Lasting impacts?

In summary, the Blob had major effects beyond just temperature. In the open ocean, the Blob could have altered some portions of the Central Pacific from a sink to a source for carbon to the atmosphere. In coastal regions, the Blob brought warm, high oxygen, low carbon water to the CCS and the GOA. Ecosystems shifted northwards from the equatorial regions and harmful algae dominated the massive plankton bloom that erupted on the coast. The source of the nutrients that fueled that plankton bloom is the subject of current research. While observations of high nutrients on the shelf were made in 2015, these results are inconsistent with the oxygen and carbon signals.

As the 2015-16 El Niño began to influence the Pacific, the Blob's influence was reduced (see Amaya et al., this issue). It is not clear, yet, whether the ocean biogeochemistry and ecosystem will also return to a relatively more "normal" state or if the Blob's impacts will continue to influence the Pacific post mortem. Only time and observations will tell.

References

Bond, N. A., M. F. Cronin, H. Freeland, and N. Mantua, 2015: Causes and impacts of the 2014 warm anomaly in the Pacific. *Geophys. Res. Lett*., **42**, 3414–3420, doi:10.1002/2015GL063306.

Cosca, C. E., R. A. Feely, S.R . Alin, 2016: Data management and preservation of underway pCO2 observations from VOS ships. ASLO Ocean Sciences Meeting, 2016 New Orleans.

Feely, R. A., C. L. Sabine, J. M. Hernandez-Ayon, D. Ianson, and B. Hales, 2008: Evidence for upwelling of corrosive "acidified" water onto the continental shelf. *Science*, **320**, doi:10.1126/science.1155676.

Leising, A. W., and Coauthors, 2015: State of the California Current 2014-15: Impacts of the warm-water "Blob." CalCOFI Rep., **56**, 31-68, http://www.calcofi.org/publications/calcofireports/v56/Vol56-SOTCC.web.31-69.pdf.

National Marine Fisheries Service, 2014: Fisheries economics of the United States, 2012. U.S. Dept. Commerce, NOAA Tech. Memo. NMFS-F/SPO-137, 175p., https://www.st.nmfs.noaa.gov/st5/publication/index.html.

Peterson, W., M. Robert, and N. Bond, 2015: The warm blob continues to dominate the ecosystem of the northern California Current. PICES Press, **23**, 44-46, https://www.pices.int/publications/pices_press/volume23/PPJuly2015.pdf.

Peterson, W., N. Bond and M. Robert, 2016: The Blob (Part Three): Going, going, gone?. PICES Press, **24**, 46-48, https://www.pices.int/publications/pices_press/volume24/PPJan2016.pdf.

Waldbusser, G. G., B. Hales, C. J. Langdon, B. A. Haley, P.Scrader, E. L. Brunner, M. W. Gray, C. A. Miller, and I. Gimenez, 2015: Saturation-state sensitivity of marnine bivalve larvae to ocean acidification, *Nat. Climate Change*, **5**, 273–280, doi:10.1038/nclimate2479.

Climate interpretation of the North Pacific marine heatwave of 2013-2015

Emanuele Di Lorenzo[1], Giovanni Liguori[1], and Nathan Mantua[2]

[1]Georgia Institute of Technology
[2]National Marine Fisheries Service, NOAA

The prolonged and record-breaking warming of the Northeast Pacific Ocean between the winters of 2013/14 and 2014/15, also referred to as the "Warm Blob" or more generally as a marine heatwave (Hobday et al. 2016), had extreme impacts on marine ecosystems, some of which are ongoing (see Siedlecki et al. this issue). Whether these multi-year climate extremes will become more frequent under greenhouse forcing is a key question for scientists, resource managers, and society. Here we interpret the forcing, persistence, and evolution of the warm blob in the context of the large-scale climate dynamics of the Pacific Ocean. After identifying these dynamics, we explore the warm blob mechanisms in the Community Earth System Model Large Ensemble (CESM-LE) to quantify how and if the climate variance of the North Pacific is impacted by greenhouse forcing.

