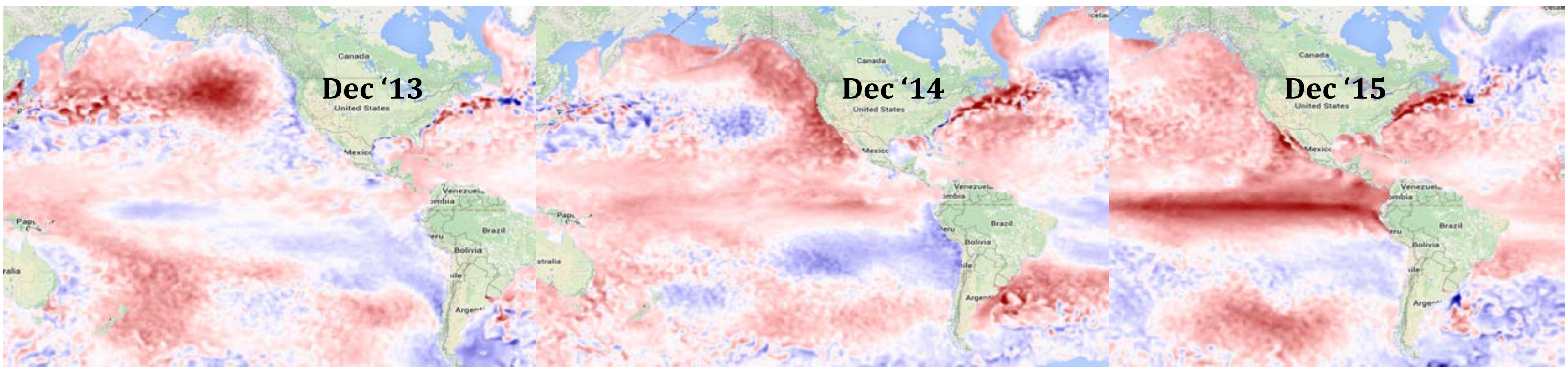
Pacific Anomalies Workshop 2 Report:

Summary and Recommendations of the
Second Pacific Anomalies Science and Technology Workshop
University of Washington, Seattle, WA
January 2016



SST anomaly plots: http://nvs.nanoos.org/Climatology

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http://www.nanoos.org/resources/anomalies_workshop/workshop2.php

Introduction

The unusual ocean weather and climate patterns observed during 2014 across the North Pacific basin, earning the nickname the "blob", persisted into 2016 and were accompanied by a strong El Niño during 2015-2016. The extreme conditions in physical and biogeochemical parameters appeared to impact the pelagic ecosystem, including fisheries.

From 2015-2016, the ocean observing community, with representatives spanning regional to global systems, came together to design two workshops to understand the timing, scale, and drivers of these anomalous oceanographic conditions in the North Pacific, with the intent of maximizing our global and coastal ocean observing systems to deliver information to meet societal needs.

The first workshop, held on May 5-6, 2015 at the Scripps Institution of Oceanography, La Jolla, California, chaired by Julie Thomas, SCCOOS, was attended by 110 people who generated a series of research and development questions and issues related to these anomalies. Workshop presentations and output can be found at:
http://www.nanoos.org/resources/anomalies_workshop/workshop1.php

This is the report for the second Pacific Anomalies Workshop, which was held on the University of Washington campus on 20-21 January 2016, attended by 180 people. The aim of the second workshop (PAW 2) was to improve our understanding of how these significant oceanographic variations arose, their biological impacts, and ways in which we can potentially improve predictive capabilities. Specifically, workshop goals were to:

- Succinctly articulate what is known re mechanisms underlying the 2013-15 anomalies, including the "blob" and extending to how it interacted with the coast and ecosystems.
- Identify needs (observing, modeling, knowledge, indices) to increase our ability to predict, react to, or understand these anomalies.

PAW 2 focused on three topical areas: **Atmosphere-ocean interactions; Open ocean-coastal interactions; Ecosystem responses.** PAW 2 presentations and output can be found at: http://www.nanoos.org/resources/anomalies_workshop/workshop2.php

This summary report is intended to present a high-level overview of the knowledge at the time of the workshop on the status and mechanisms involved in each of the three focus areas with respect to Pacific anomalies, and specific recommendations on needs (observations, modeling, or studies) that limit our understanding or ability to predict dynamics or impacts of the anomalous conditions. Each chapter was written by two University of Washington students (one graduate, one undergraduate) who attended; the report was reviewed by the Session Chairs and PAW 2 Steering Committee.

