Causes and Impacts of the 2014 Warm Anomaly in the NE Pacific

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Abstract

Strongly positive temperature anomalies developed in the NE Pacific Ocean during the boreal winter of 2013-14. Based on a mixed layer temperature budget, these anomalies were caused by lower than normal rates of the loss of heat from the ocean to the atmosphere, and of relatively weak cold advection in the upper ocean. Both of these mechanisms can be attributed to an unusually strong and persistent weather pattern featuring much higher than normal sea level pressure over the waters of interest. This anomaly was the greatest observed in this region since at least the 1980s. The region of warm SST anomalies subsequently expanded and reached coastal waters in spring and summer 2014. Impacts on fisheries and regional weather are discussed. It is found that sea surface temperature anomalies in this region affect air temperatures downwind in Washington state.

Key words: SLP anomalies, warm SST, seasonal heating mechanisms, regional and downwind impacts, northeast Pacific Ocean

Key points

Anomalous atmospheric forcing in the NE Pacific in winter 2013-14

Weak seasonal cooling due to reduced heat fluxes and anomalous advection

SST anomalies have impacts on the ecosystem and air temperatures

1. Introduction

Offshore sea surface temperatures (SSTs) in the NE Pacific were remarkably warm during the winter of 2013-2014. By February 2014, peak temperature anomalies of the near-surface (upper ~100 m) waters were greater than 2.5°C (Figs. 1a-c), while temperature anomalies were below normal in the immediate vicinity of the coast. The largest anomalies exceeded 3 standard deviations (Fig. 1c and Fig. S1), and were the greatest observed in this region for the month of February since at least the 1980s and possibly as early as 1900. The warm anomaly in winter was most prominent in the south-central part of the Gulf of Alaska, but extended to the continental shelf. By May 2014 the region of anomalously warm SST extended into the coastal zone, and anomalously warm SSTs persisted throughout the NE Pacific Ocean through March 2015. In recognition of its extensive and extraordinary magnitude and its potential for impacting both the regional weather and fisheries, the lead author referred to the anomaly as “The Blob” in his June 3 2014 newsletter for the Office of the Washington State Climatologist, and it has since taken on this moniker in the general press.

The development of extraordinarily warm SST anomalies in winter 2014 is linked to a highly anomalous weather pattern, as characterized by the distribution of anomalous sea level pressure (SLP). During the period of October 2013 through January 2014, much higher than normal SLP was present in the mean over the eastern North Pacific (Fig 2), with a peak magnitude approaching 10 hPa. For the region of 55-45 °N, and 150-130 °W, this was a record high value for the years of 1949-2014 (about 2.6 standard deviations above normal for the period of October through January) with the next largest value being about 2.2 standardized units above normal during October 1978-January 1979. A similar pattern of anomalous SLP occurred during January through March of 2013, accompanied by anomalous warming that lasted into the summer of 2013 (Fig. 1c). Our focus here is on the winter of 2013-14 because it was so extreme, as illustrated by the time series shown in Fig. 1c.

As we will show, the unusually high SLP in the region of interest impacted the wind forced currents and wind generated mixing, as well as the surface heat loss due to the combination of evaporation, conduction, and net shortwave (solar) and infrared radiation. The objectives of the present paper are two-fold: (1) to diagnose the mechanisms that caused the wintertime warming in the NE Pacific (NEP), and (2) to examine implications of this type of anomaly for the ecosystem in the Gulf of Alaska and for seasonal weather in the Pacific Northwest.

2. Data and Methods

Our analysis of the processes responsible for the wintertime warming in the region of interest in the NE Pacific is based on data from the NCEP Global Ocean Data Assimilation System (GODAS) for the period of 1980 to early 2014, as available at http://www.esrl.noaa.gov/psd/data/gridded/data.godas.html. This system is based on the GFDL MOM.v.3 numerical ocean model with assimilation of ocean profile information from expendable bathythermographs, moored buoys and Argo profiling floats, and surface fluxes from the NCEP Reanalysis 2. For more information on GODAS see Behringer and Xue [2004] and Behringer [2007].

