Satellite tagging, remote sensing, and autonomous vehicles reveal interactions between foraging and migration behaviors of a top marine predator and the environment in the North Pacific Ocean

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Overview

- Northern fur seals (NFS; *Callorhinus ursinus*) breeding on the Pribilof or Bogoslof Islands in the Bering Sea account for the majority of worldwide pup production in this species[1].
- NFS from these two sites undergo an annual migration of ~8 mo. in late autumn, winter, spring.
- Different NFS groups face different pressures:
  - Reproductive males must acquire energy stores to fast and hold territories on land the following summer;
  - Pregnant adult females must acquire resources for fetal growth prior to giving birth after the migration;
  - Newly-weaned pups face winter storms, large waves, declining sea and air temperatures on their first migration, but are of much smaller size than adults and lack experience.
  - In a typical year, more than half of these pups do not survive[2].
- Over the past two decades, the Alaska Ecosystems Program at the NOAA National Marine Mammal Laboratory has engaged in extensive satellite tracking of Bering Sea NFS in order to better understand **habitat requirements and foraging strategies** during the migratory period.
- Here, **key findings from published and ongoing studies are summarized.**

Methods

National Marine Mammal Laboratory researchers equipped 256 NFS (135 pups, 106 adult females, 15 adult males) from the Pribilof and Bogoslof Islands with satellite-telemetery tags capable of providing animal location estimates, and in some cases, dive data.

Location data were fit with a switching state-space movement model. Movement and dive behavior were compared to remotely sensed data, atmospheric reanalysis, autonomous in situ ocean sampling, and animal-borne temperature and salinity data. These procedures are described in Sterling *et al.*[3] and Pelland *et al.*[4]

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References:

[1]U.S. Department of Commerce (2007). Conservation Plan for the Eastern Pacific Stock of Northern Fur Seal (*Callorhinus ursinus*). Juneau, AK: National Marine Fisheries Service.

[2]Lander, R.H. (1979) Fishery Bulletin 77(1):311:314.

[3]Sterling, J.T., *et al.* (2014) PLoS ONE 9(4):e93068 doi:10.1371/journal.pone.0093068.

[4]Pelland, N.A. *et al.* (2014) PLoS ONE 9(8):e101268 doi:10.1371/journal.pone.0101268.

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1 NFS migrate to different regions depending on their age and/or sex.

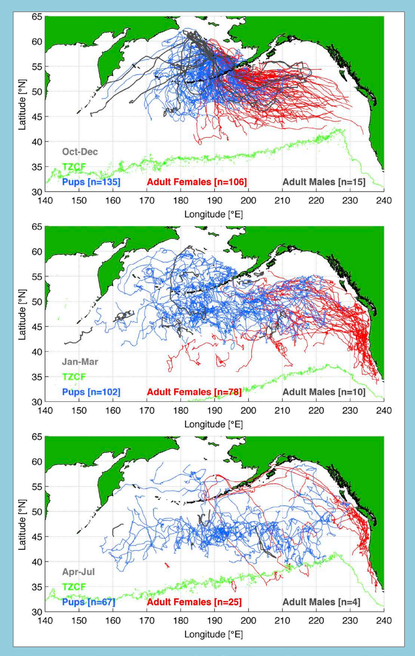

Figure 1. Migratory tracks of 256 satellite-tagged Bering Sea NFS. Oct-December (top panel), January-March (middle), April-July (bottom). Green contour indicates Transition Zone Chlorophyll Front (TZCF).

This had been shown previously but with different sexes/ages in separate years. It has probably been known in traditional historical knowledge for millenia.

2 These groups face differing environmental conditions.

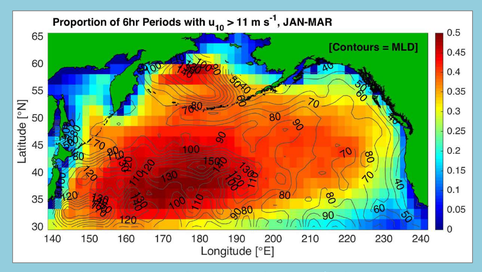

Figure 2. Proportion of high-wind (>11 m s^{-1}) 6hr periods in January-March, NCEP Reanalysis 1, 1991-present. Contours are climatological MLD for these months from Argo array.

In particular, most adult females and some pups migrate to productive eastern boundary currents that, compared to the interior North Pacific, have a shallower mixed-layer depth (MLD), fewer high-wind days (**Fig. 2**), and topographic features where eddy generation is common[4].

3 Despite this, adults have similar diving behavior.

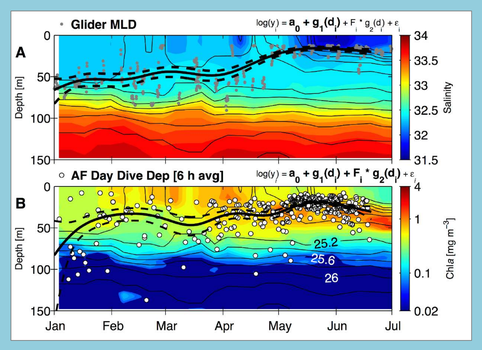

Figure 4. (top) Climatological MLD (dots) and salinity (colors) in Washington coastal transition zone from autonomous underwater gliders. (bottom) Adult female NFS mean 6hr dive depth (circles) and climatological chlorophyll (colors). Black lines show generalized additive model fit to MLD/diving[4].