Relationship between the Warm Blob patterns and Pacific climate modes

It has been previously noted that the spatial pattern of the warm blob evolved in space and time from the winter of 2014 to the winter of 2015, here defined as the January-February-March (JFM) mean (see Amaya et al. this issue). While in JFM of 2014, the warm water mass is centered in the Gulf of Alaska (GOA), in the following winter of 2015 the warm waters spreads along the entire Pacific coast of North America to form the so called ARC pattern. These two types of patterns are recurrent in the Northeast Pacific and captured by the two dominant modes of winter sea surface temperature anomalies (SSTa) inferred by an Empirical Orthogonal Function (EOF) analysis (Figure 1a and 1b). If we compare the timeseries of the winter SSTa values averaged in the center of the GOA pattern (see Amaya et al. this issue) with the timeseries of EOF2, referred to as the second Principal Components (PC2), we find a correlation of R=0.95 and a clear maximum in 2014 (Figure 1c). The same is true if we compare with EOF2/PC2 (Figure 1d). Both the GOA and ARC pattern that emerge in the wintertime SSTa EOFs are connected to well known modes of climate variability such as the North Pacific Gyre Oscillation (NPGO, Di Lorenzo et al. 2008) and the Pacific Decadal Oscillation (PDO, Mantua et al. 1997). Specifically, the GOA pattern is connected to NPGO-like variability (R=0.71, Figure 1c), while the ARC pattern tracks PDO-like variability (R=0.75, Figure 1d). The NPGO and PDO are ocean expressions of atmospheric forcing associated with changes in the North Pacific Oscillation (NPO) and in the strength and location of the Aleutian Low (AL; Di Lorenzo et al. 2008; Chhak et al., 2009). Consistent with this view, it has been shown that in 2014 the GOA pattern was forced by atmospheric variability typical of the NPO (Bond et al. 2015; Wang et al. 2014; Hartman 2015; Seager et al. 2015;

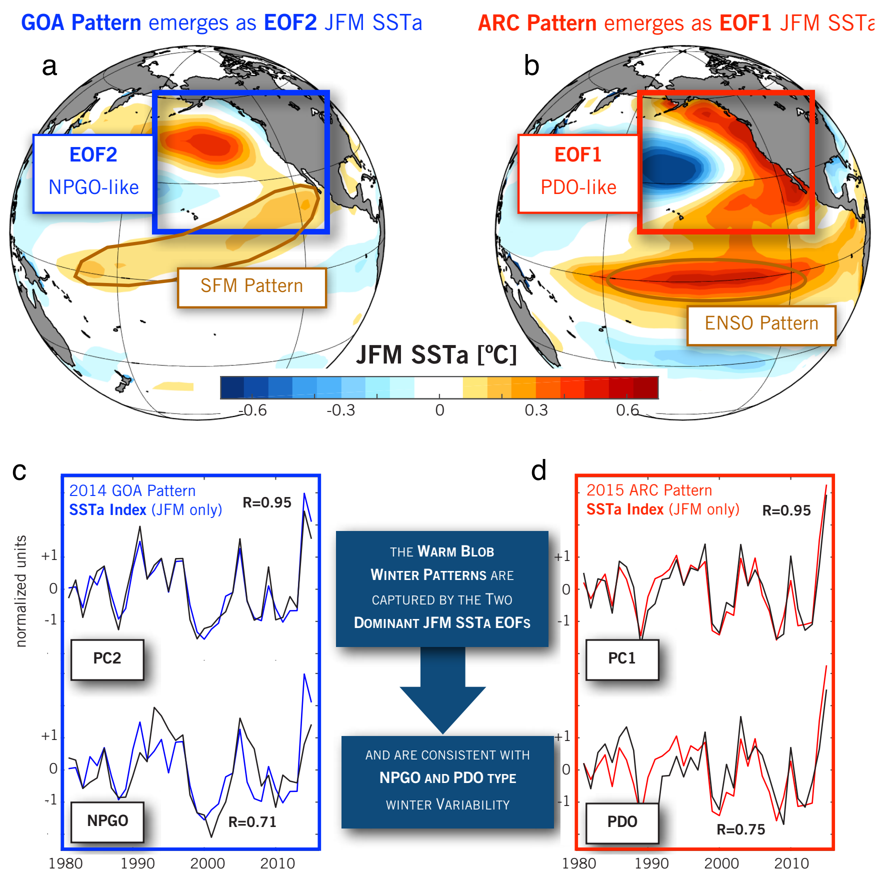

Figure 1: Relationship of Warm Blob Patterns to Dominant EOFs. Dominant patterns of winter (JFM) SSTa (°C) variability in the Northeast Pacific inferred from Empirical Orthogonal Functions (EOFs; are computed over the region outlined by the blue and red bounding boxes, the principal components are then regressed on Pacific JFM SSTa). (**a**) EOF2 and (**b**) EOF1 capture the GOA and ARC patterns observed in the evolution of the Warm Blob from JFM 2014 to JFM 2015. (**c**) The timeseries of the GOA SSTa pattern are strongly correlated to PC2 and exhibit an NPGO-like variability. (**d**) The timeseries of the ARC SSTa pattern are strongly correlated to PC1 and exhibit an NPGO-like variability. EOF1 and EOF2 explain ~60% and ~22% of the winter SSTa variance. [*Figure redrawn from Di Lorenzo and Mantua 2016*]