We consider the heating of a volume bounded by 40 °N and 50 °N, 150 °W and 135 °W, and the air-sea interface to the depth where the density is 0.03 kg m^{-3} greater than at the surface for the upper and lower boundary. The depth defined by the bottom boundary condition here is often referred to as the "mixed layer depth", above which the waters are generally mixed and similar in properties to those found at the sea surface. We use a density-based definition for the mixed layer to account for the potential effects of salinity on the stratification. The value of 0.03 kg m^{-3} is based on inspection of density profiles from GODAS for the region of interest and is consistent with a definition used by de Boyer Montegut et al. [2004]. Temperature of the water in this box can be changed due to air-sea heat exchanges across the top surface (i.e. net surface heat fluxes), heat exchanges across the east, west, north, and south sides of the box (i.e. horizontal advection), and heat exchanges across the bottom boundary (i.e. vertical advection and mixing).

3. Results

Here we use time series of 4-month (October-January) mean values for a variety of quantities for the region of 40-50 °N, 150-135 °W to put 2013-14 in historical context. From the atmospheric forcing perspective, we consider the wind speed cubed, which relates to the power delivered by the atmosphere to the ocean for turbulent mixing, and the wind stress curl, which relates to the flux of vorticity to the upper ocean (Fig. 3, top). The wind speed cubed was a record minimum during 2013-14 and the wind stress curl was negative, which has precedence but is still quite unusual. From the ocean response perspective, the deepening of the mixed layer, i.e., the change in depth from September to February, was less than any previous winter during the analysis period, and the static stability at the base of the mixed layer was a record maximum (Fig. 3, bottom). Based on the data sets considered here, the winter of 2013-14 was an extreme for the region of interest.

Further insight into development of the “blob” can be gained through consideration of winter averages of the terms in a mixed layer temperature budget (Fig. 4), using the framework of equation 2 in *Cronin et al.* [2013], but in an area-averaged versus point sense, with advection expressed as in *Lee et al.* [2004]. Local cooling of 5.5 °C from October 2013 to February 2014 was about 30% lower than the mean, and the smallest magnitude in this record extending back to 1980. The net surface heat fluxes caused about 2 °C of cooling in 2013-14 versus a normal value of about 3 °C over the 4 month period. The net effect of the heat exchange at the base of the mixed layer, often termed entrainment and here estimated as a residual, was close to normal. It bears noting that the deduced heat fluxes due to entrainment were actually weaker than normal, but the actual cooling rate associated with the fluxes across the mixed layer was typical because these fluxes were distributed over a relatively thin mixed layer. The horizontal advection term was near zero; this term generally accounts for about 1 °C cooling. The large interannual temperature anomaly thus appears to be due to a combination of anomalous advection and reduced surface heat loss.

The task now is to explain variations in the budget terms. The anomalous horizontal advection is due in part to anomalous wind-forced (“Ekman”) currents acting on the climatological upper-ocean temperature gradient. For the southern portion of the high SLP anomaly, weaker than normal winds from the west induced anomalously weak Ekman transports of colder water from the north. An additional contribution was made by a near-normal eastward component of the current acting on a pre-existing zonal gradient in the SST anomaly distribution. As shown in Figure 4, horizontal advection of heat is typically a very weak process in the NE Pacific, although it can play a role in interannual variability [Large 1996]. For the 2014 event, the anomalous advection appears to be an order one process.

The net surface heat fluxes comprise the turbulent fluxes of sensible and latent heat and the radiative (solar and infrared) fluxes. During Oct 2013-March 2014, the reduced surface heat flux out of the ocean appears to be primarily associated with the turbulent flux terms. The extremely weak surface heat losses might seem somewhat surprising as one might expect that the warm SST would cause increased surface heat losses. Instead, it appears that the anomaly in the turbulent heat fluxes can be attributed partly to the wind speeds, (Fig. 3 top), which were the lowest in the record extending back to 1980 and the 2nd lowest during the period of 1949-2014.