We thank the sponsors of the second workshop: U.S. IOOS, NOAA OAR Ocean Climate Observation Program, NOAA Western Regional Team, Washington Sea Grant, California Sea Grant, University of Washington College of the Environment, Applied Physics Laboratory - University of Washington, and the Joint Institute for the Study of Atmosphere and Ocean.

PAW 2 discussion format

To address the three topical areas listed below, a set of focused discussion questions was developed by the Steering Committee for the workshop. For each topic, a plenary presentation was given by the two session chairs, followed by facilitated discussion. In subsequent concurrent break-out sessions, the questions were further discussed and recommendations on research needs were developed. The report chapters provide a succinct synopsis of the information from the presentations and discussions of each topical area, along with the recommendations on needs from the participants.

Atmosphere-ocean interactions

- What is the 'blob' generating mechanism and is it unprecedented?
- Could we have/how could we have predicted this?
- Is this representative of a new state of the ocean?
- Is there a mechanism for this be linked to long-term effects of greenhouse gases?

Session Chairs: Nicholas Bond, University of Washington and Manu Di Lorenzo, Georgia Institute of Technology

Open ocean-coastal interactions

- What large and meso-scale processes, including upwelling, kept the blob offshore on the west coast?
- How did the offshore ocean interact with the upwelling zone?
- Was this predictable or were there interactions with El Niño that made it complicated?
- What was the geographical variation in relative balance of atmospheric forcing, alongshore advection and propagation?

Session Chairs: Mike Kosro, Oregon State University (OR, N) and Uwe Send, Scripps Institution of Oceanography (CA, S)

Ecosystem responses

- What are the mechanisms of ecosystem responses from plankton to predators, including effects from physical and chemical states associated with the blob?
- Can we extrapolate physical drivers to biological responses?

Session Chairs: Bill Sydeman, Farallon Institute and Art Miller, Scripps Institution of Oceanography

The understanding of the "blob" emerging from PAW2 evolved to encompass a diversity of warm anomaly phenomena. Since then, Hobday et al., 2016 offer an approach to defining warm anomaly events or "marine heat waves". In this report, we did not overly constrain usage of the term "blob," recognizing its meaning may reflect a diversity of phenomena, and these more precisely can be referred to as warm anomalies or marine heat waves.

A.J. Hobday, L.V. Alexander, S.E. Perkins, D. A. Smale, S.C. Straub, E.C.J. Oliver, J.A. Benthuysen, M.T. Burrows, M.G. Donat, M. Feng, N.J. Holbrook, P.J. Moore, H.A. Scannell, A.S. Gupta, T. Wernberg, A hierarchical approach to defining marine heatwaves, Progress in Oceanography, Volume 141, 2016, http://dx.doi.org/10.1016/j.pocean.2015.12.014.

Atmosphere-Ocean Dynamics

Lingham Li and Andrew Shao

Chronology and Patterns of the 2013-2016 Warm Anomalies in the North Pacific

Observations of sea surface temperature (SST) anomalies in the North Pacific from satellites show four distinct warm anomalies that are separated both in time and space. The so-called 'blob' first emerged as an unprecedented warm SST anomaly (3-sigma event) in open ocean waters of the Gulf of Alaska in late 2013 and persisted through summer 2014. In Fall 2014, following a weak El Niño in the tropical Pacific, anomalous warming was observed along the western coast of North America. A localized surface warming off the coast of Baja California emerged in May 2014 and strengthened both horizontally and vertically through summer 2015 while the strong El Niño of 2015/16 developed in the tropical Pacific.