Anderson et al. 2016; Baxter and Nigam 2015), while in 2015 a stronger AL forced the ARC pattern (Di Lorenzo and Mantua 2016). This result is recovered by a simple correlation of the JFM SSTa PC2 (GOA pattern) and PC1 (ARC pattern) with sea level pressure anomalies (SLPa; Figure 2a and 2b). The SLPa correlation patterns show the typical dipole structure of the NPO (Figure 2a) as the forcing of the GOA pattern and a deeper AL (Figure 2b) as the forcing of the GOA pattern.

Climate mechanisms underlying the evolution and persistence of the Warm Blob

The close similarity of the ocean and atmosphere patterns of the warm blob in 2014 and 2015 with known modes of climate variability (e.g., NPO/NPGO in 2014, AL/PDO in 2015) allows us to use previous knowledge of large-scale Pacific climate dynamics to interpret the forcing, evolution, and persistence of the blob. In 2014, the winter NPO-like atmospheric forcing of the GOA SSTa pattern (Figure 2a) is connected to well-known El Niño precursor dynamics referred to as the seasonal footprinting mechanisms (SFM, Vimont et al. 2003). Specifically, the subtropical expression of the NPO (e.g., around Hawaii, SFM region in Figure 2a) causes a reduction of the trade winds, which in turn reduces evaporation and generates warm SSTa, as evident in the JFM SSTa EOF2 (Figure 1a, SFM region). This coupling between the ocean and atmosphere creates a positive feedback between winds-evaporation-SST (Xie et al. 1999), which energizes the so-called “meridional modes” (Chiang and Vimont 2004; Vimont 2010). The meridional modes propagate and amplify the SSTa in the spring from the subtropics into the central equatorial Pacific. Once these positive SSTa arrive at the equator, they favor the development of the El Niño Southern Oscillation (ENSO) (Alexander et al. 2010). Once El Niño variability begins to peak in the fall, the re-arrangement of tropical convection excites atmospheric ENSO teleconnections that inject variance into the extratropical atmosphere, which ultimately impacts the AL variability in the next boreal winter (Alexander et al. 2002). It is the changes in the AL that drive the oceanic PDO-type expression in winter SSTa (Figure 1b; Newman et al. 2003; Schneider and Cornuelle 2005). This succession of events, which is summarized in Figure 3 in the context of the 2014/15 warm blob evolution (Steps 1, 2, 3, and 4), is shown to be an important source of the persistence and reinforcement of the blob ARC pattern in the winter of 2015 (Di Lorenzo and Mantua 2016). Although the El Niño expression in the fall of 2014 (Figure 3) appears weak, the ENSO teleconnections still account for ~50% of the ARC warming pattern of 2015 (Di Lorenzo and Mantua 2016). Other research also strongly suggests that teleconnections from the tropics to the extratropics contributed to the exceptional persistence of the NPO-type variability in 2014 (Hartmann 2015; Seager et al. 2015). These teleconnection dynamics, from extratropics (winter year 0) to tropics to extratropics (winter year +1), have been shown to be important mechanisms and memory for generating Pacific decadal and multi-decadal variability (Di Lorenzo et al. 2015), and are here recognized as potential mechanisms for the multi-year persistence and evolution of SSTa ocean extremes in the Northeast Pacific.