The influence of the shallower mixed layer depth during the fall-early winter of 2013-14 may have also meant that the momentum supplied by the surface wind stress would be that much more effective towards generating mixed layer currents. This would tend to enhance the vertical shear across the base of the mixed layer, thus maintaining typical cooling rates due to entrainment despite the weaker winds. It should be noted that the GODAS surface heat flux is anomalously positive (22 W m^{-2}) relative to the NOAA Station Papa mooring observations at 50°N, 145°W [*Cronin et al.*, 2012] in November 2013 and January–February 2014 (Fig. S2). If the GODAS fluxes were adjusted by this bias, then the residual term involving the heat flux at the base of the mixed layer would be less negative than usual, again consistent with the reduced wind speeds. The wind stress curl and hence Ekman pumping anomalies were negative, which also is consistent with relatively weak entrainment.

In summary, the near-surface temperature anomalies that exceeded 2 °C in the NE Pacific during winter 2013-2014 can be accounted for by anomalous vertical processes (air-sea heat exchanges and possibly vertical mixing across the base of the mixed layer) and oceanic horizontal advection associated with the anomalous weather pattern in the 4 month period leading up to the time of the maximum SST anomaly.

4. Biological Impacts

The region of warm SST anomalies in winter 2013-14 spread into the coastal domain of Alaska and northern British Columbia in May 2014, and then into the nearshore waters of the US Pacific Northwest in September 2014. The NE Pacific's anomalously warm water in spring, summer and fall 2014 was coincided with a variety of unusual biological events and species sightings. From the bottom-up forcing perspective, Whitney [2015] documented extremely low chlorophyll levels during the late winter/spring of 2014 in the region of the warm anomalies, presumably due to suppressed nutrient transports into the mixed layer. Examples of dramatic species range-shifts in summer and fall 2014 that have come to our attention include the following: (1) a skipjack tuna caught near the mouth of the Copper River in July (Medred, 2014), (2) ocean sunfish and a thresher shark caught in summertime surveys off the coast of SE Alaska, where distributions of juvenile salmon and pomfret were also much different than usual (Wyatt Fournier, pers. comm.), (3) a record high northern diversion rate of Fraser River sockeye salmon, i.e., the proportion of adults returning around the north versus south side of Vancouver Island, (4) rhinoceros auklets in British Columbia preying on Pacific saury (associated with sub-tropical waters) rather than sand lance (associated with sub-arctic waters) in summer (Jen Zamon, pers. comm.), (5) high catches of albacore tuna near the coast of WA and OR during summer and fall 2014, (6) juvenile pompano collected during surveys near the mouth of the Columbia River in summer (Laurie Weitkamp, pers. Comm.) and (7) widespread strandings of Velella from British Columbia to California in July and August. There was also a massive influx of dead or starving Cassin's Auklets onto PNW beaches from October through December 2014 (Opar, 2015). The list is much more illustrative than comprehensive but does suggest that the physical oceanographic conditions had substantial and widespread impacts on the ecosystem. The full ecosystem response remains to be determined but it is liable to be profound, as occurred in the California Current during a period of weak coastal upwelling in 2005 [Warm Ocean Conditions in the California Current in Spring/Summer 2005: Causes and Consequences, GRL special issue 2006].

5. Impacts on Seasonal Weather of the Pacific Northwest

The spatial extent and duration of the warm water anomalies that developed in the winter of 2013-14 suggests the potential for a regional atmospheric response. Here we examine the strength of the relationship between the SST in the area of interest and the weather in the continental Pacific Northwest, which is downwind in the prevailing sense.

Our approach consists of a comparison between the mean SST during February in the study area with the mean surface air temperature in Washington state (indicated with "WA" in Fig. 2) during the following spring months of March through May for the years of 1948-2014. A scatter plot of the relationship between these variables is shown in Figure 5; the linear correlation coefficient between them is 0.42. Similar results were found for other times of the year and for thermodynamic properties such as moist static energy in the atmospheric boundary layer, with slightly higher correlation coefficients for contemporaneous comparisons. On the other hand, the relationship between offshore SST and precipitation downstream was negligible (not shown), presumably because of the SST's lack of influence on the regional scale atmospheric circulation.

