan") # using NDJ as wind period to relate to FMA PDO

# define winter years
win.y1 <- as.numeric(as.character(y1))
win.y1[m1 %in% c("Nov", "Dec")] <- win.y1[m1 %in% c("Nov", "Dec")] + 1

# restrict to our selected winter months
tauX <- tauX[m1 %in% win,]

# restrict the indexing vector of winter years
win.y1 <- win.y1[m1 %in% win]

# and get annual means of these winter values
ff <- function(x) tapply(x, win.y1, mean)
```

```r
tauX <- apply(tauX, 2, ff)

# now regress on the PDO for 1950:1988 and 1989:2010

# get rid of NAs for regression
land <- is.na(colMeans(tauX))  # Logical vector that's true over land!

# For analysis, we only use the columns of the matrix with non-missing values:
tauX <- tauX[,!land]

regr.early.X <- regr.late.X <- NA # vectors for regression coefficients in both eras
X.pvals <- NA # object to catch p values

for(j in 1:ncol(tauX)){

  # subset for cell of interest
  temp <- data.frame(tauX=tauX[2:62, j], pdo=pdo.FMA[51:111], era=c(rep("early", 39), rep("late", 22)))
  mod <- gls(tauX ~ pdo*era, data=temp, corAR1()) # again, autocorrelated residuals allowed
  regr.early.X[j] <- summary(mod)$tTable[2,1]
  regr.late.X[j] <- regr.early.X[j] + summary(mod)$tTable[4,1]
  X.pvals[j] <- summary(mod)$tTable[4,4]
}
```

And now the northward wind stress.

```r
# northward wind stress!
tauY <- ncvar_get(nc, "tauy") # get all the data!

# process!
tauY <- aperm(tauY, 3:1)  # First, reverse order of dimensions ("transpose" array)

tauY <- matrix(tauY, nrow=dim(tauY)[1], ncol=prod(dim(tauY)[2:3]))  # Change to matrix

dimnames(tauY) <- list(as.character(d), paste("N", lat, "E", lon, sep=""))

# re-define winter years
win.y1 <- as.numeric(as.character(y1))
win.y1[m1 %in% c("Nov", "Dec")] <- win.y1[m1 %in% c("Nov", "Dec")] + 1

# restrict to our selected winter months
tauY <- tauY[m1 %in% win,]

# restrict the indexing vector of winter years
win.y1 <- win.y1[m1 %in% win]

# and get annual means of these winter values
tauY <- apply(tauY, 2, ff)

# now regress on the PDO for 1950:1988 and 1989:2010

# For analysis, we only use the columns of the matrix with non-missing values:
tauY <- tauY[,!land]

regr.early.Y <- regr.late.Y <- NA # vectors for regression coefficients in both eras
```

```
Y.pvals <- NA # object to catch p values

for(j in 1:ncol(tauY)){

  # again subset by cell
  temp <- data.frame(tauY=tauY[2:62, j], pdo=pdo.FMA[51:111], era=c(rep("early", 39), rep("late", 22)))
  mod <- gls(tauY ~ pdo*era, data=temp, corAR1())
  regr.early.Y[j] <- summary(mod)$tTable[2,1]
  regr.late.Y[j] <- regr.early.Y[j] + summary(mod)$tTable[4,1]
  Y.pvals[j] <- summary(mod)$tTable[4,4]
}
```

Now plot the combined regression coefficients.

```
# combine the regression coefficients for the two directions
regr.early.XY <- sqrt(regr.early.X^2 + regr.early.Y^2)
regr.late.XY <- sqrt(regr.late.X^2 + regr.late.Y^2)

# and combine p-vals
# into separate incr(easing) and decr(easing) sets!
p.both <- p.incr <- p.decr <- NA

for(i in 1:length(X.pvals)){
p.both[i] <- min(X.pvals[i], Y.pvals[i])
p.incr[i] <- ifelse(regr.late.XY[i]  > regr.early.XY[i], p.both[i], 1)
p.decr[i] <- ifelse(regr.late.XY[i]  < regr.early.XY[i], p.both[i], 1)
}
```

And now produce Fig. 1 for the paper.