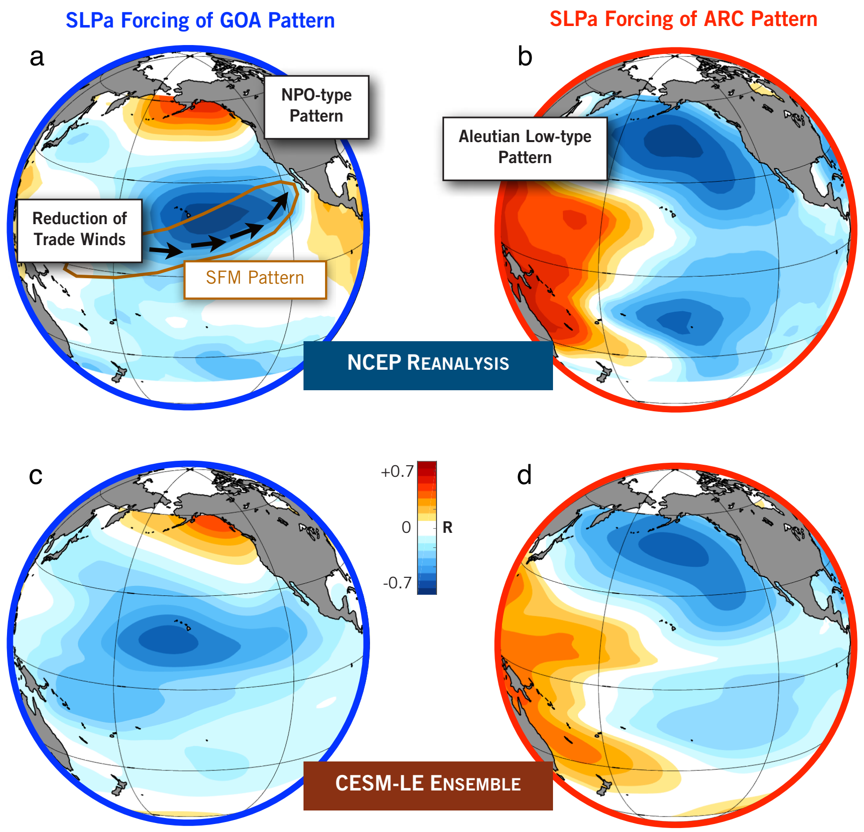

Figure 2: Atmospheric Forcing of Warm Blob Patterns. Correlation of JFM SSTa PCs in the Northeast Pacific with SLPa. PC2 and PC1 track the GOA (a) and ARC (b) patterns in the SSTa and are used to extract the corresponding patterns of atmospheric forcing. The same analysis is conducted on the Community Earth System Model Large Ensemble (CESM-LE, 30 members). The ensemble mean patterns are show in (c) for CESM-LE PC2 and in (d) for CESM-LE PC1.

Changes in variance of the Warm Blob patterns under greenhouse forcing

Previous studies have suggested that the NPO-type variability that initiated the drought in 2014 will intensify in response to greenhouse forcing (Wang et al. 2015; 2015; Yoon et al. 2015; Sydeman et al. 2013). This suggests that the oceanic expression of the NPO, that is the GOA/NPGO-like pattern, will also increase in variance. Unfortunately current observations are not sufficient to test if the North Pacific variance has increased. In fact, Johnstone and Mantua (2014) suggest that observed SST variations and trends in the Northeast Pacific from 1900-2012 are largely a response to atmospheric forcing that shows no robust century-scale trends in CMIP5 historical forcing experiments and that instead may be one phase in the slow (~10 year) progression of atmospheric pressures around the North Pacific (Anderson et al. 2016).