The anomaly patterns of the blob are likely connected to the dynamics of known modes of atmospheric and ocean variability. The emergence of the warm blob in the winter of 2013/14 resembled the pattern of the North Pacific Gyre Oscillation (NPGO) and was forced by a persistent atmospheric ridge over the North Pacific that resulted in unusually weak seasonal cooling of the upper ocean. This ridge was probably reinforced by large-scale atmospheric teleconnections associated with SST anomalies in the far western tropical Pacific. The reemergence and re-intensification of the blob in the following winter of 2014/15 brought a SST anomaly pattern resembling that of the positive phase of the Pacific Decadal Oscillation (PDO) and likely involved atmospheric forcing related to tropical/extra-tropical teleconnections associated with the weak El Niño in the Summer/Fall of 2014, and coastal upwelling dynamics in the nearshore (0-200km from the coast). However, both the persistence of such anomalies, and the causes for the extraordinary magnitude of the anomaly, require further investigation. To move beyond a phenomenological understanding of these events, future process studies must take advantage of atmospheric reanalysis and observations of near-surface ocean temperature and salinity from Argo profiling floats, hydrographic cruises, and the moorings of the Tropical Atmosphere Ocean Array. Numerical simulations with regional ocean models may also help diagnose the interplay between local atmospheric forcing of the warm blob and the role of internal ocean dynamics (e.g. coastal upwelling).

There are four patterns of warm anomalies in the North Pacific in recent years: (1) blob in the interior Gulf of Alaska (GOA pattern, NPGO-like), (2) Baja pattern near Mexico/southern California, (3) NE Pacific warming (ARC pattern, PDO-like), and (4) Bering Sea.

(1) The warm GOA/NPGO-like pattern emerged in late 2013 and lasted into summer 2014. It re-emerged in summer 2015. It was also warm in spring and summer of 2013. Additionally, the sub-surface ocean warming were observed in summer 2013 and all months in 2014 and 2015. Atmospheric forcing plays an important role in the generation and evolution of this warm blob in SST and mixed layer warming.

The 2013-2014 winter warm anomalies were due to lack of cooling and relatively weak cold advection, which are attributed to a persistent high sea level pressure ridge over the Gulf of Alaska. This pattern is likely to be induced by western tropical Pacific SST through atmospheric teleconnection.

(2) The Baja pattern appeared from May 2014 to present, intensified and expanded in summer 2015. This pattern started as near surface warming, and evolved into deeper warming. There was also record number of ETP tropical storms/hurricanes, which tended to hug the coast rather than to propagate to the northwest. The Baja warming pattern is likely to be induced by atmospheric forcing through weaker northeast trade winds and reduced latent heat flux. Coastally trapped Kelvin waves originating from the tropics may also influence the nearshore region.

(3) The NE Pacific Arc/PDO pattern emerged in fall 2014. Atmospheric forcing had a major influence on the broad SST warming pattern; meanwhile, variations in coastal upwelling plays a major role in the local/regional effects. It may play an important role for atmospheric teleconnection. It is noted that the variations in SST anomalies in the Gulf of Alaska correlate with the variations in SST anomalies of California Current System with a lead of 12 months.

(4) Bering Sea experienced two consecutive warm years recently: 2014 and 2015. In contrast, a persistent cold period occurred in the Bering Sea beforehand. The intense warming in the Bering Sea has had large impacts on the ecosystem.

A variety of indices (e.g., PDO, NPGO, PNA) have been used characterize the variability of the atmosphere-ocean system in the North Pacific. The recent warm event illustrates that no single index is adequate for this purpose

Recommendations on Needs for Future Work

Recommendations focused on knowledge gaps as the strongest needs. Specifically, we need better understanding of:

- the causes and impacts of Bering Sea warming
- connections between the recent Pacific anomalies to global warming
- the causes and effects of salinity anomalies
- the hemispheric connections (e.g. with the North Atlantic) and interhemispheric patterns (warm blob in South Pacific)
- the relative merits of Tropical Pacific observations such as the TAO array versus Argo floats over a broader area
- the driving mechanism of the NE Pacific Arc/PDO pattern, in particular, the relative roles of direct atmospheric forcing, horizontal advection and vertical mixing.
- the cause for persistence in atmospheric forcing in the North Pacific
- the stability or evolution of high-variance regions in the North Pacific. Are blob variations important in the future and in the past?
- the role of the Arctic in terms of forcing mid-latitude atmospheric circulation anomalies
- the atmospheric sensitivity to SST anomalies in the Kuroshio-Oyashio Extension region
- extratropical/subtropical influences on the tropics
- sources of predictability of on time scales of months to years