6. Final Remarks

A prominent mass of positive temperature anomalies developed in the NE Pacific Ocean during winter of 2013-14. This development can be attributed to strongly positive anomalies in SLP, which served to suppress the loss of heat from the ocean to the atmosphere, and lead to a lack of the usual cold advection in the upper ocean. The extra mixed layer heat persisted through the summer of 2014, and may have represented a significant contribution to the unusually warm summer (in some locations record high temperatures) observed in the continental Pacific Northwest. The linkage between the upper ocean temperature and downstream temperatures over the coastal region of the Pacific Northwest may provide a secondary source of predictability for seasonal weather forecasts. In particular it suggests that coupled atmosphere-ocean models such as NCEP's Coupled Forecast System (CFS) model may need to properly handle the evolution of the upper ocean in the NE Pacific because of its regional influences.

The present analysis does not focus on the cause(s) of the anomalous atmospheric forcing. A broad region extending from the North Pacific across North America is known to be subject to the effects of teleconnections from the tropical Pacific in association with El Niño -Southern Oscillation (ENSO) events, i.e., the “atmospheric bridge” [e.g., *Alexander et al.,* 2002; *Lau and Nath,* 1996]. But such an explanation fails to account for the winter of 2013-14 since ENSO was in a neutral phase. On the other hand, SST anomalies in the far-western tropical Pacific, and accompanying deep cumulus convection, appear to account for a significant portion of the anomalous circulation [Seager et al., 2014; Hartmann 2015; Lee et al. 2015] that occurred in the winters of both 2012-13 and 2013-14, with intrinsic atmospheric variability probably an additional important factor.

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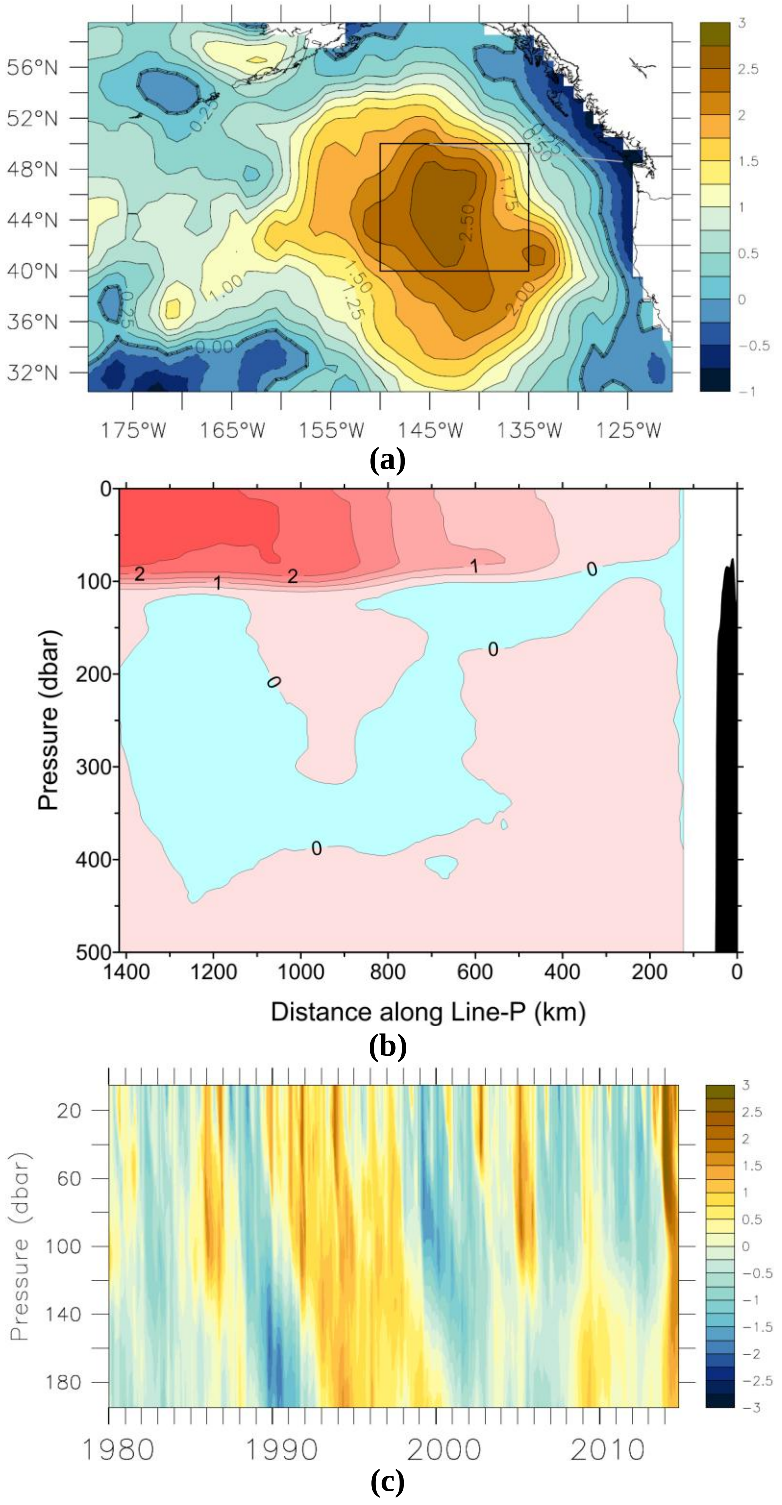