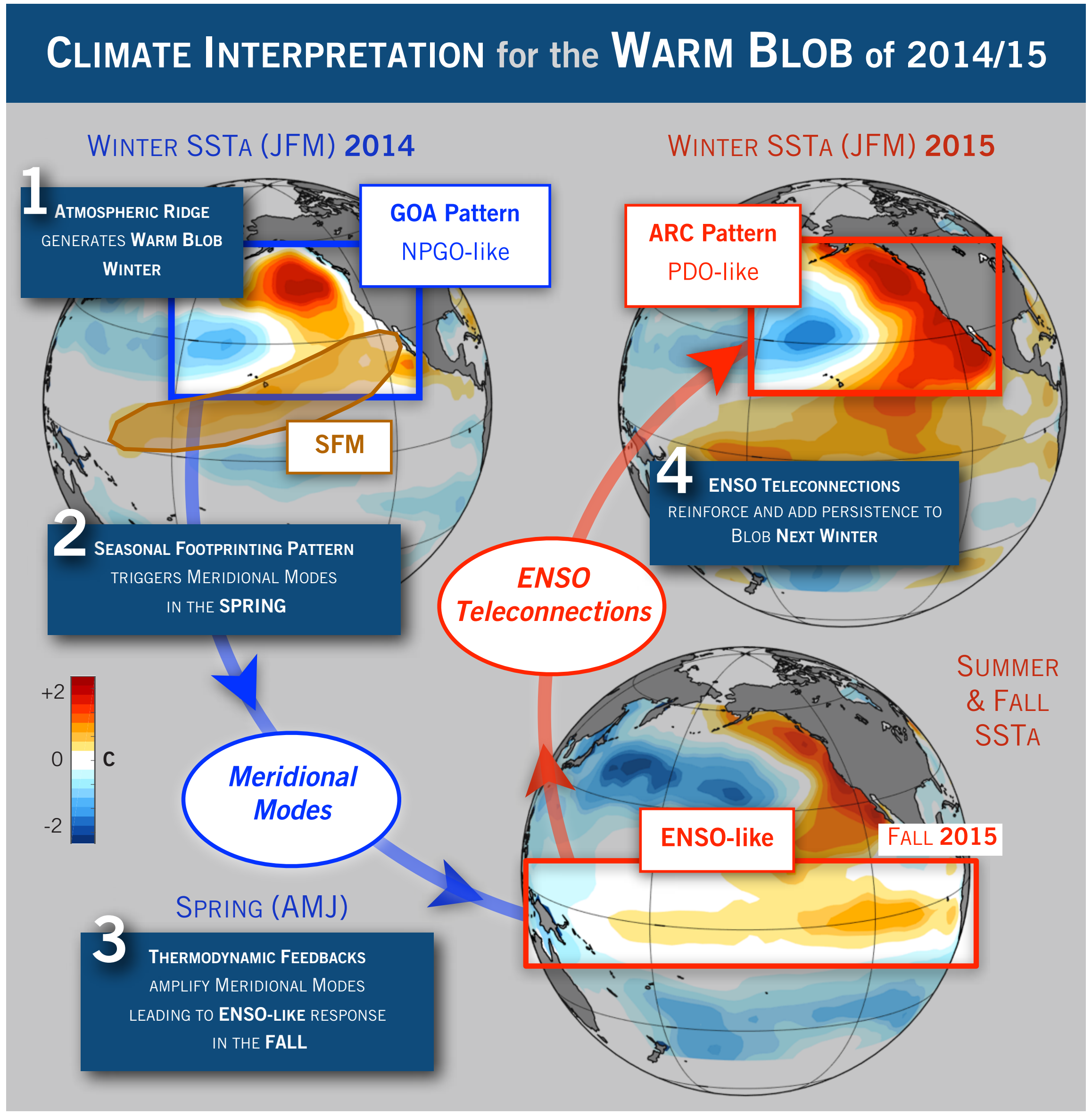

Figure 3: Schematic of SSTa (ºC) evolution associated with the warm blob from the winter of 2014 to winter of 2015 and relationship to mechanisms of large-scale climate variability.

To better separate the changes in North Pacific SSTa variance that are internal (e.g., natural) from the forced (e.g., climate change), we explore the variability of the GOA and ARC winter patterns in the Community Earth System Model Large Ensemble (CESM-LE greenhouse simulations, 30 ensemble members from 1920-2100 under the regional concentration pathway (RCP8.5) scenario (Kay et al. 2015). We extract the GOA and ARC pattern with the same approach used for the observations by computing the EOF1 and EOF2 of the JFM SSTa over the Northeast Pacific region (Figure 4a and 4b). The EOFs are computed for each of the 30 ensemble members, and then the patterns are averaged together to obtain an ensemble mean EOF structure. The CESM-LE EOFs are almost identical to the observations (compare with Figure 1a and 1b) and explain a similar amount of variance. Given the close similarity between the observations and the model simulations, we quantify the anthropogenically forced changes in the variance of the GOA and ARC patterns by computing the 20-year running variance of the CESM-LE PC2 and PC1. The ensemble mean of the running variance shows a significant trend in the GOA pattern (PC1) with an increase of ~16% from 1920 to 2100 (Figure 4c). The variance of the ARC pattern also increases but only by ~7% (Figure 4d). Given that the forcing pattern of the GOA pattern (EOF2) in the CESM-LE also captures the typical NPO structure (Figure 2c), there is strong indication that the NPO/NPGO-like variability associated with the GOA pattern may intensify under greenhouse forcing (see also Sydeman et al. 2013 for an observational analysis).