```
# set up color schemes
new.col <- my.col <- tim.colors(64)
grays <- c("gray98", "gray97", "gray96", "gray95", "gray94", "gray93", "gray92", "gray91", "gray90", "g

my.col[22:43] <- c(grays[11:1], grays)
new.col[27:36] <- c(grays[5:1], grays[1:5])

png("Fig 1.png", 11.4/2.54, (4/3)*11.4/2.54, units="in", res=300)

# setup the layout
mt.cex <- 1.1
l.mar <- 3
l.cex <- 0.8
l.l <- 0.2
tc.l <- -0.2

par(mar=c(1.5,2.5,1,0.5),  tcl=tc.l, mgp=c(1.5,0.3,0), las=1, mfrow=c(4,2), cex.axis=0.8, cex.lab=0.8, 

plot(ind.weighted.21$dec.yr, abs(ind.weighted.21$pdo.pc1.cor), type="l", col="#CC79A7", ylim=c(0,1), xl
lines(ind.weighted.21$dec.yr, abs(ind.weighted.21$npgo.pc1.cor), col="#0072B2", lwd=1.5)
legend("bottomright", c("PDO", "NPGO"), text.col = c("#CC79A7", "#0072B2"), bty="n", horiz = F, cex=1)
mtext("a", adj=0.05, line=-1.4, cex=1.1)
mtext("SST PC1 correlation",cex=0.8)
abline(v=1989.042, lty=2)
```

```r
plot(ind.weighted.21$dec.yr, abs(ind.weighted.21$pdo.pc2.cor), type="l", col="#CC79A7", ylim=c(0,1), xla
lines(ind.weighted.21$dec.yr, abs(ind.weighted.21$npgo.pc2.cor), col="#0072B2", lwd=1.5)
legend("bottomright", c("PDO", "NPGO"), text.col = c("#CC79A7", "#0072B2"), bty="n", horiz = F, cex=1)
mtext("b", adj=0.05, line=-1.4, cex=1.1)
mtext("SST PC2 correlation",cex=0.8)
abline(v=1989.042, lty=2)

# set lines to mark out study area!
linex <- c(199, 201, 201, 203, 203, 207, 207, 221, 221, 227, 227, 199, 199)
liney <- c(55, 55, 57, 57, 59, 59, 61, 61, 59, 59, 53, 53, 55)

par(mar=c(0.5,0.5,1.5,1))

# set the limit for plotting
lim <- range(r1, r2)

z <- r1   # replace elements NOT corresponding to land with loadings!
z <- t(matrix(z, length(y.slp)))  # Convert vector to matrix and transpose for plotting

image.plot(x.slp,y.slp,z, col=my.col, zlim=c(lim[1], -lim[1]), xlab = "", ylab = "", yaxt="n", xaxt="n"
contour(x.slp,y.slp,z, add=T, col="white",vfont=c("sans serif", "bold"))
map('world2Hires',fill=F, xlim=c(130,250), ylim=c(20,66),add=T, lwd=1)
lines(linex, liney, lwd=2, col="black")
mtext("c", adj=0.05, line=-1.4, cex=mt.cex)
mtext("SLP-PDO 1950-1988", cex=0.8)

z <- r2   # replace elements NOT corresponding to land with loadings!
z <- t(matrix(z, length(y.slp)))  # Convert vector to matrix and transpose for plotting

image.plot(x.slp,y.slp,z, col=my.col, zlim=c(lim[1], -lim[1]),  xlab = "", ylab = "", yaxt="n", xaxt="n
contour(x.slp,y.slp,z, add=T, col="white",vfont=c("sans serif", "bold"))
map('world2Hires',fill=F, xlim=c(130,250), ylim=c(20,66),add=T, lwd=1)
lines(linex, liney, lwd=2, col="black")
mtext("d", adj=0.05, line=-1.4,cex=mt.cex)
mtext("SLP-PDO 1989-2012", cex=0.8)

zlim <- range(regr.early.XY, regr.late.XY)

z <- rep(NA, ncol(tauY))
z[!land] <- regr.early.XY
z <- t(matrix(z,length(y)))  # Re-shape to a matrix with latitudes in columns, longitudes in rows
image.plot(x,y,z, col=new.col, zlim=c(-zlim[2],zlim[2]), ylab="", xlab="", yaxt="n", xaxt="n",legend.ma

contour(x, y, z, add=T, drawlabels = F, lwd=0.7, col="grey")
map('world2Hires', 'Canada', fill=T,xlim=c(130,250), ylim=c(20,70),add=T, lwd=0.5, col="darkgoldenrod3")
map('world2Hires', 'usa',fill=T,xlim=c(130,250), ylim=c(20,70),add=T, lwd=0.5, col="darkgoldenrod3")
map('world2Hires', 'USSR',fill=T,xlim=c(130,250), ylim=c(20,70),add=T, lwd=0.5, col="darkgoldenrod3")
map('world2Hires', 'Japan',fill=T,xlim=c(130,250), ylim=c(20,70),add=T, lwd=0.5, col="darkgoldenrod3")
map('world2Hires', 'Mexico',fill=T,xlim=c(130,250), ylim=c(20,70),add=T, lwd=0.5, col="darkgoldenrod3")
map('world2Hires', 'China',fill=T,xlim=c(130,250), ylim=c(20,70),add=T, lwd=0.5, col="darkgoldenrod3")
map('world2Hires',fill=F, xlim=c(130,250), ylim=c(20,66),add=T, lwd=1)
lines(linex, liney, lwd=2, col="black")
mtext("e", adj=0.05, line=-1.4, cex=mt.cex)
```