Open Ocean-Coastal Interactions

Hally B. Stone and Miguel Jimenez Urias

The regional circulation along the West Coast of the United States is mostly wind driven, with wind blowing south along the coast promoting upwelling favorable conditions near the shore. In addition, there exists a persistent subsurface counter-current flowing poleward along the coast. The recent effects of anomalous surface warming in the Pacific Ocean, otherwise known as the "warm blob", can be split into two sub-regions of the West Coast: the Northern California Current System (north of Cape Mendocino; including the Pacific Northwest) and the Southern California Current System (south of Cape Mendocino; including Baja, Mexico). Based on observations, there were likely two regions of anomalous warming during the 2014-2015 reign of the so-called "warm blob" or more properly termed "marine heat waves," each associated with the circulation regimes described above: A northern "blob" that originated offshore north of Cape Mendocino that moved inshore, and a southern warm anomaly that occurred separately over a wide area off southern California. Further differences between 2014 and 2015 that bring added dynamical complexity to the regional dynamics include the onset of El Niño conditions in 2015 and the change in sign of the Pacific Decadal Oscillation from 2014 to 2015.

In the North California Current System (NCCS), observations suggest that the "warm blob" (anomalous warm water) originated offshore, due to strong and persistent solar input. In contrast, the near-shore experienced colder waters coming from deep. Though the timing of the intrusion of warm water onshore varied geographically within the NCCS, on average, warmer temperatures were measured near the coast in late 2014. This picture suggests a mechanism where the "warm blob" was able to move onshore during periods of reduced wind strength (relaxation of upwelling-favorable winds), with this movement onshore evident in the temperature field. The temperature record seems to agree well with this mechanism during 2014, but there is less agreement during 2015 where near-shore warming began during upwelling-favorable conditions. Additionally, zooplankton (copepods) collected during this time were unusual and thought to be species usually found offshore, supporting the idea that the warm anomaly advected from offshore rather than poleward along the coast.

In the Southern California Current System (SCCS), anomalous surface warming started at the beginning of 2014, and with the onset of El Niño conditions in 2015, this surface warming extended into the subsurface. During this time period, there seem to have been slightly anomalously higher surface heat fluxes in the region. While some indications exist of lower overall wind magnitudes, upwelling-favorable alongshore winds near the coast continued with approximately their normal strength, suggesting near-normal upwelling intensity. Anomalous poleward currents are found on the shelf and the slope. This is consistent with unusual poleward advection of biota, since those observed off Southern California at this time originate largely from further south near Baja, Mexico. Questions into the extent of this geostrophic current and the dynamical regime controlling such current are not entirely known.

Recommendations on Needs for Future Work

The collection of efforts needed in order to tackle important questions regarding our understanding of "blob" dynamics includes the need for more observations and modeling, as well as knowledge needs regarding simple questions or specific patterns and integrated studies focusing on big picture ideas and questions.

Observational:

- Additional moorings and gliders to adequately define regional variation:
  - It is important that observational tools are in place before onset of abnormal conditions and are sustained year-round.
  - Also important for driving regional models via boundary conditions.
- Winter observations: Do winter conditions precondition blob dynamics?
- Subsurface observations, especially on moorings, to define and understand vertical density stratification and mixing, advection, and biogeochemical properties.
- Zooplankton observations:
  - Zooplankton are not just important for understanding community shifts, but are also bio-indicators of coastal dynamics.
  - Explore whether zooplankton observations can be put on moorings to enhance understanding of bio-physical connections.
- Surface heat flux: Need to capture surface heat input correctly to capture the mechanisms driving the blob. Need high accuracy, since small changes accumulate over months.

Ideas for regional study (non-integrated)

- Need a study contrasting offshore-onshore dynamics (open vs coastal ocean).
- Understand wind-stress upwelling/downwelling changes during the warm anomaly.
- Need to contrast along-shore vs across-shore dynamics.
- Understand differences between 2014-15:
  - Was the blob different during El Nino event?
  - Does the change in sign of PDO matter?
- Understand dynamics of how high nitrate translates to hypoxia
- Assess frequency of relaxation events (upwelling system, accumulation of warm water offshore and to the south, then shut down winds):
  - Was there a difference between 2014-15?
    - From high frequency, such as via daily buoy data.
  - From models: Is there a latitudinal difference? What about past years?
    - Possible outcome: Different stratification from Baja to PNW.