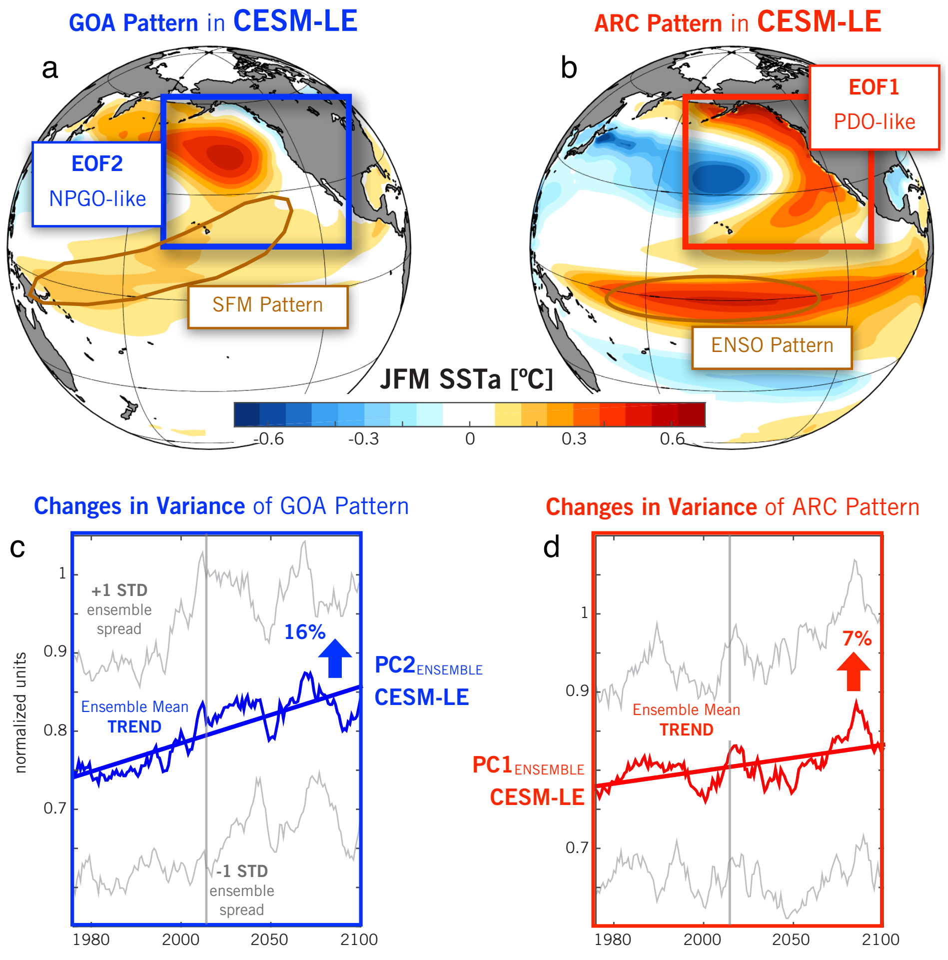

Figure 4: Warm Blob JFM Patterns under Greenhouse forcing. Dominant patterns of winter (JFM) SSTa (ºC) variability in the Northeast Pacific from the CESM-LE (blue and red bounding boxes) inferred the two dominant EOFs from 1920-2100 under the RCP8.5 greenhouse scenario. (a) EOF2 and (b) EOF1 capture the warm blob GOA and ARC patterns. The SFM and ENSO pattern in the CESM-LE are shifted to the west, a known bias of climate models. The 20-year running variance of the PCs show an increase in variance. (c) The PC2 shows an increase of 16% in the variance of the GOA SSTa pattern, while PC1 an increase in 7% of the ARC pattern. EOF1 and EOF2 explains ~67% and ~22% of the winter SSTa variance. [Figure redrawn from Di Lorenzo and Mantua 2016]

The intensification of the NPO activity is likely linked to the activity of meridional modes. Preliminary analysis of the CESM-LE (Liguori et al., personal communication) reveals that the thermodynamic coupling between ocean and atmosphere associated with the winds-evaporation-SST feedback is intensifying. This may lead not only to and enhanced variance of the NPO system, but to a stronger coupling between meridional modes and ENSO. This stronger coupling results from the propagation of larger amplitude meridional modes SST anomalies from the subtropics to the tropics, where they are more likely to trigger ENSO and its teleconnections back to the extra-tropics (e.g., multi-year memory). An intensification of the meridional modes/ENSO coupling should translate into a stronger coupling between the GOA pattern and the following year ARC pattern (e.g., multi-year warm events).

While the analyses and discussion presented in this short article lay out a set of mechanistic pathways/hypotheses to understand warm blob dynamics and the climate teleconnections that lead to multi-year persistence of ocean SSTa extremes in the Northeast Pacific, future studies will need to develop numerical experiments to test these dynamics under the uncertainties of a changing climate with a large range of natural decadal variability.