```
mtext("Wind stress-PDO 1950-1988", cex=0.8)

z <- rep(NA, ncol(tauY))
z[!land] <- regr.late.XY
z <- t(matrix(z,length(y)))  # Re-shape to a matrix with latitudes in columns, longitudes in rows
image.plot(x,y,z, col=new.col, zlim=c(-zlim[2],zlim[2]), ylab="", xlab="", yaxt="n", xaxt="n",legend.ma

contour(x, y, z, add=T, drawlabels = F, lwd=0.7, col="grey")
map('world2Hires', 'Canada', fill=T,xlim=c(130,250), ylim=c(20,70),add=T, lwd=0.5, col="darkgoldenrod3"
map('world2Hires', 'usa',fill=T,xlim=c(130,250), ylim=c(20,70),add=T, lwd=0.5, col="darkgoldenrod3")
map('world2Hires', 'USSR',fill=T,xlim=c(130,250), ylim=c(20,70),add=T, lwd=0.5, col="darkgoldenrod3")
map('world2Hires', 'Japan',fill=T,xlim=c(130,250), ylim=c(20,70),add=T, lwd=0.5, col="darkgoldenrod3")
map('world2Hires', 'Mexico',fill=T,xlim=c(130,250), ylim=c(20,70),add=T, lwd=0.5, col="darkgoldenrod3")
map('world2Hires', 'China',fill=T,xlim=c(130,250), ylim=c(20,70),add=T, lwd=0.5, col="darkgoldenrod3")
map('world2Hires',fill=F, xlim=c(130,250), ylim=c(20,66),add=T, lwd=1)
lines(linex, liney, lwd=2, col="black")
mtext("f", adj=0.05, line=-1.4, cex=mt.cex)
mtext("Wind stress-PDO 1989-2012", cex=0.8)

zlim <- range(regr.early.XY, regr.late.XY)

z <- rep(NA, ncol(tauY))
z[!land] <- regr.early.XY
z <- t(matrix(z,length(y)))  # Re-shape to a matrix with latitudes in columns, longitudes in rows
image(x,y,z, col=new.col, zlim=c(999,9999), ylab="", xlab="", yaxt="n", xaxt="n")

z <- rep(NA, ncol(tauY))
z[!land] <- p.decr
z <- t(matrix(z,length(y)))
contour(x, y, z, add=T, drawlabels = F, levels = seq(0.05, 0, length.out = 1000), col="#56B4E9", lwd=2)

z <- rep(NA, ncol(tauY))
z[!land] <- p.incr
z <- t(matrix(z,length(y)))
contour(x, y, z, add=T, drawlabels = F, levels = seq(0.05, 0, length.out = 1000), col="#CC79A7", lwd=2)

map('world2Hires', 'Canada', fill=T,xlim=c(130,250), ylim=c(20,70),add=T, lwd=0.5, col="darkgoldenrod3"
map('world2Hires', 'usa',fill=T,xlim=c(130,250), ylim=c(20,70),add=T, lwd=0.5, col="darkgoldenrod3")
map('world2Hires', 'USSR',fill=T,xlim=c(130,250), ylim=c(20,70),add=T, lwd=0.5, col="darkgoldenrod3")
map('world2Hires', 'Japan',fill=T,xlim=c(130,250), ylim=c(20,70),add=T, lwd=0.5, col="darkgoldenrod3")
map('world2Hires', 'Mexico',fill=T,xlim=c(130,250), ylim=c(20,70),add=T, lwd=0.5, col="darkgoldenrod3")
map('world2Hires', 'China',fill=T,xlim=c(130,250), ylim=c(20,70),add=T, lwd=0.5, col="darkgoldenrod3")
map('world2Hires',fill=F, xlim=c(130,250), ylim=c(20,66),add=T, lwd=1)

lines(linex, liney, lwd=1.5, col="black")

legend("bottomleft", c("Weaker", "Stronger"), xjust=0, text.col=c("#56B4E9", "#CC79A7"), cex=1.2)
mtext("g", adj=0.05, line=-1.4, cex=mt.cex)
mtext("P < 0.05: wind stress-PDO", cex=0.8)
dev.off()
```

```
## pdf
##   2
```