Integrated (Unifying) problems

- Better understand winter preconditioning.
- Better resolve freshwater influences.
- Can we infer from integrated biological responses something about the large-scale physics?
  - Presence of different zooplankton species than normally found in regions.
- Resolve influence of source water variability.
- Differentiate between mechanisms that cause the blob and the blob's effects.

Ecosystem

Lingbo Li and Kathryn O'Brien Beaumont

Ecosystem effects from the 2013-2016 Warm Anomalies in the North Pacific

Across the coast of western North America, researchers have seen many different biotic response patterns to the warm anomalies. Current observed ecosystem responses range from increased or decreased phytoplankton and increased rockfish recruitment to copepod community shifts to seabird die-offs. However, the pathways of these biotic responses are not yet well understood.

Further work needs to be done addressing broader trends such as shifts in phenology, species distribution, abundance, community structure, mortality, and transport. Both bottom-up and top-down mechanisms should be considered. Current work should focus on summarizing observations and identifying mechanisms. Modelers should make predictions about ecosystem changes currently ongoing so we can later compare predictions to data.

Diverse data are still being collected while the ecosystems recover from the effects of the anomalous conditions. However, we have significant gaps in our data collection particularly during the wintertime. In order to improve event response by both managers and scientists more time series need to be consistently sampled. The anomalies were short-term acute perturbations, so ecosystem responses to them may not fully capture the possibility for gradual adaptation that ecosystems have to long-term global warming trends. However, some responses may be comparable to those observed during El Niño events.

Summary of observations sorted by trophic level:

- Phytoplankton
  - Increased chlorophyll in most northern regions
  - Decreased chlorophyll in southern California
  - Species composition changed in multiple regions: e.g., a shift towards pennate diatoms observed in Gulf of Alaska
- Harmful Algae Blooms (HABs)
  - Strong HABs in Northern California Current System during 2015, with major impacts to crab fisheries & the food web
- Mesozooplankton
  - Community shift towards warm water species for copepods in most regions
  - Euphausiid community shifted towards warm water species in California
  - Offshore copepod species identified inshore in California & Washington
- Fish
  - Very variable by region and species: good rockfish recruitment in California; a decline in age-0 pollock in Gulf of Alaska; and an increase in age-1 Pacific hake in west coast British Columbia.
- Birds / mammals
  - Regionally variable die offs in both birds and sea lions
  - Murres and Cassin's Auklets died in multiple regions
- Viruses / disease
  - Sea star wasting disease reached Gulf of Alaska in 2015, not present in 2014

Recommendations on Needs for Future Work

There are many gaps in our current knowledge:

- Few wintertime data are currently collected in regions outside Southern and Central California
- Mostly there are inconsistent time series, meaning comparability is low
- Pelagic seabird distributions are undersampled, particularly offshore in the north
- Nutrients, viruses, microplankton, benthic fauna, forage fish are undersampled in some regions
- Data on many fundamental rates / processes for various organisms are lacking
    - For example: respiration vs. temperature functions for different species of plankton

What is needed to address these gaps:

- Better understanding of ecosystem recovery and pathways of biotic responses
- Increased winter time sampling
    - At a minimum, emphasize for moorings
    - Physical data on currents and advection needed to inform transport
    - Winter zooplankton and fish surveys needed in more regions
- Specifically, we are data poor with respect to:
    - Nutrients
    - Viruses / Disease ecology
    - Microplankton
    - Benthic fauna
    - Forage fish (e.g., sandlance)
    - Pelagic seabirds
- Data on fundamental rates / processes, e.g., respiration
- More consistency in terms of time series data
    - Particularly need more time series in Washington
    - Standardized portal to enter biological survey data, accessible by all organizations
- Better data & sampling standardization
    - Standardize fish body condition measurements
    - Standardize sampling methods for comparability across CCS
- More, and accessibility to, large marine ecosystem models
- Synthesis efforts to produce summary papers
    - Synthesize observations to date
    - Use these to elucidate possible mechanisms of responses
- Shared knowledge of vessels of opportunity to maximize usage
- More communication with fisheries and ecosystem managers to exchange observations and better understand needs.
- More interdisciplinary and inter-organizational collaboration to focus on the many factors affecting biological response. Many perspectives are needed; this requires breaking through institutional and disciplinary silos.