References

Alexander, M. A., I. Blade, M. Newman, J. R. Lanzante, N. C. Lau, and J. D. Scott, 2002: The atmospheric bridge: The influence of ENSO teleconnections on air-sea interaction over the global oceans. *J. Climate*, **15**, 2205-2231, doi:10.1175/1520-0442(2002)015<2205:tabtio>2.0.co;2.

Alexander, M. A., D. J. Vimont, P. Chang, and J. D. Scott, 2010: The impact of extratropical atmospheric variability on ENSO: Testing the seasonal footprinting mechanism using coupled model experiments. *J. Climate*, **23**, 2885-2901, doi:10.1175/2010jcli3205.1.

Anderson, B. T., D. J. Gianotti, J. C. Furtado, and E. Di Lorenzo, 2016: A decadal precession of atmospheric pressures over the North Pacific. *Geophys. Res. Lett.* **43,** doi:10.1002/2016GL068206.

Baxter, S., and S. Nigam (2015), Key Role of the North Pacific Oscillation-West Pacific Pattern in Generating the Extreme 2013/14 North American Winter, *J. Climate*, **28** (20), 8109-8117, doi:10.1175/jcli-d-14-00726.1.

Bond, N. A., M. F. Cronin, H. Freeland, and N. Mantua, 2015: Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophys. Res. Lett.*, **42**, 3414-3420, doi:10.1002/2015gl063306.

Chhak, K. C., E. Di Lorenzo, N. Schneider, and P. F. Cummins, 2009: Forcing of low-frequency ocean variability in the Northeast Pacific. *J. Climate*, **22**, 1255-1276, doi:10.1175/2008jcli2639.1.

Chiang, J. C. H., and D. J. Vimont, 2004: Analogous Pacific and Atlantic meridional modes of tropical atmosphere-ocean variability. *J. Climate*, **17**, 4143-4158, doi:10.1175/jcli4953.1.

Di Lorenzo, E. and N. Mantua, 2016: Multi-year persistence of the 2014/15 North Pacific marine heatwave. *Nat. Climate Change*, accepted.

Di Lorenzo, E., and Coauthors, 2008: North Pacific Gyre Oscillation links ocean climate and ecosystem change. *Geophys. Res. Lett.*, **35**, doi:10.1029/2007gl032838.

Di Lorenzo, E., G. Liguori, J. Furtado, N. Schneider, B. T. Anderson, and M. Alexander, 2015: ENSO and meridional modes: a null hypothesis for Pacific climate variability. *Geophys. Res. Lett.*, **42**, doi:10.1002/2015GL066281.

Hartmann, D. L., 2015: Pacific sea surface temperature and the winter of 2014. *Geophys. Res. Lett.*, **42**, 1894-1902, doi:10.1002/2015gl063083.

Hobday, A. J., and Coauthors, 2016: A hierarchical approach to defining marine heatwaves. *Prog. Oceanogr.*, **141**, 227-236, doi:10.1016/j.pocean.2015.12.014.

Johnstone, J. A., and N. J. Mantua, 2014: Atmospheric controls on northeast Pacific temperature trends and variations, 1900-2012. *Proc. Nat. Acad. Sci.*, **111**, 14360-14365, doi:10.1073/pnas.1318371111.

Kay, J. E., and Coauthors, 2015: The Community Earth System Model (CESM) Large Ensemble Project: A community resource for studying climate change in the presence of internal climate variability. *Bull. Amer. Meteorol. Soc.*, **96**, 1333-1349 doi:10.1175/BAMS-D-13-00255.1..

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis, 1997: A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Amer. Meteorol. Soc.*, **78,** 1069-1079, doi:10.1175/1520-0477.

Newman, M., G. P. Compo, and M. A. Alexander, 2003: ENSO-forced variability of the Pacific Decadal Oscillation. *J. Climate*, **16**, 3853-3857, doi:10.1175/1520-0442.

Schneider, N., and B. D. Cornuelle, 2005: The forcing of the Pacific Decadal Oscillation. *J. Climate*, **18**, 4355-4373, doi:10.1175/jcli3527.1.

Seager, R., M. Hoerling, S. Schubert, H. L. Wang, B. Lyon, A. Kumar, J. Nakamura, and N. Henderson, 2015: Causes of the 2011-14 California drought*. *J. Climate*, **28**, 6997-7024, doi:10.1175/jcli-d-14-00860.1.

Sydeman, W. J., J. A. Santora, S. A. Thompson, B. Marinovic, and E. Di Lorenzo, 2013: Increasing variance in North Pacific climate relates to unprecedented ecosystem variability off California. *Global Change Bio.*, **19**, 1662-1675, doi:10.1111/gcb.12165.