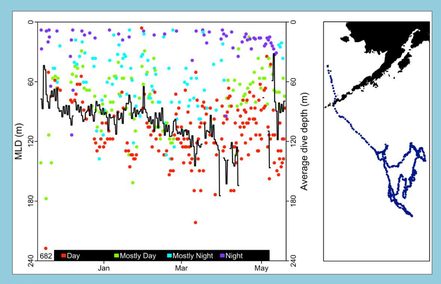

Figure 3. Example diving record from migratory adult male NFS[3]. (Left) Mean 6hr dive depth vs. time; 6hr periods colored by time of day. Black line shows MLD from animal-borne sensors. (Right) Horizontal track.

Adult males dived during all times of day and to the base of the mixed layer or below during daytime[3] (*e.g.*, **Fig. 3**). Females entering the California Current exhibited similar patterns[4] in a region of shallower MLDs (**Fig. 4**).

Correlation with the MLD **implies that upper-ocean stratification affects the depth of NFS prey fields[3,4]**.

4 NFS of all groups respond to the wind.

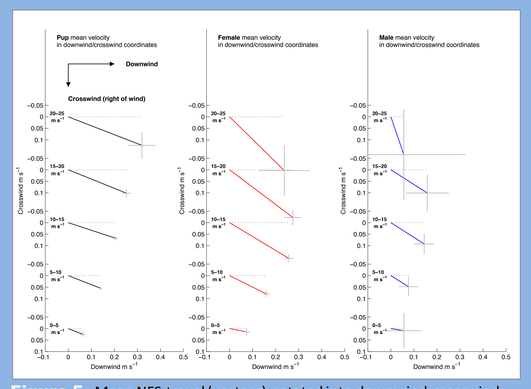

Figure 5. Mean NFS travel (vectors), rotated into downwind-crosswind coordinate system based on NCEP Reanalysis 1 winds interpolated to animal location. (left) Pups, (center) adult females, (right) adult males. Mean travel computed in five bins based on wind speed (rows). Whiskers are 95% Student's-*t* confidence bounds on mean travel.

High wind was associated with decreasing area-restricted search and increased transit for all groups (**Fig. 7**).
NFS travel correlates with wind direction and speed, being on average downwind and to the right (**Fig. 5**).

At very low winds, adult females show a travel preference to the SE compared to pups (**Fig. 6**), likely reflecting prior knowledge/experience.

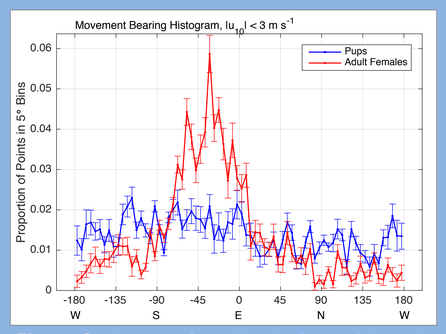

Figure 6. Histogram of travel bearing for pup (blue) and adult female (red) NFS during Oct.-Jan. at very low wind speeds (<3 m s^{-1}), where wind effect on travel is weak. Whiskers are RMS confidence bounds on bin proportion.

5 Results are consistent with large differences in size and experience between adults and pups, and in size between sexes.

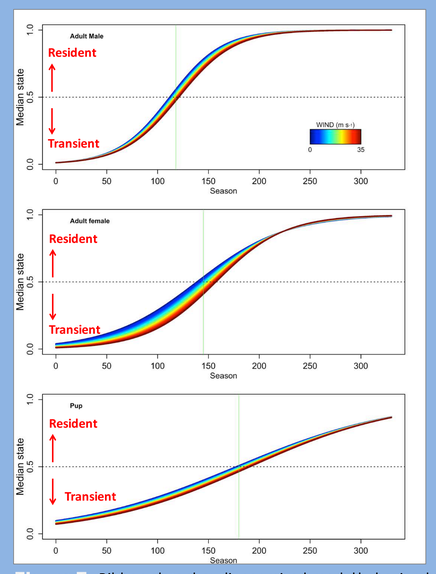

Figure 7. Ribbon plots show linear mixed-model behavioral state response due to days since 1 October (x-axis) and due to wind speed (ribbon colors), for adult males (top), adult females (middle), and pups (bottom). High behavioral state corresponds to resident, area-restricted search movement.

NFS mass correlates with maximum dive depth and size with the ability to withstand cold temperatures.

Larger adult males:
- Have dive depths that correlate with deep, interior MLDs,
- Exhibit movements that are least correlated with the wind, and
- Initiate consistent resident behavior earliest in the winter (**Fig. 7**).

They are followed by **smaller adult females**, and later by the **still-smaller pups (Fig. 7)**.

We conclude[3] that:
- Adult females are constrained by their physical characteristics to migrate to temperate, productive eastern boundary currents (predictable and accessible prey resources).
- Adult males do not face these same constraints, and avoid predation and competition by foraging in the interior North Pacific Ocean and southern Bering Sea.

Behavioral responses to environmental features suggest that the latter influence prey fields, and/or NFS condition, and potentially demography.

- Results suggest winds could influence a) pup dispersal patterns and b) availability of resources through forced changes in upper-ocean stratification. These factors may be relevant to unexplained large interannual variations in pup survivorship and are the subject of ongoing study.
- Basin-scale interannual variability (*e.g.*, PDO, ENSO) affects winds, upper-ocean stratification, and ecosystem productivity and plays an unknown role in Bering Sea NFS demography, but is of great significance to San Miguel NFS breeding in the California Current System.
- Observations over the past 50 yr indicate changes in character of annual cycle of wave heights in North Pacific Ocean, and a poleward shift in the midlatitude storm track. Ongoing work is investigating the impact of these trends on NFS demography during this period.