Vimont, D. J., 2010: Transient growth of thermodynamically coupled variations in the tropics under an equatorially symmetric mean. *J. Climate*, **23**, 5771-5789, doi:10.1175/2010jcli3532.1.

Vimont, D. J., J. M. Wallace, and D. S. Battisti, 2003: The seasonal footprinting mechanism in the Pacific: Implications for ENSO. *J. Climate*, **16**, 2668-2675, doi:10.1175/1520-0442(2003)016<2668:tsfmit>2.0.co;2.

Wang, S. Y., L. Hipps, R. R. Gillies, and J. H. Yoon, 2014: Probable causes of the abnormal ridge accompanying the 2013-2014 California drought: ENSO precursor and anthropogenic warming footprint. *Geophys. Res. Lett.*, **41**, 3220-3226, doi:10.1002/2014gl059748.

Wang, S. Y. S., W. R. Huang, and J. H. Yoon, 2015: The North American winter 'dipole' and extremes activity: a CMIP5 assessment. *Atmos. Sci. Lett.*, **16**, 338-345, doi:10.1002/asl2.565.

Xie, S. P., 1999: A dynamic ocean–atmosphere model of the tropical Atlantic decadal variability, *J. Climate*, **12,** 64–70, doi:10.1175/1520-0442-12.1.64.

Yoon, J. H., S. Y. S. Wang, R. R. Gillies, B. Kravitz, L. Hipps, and P. J. Rasch, 2015: Increasing water cycle extremes in California in relation to ENSO cycle under global warming. *Nat. Commun.*, **6**, doi:10.1038/ncomms9657.

The tale of a surprisingly cold blob in the North Atlantic

Aurélie Duchez[1], Damien Desbruyères[1], Joël J.-M. Hirschi[1], Eleanor Frajka-Williams[2], Simon Josey[1], and Dafydd Gwyn Evans[2]

[1]National Oceangraphy Centre Southampton, UK
[2]University of Southampton, UK

Climate change is usually assessed over years and decades, and 2015 shattered the record set in 2014 for the hottest year yet recorded for the globe's surface land and oceans since 1850. The year 2016 is also expected to set a new record, with the average global surface temperature in February 1.35°C warmer than the average temperature for the month between 1951-1980, a far bigger margin than ever seen before (see NASA Earth Observatory). Yet, one part of the planet is bucking the global sea surface temperature (SST) and upper ocean heat content (OHC) trends: southeast of Greenland and Iceland, the ocean surface has seen record cold temperatures for the past eight months of 2015.

The SST anomaly field for June 2015 (Figure 1a; 2a) shows temperatures up to 2°C colder than the 1948-2015 average. The coldest values observed over the central North Atlantic between 45°N and 60°N for this month of the year (indicated by stippling) encompass much of the eastern Subpolar Gyre. This cold "blob" represents a striking acceleration of a decadal drop in OHC that started in 2005 (Figure 1b). This negative trend may be marking a transition toward a new cold phase of the subpolar North Atlantic, following a persistent period of anomalously warm upper waters (1995-2014). The sharply cold feature reaches down to about 700 m depth, and opposes a warming trend in the intermediate layer (700 m – 2000 m) observed since the early 2000s (Figure 1d). The result is a cold anomaly in the surface layer, and increased stratification below.

Duchez et al. (2016) recently investigated the origin of the 2015 North Atlantic cold blob using reanalyses of observational data. As described below, a combination of air-sea heat loss from late 2014 through to spring 2015 and a re-emergent 2014 sub-surface OHC anomaly stand as the primary sources of the blob. The authors show that this cold Atlantic anomaly observed since 2014 is likely due to processes acting on sub-annual timescales. Consequently, this blob should not be confused with the long-term warming hole (located to the south-west of the 2015 anomaly) described by Rahmstorf et al. (2015) and Drijfhout et al. (2012) using numerical ocean models, which was identified on interannual and longer timescales. The long-term cold anomaly is presumably driven by a longer-term slowdown of the Atlantic Meridional Overturning Circulation (AMOC) and the associated reduction in northward oceanic heat transport. It is noteworthy that a 10-year long decline of the AMOC has been observed at 26°N by the RAPID array which has been monitoring the AMOC since 2004 (Smeed et al. 2014). Both the long-term trend as well as the seasonal to interannual variability of the AMOC can potentially impact the North Atlantic temperature (Duchez et al. 2015, Bryden et al. 2014).

Previous model and observation based studies suggest that atmospheric circulation changes can develop in