Fig. 1(a) Sea surface temperature anomalies (°C) in NE Pacific Ocean for February 2014. Anomalies are calculated relative to the mean from 1981 – 2010. **(b)** Upper ocean temperature anomalies (°C) along "Line P" (heavy gray line shown in part a) from 48° 34.5N, 125° 30.0°W to 50° 145°W for February 2014. Anomalies are relative to the mean from 1956-1991. **(c)** Monthly temperature anomalies (normalized) from the surface to 200 m averaged over the area of 50 to 40 °N, 150 to 135 °W (indicated by the box shown in part a) for the period of January 1980 through November 2014.

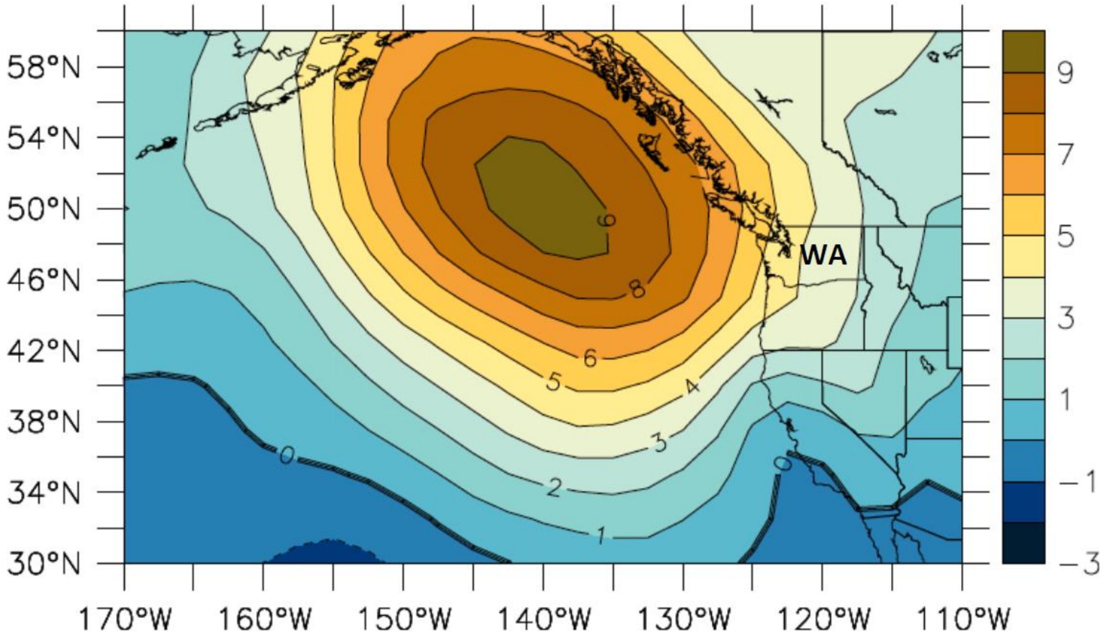

Figure 2. Mean sea level pressure anomalies (hPa) in the NE Pacific Ocean for the period of October 2013 through January 2014. Anomalies are calculated relative to the mean from 1981-2010.

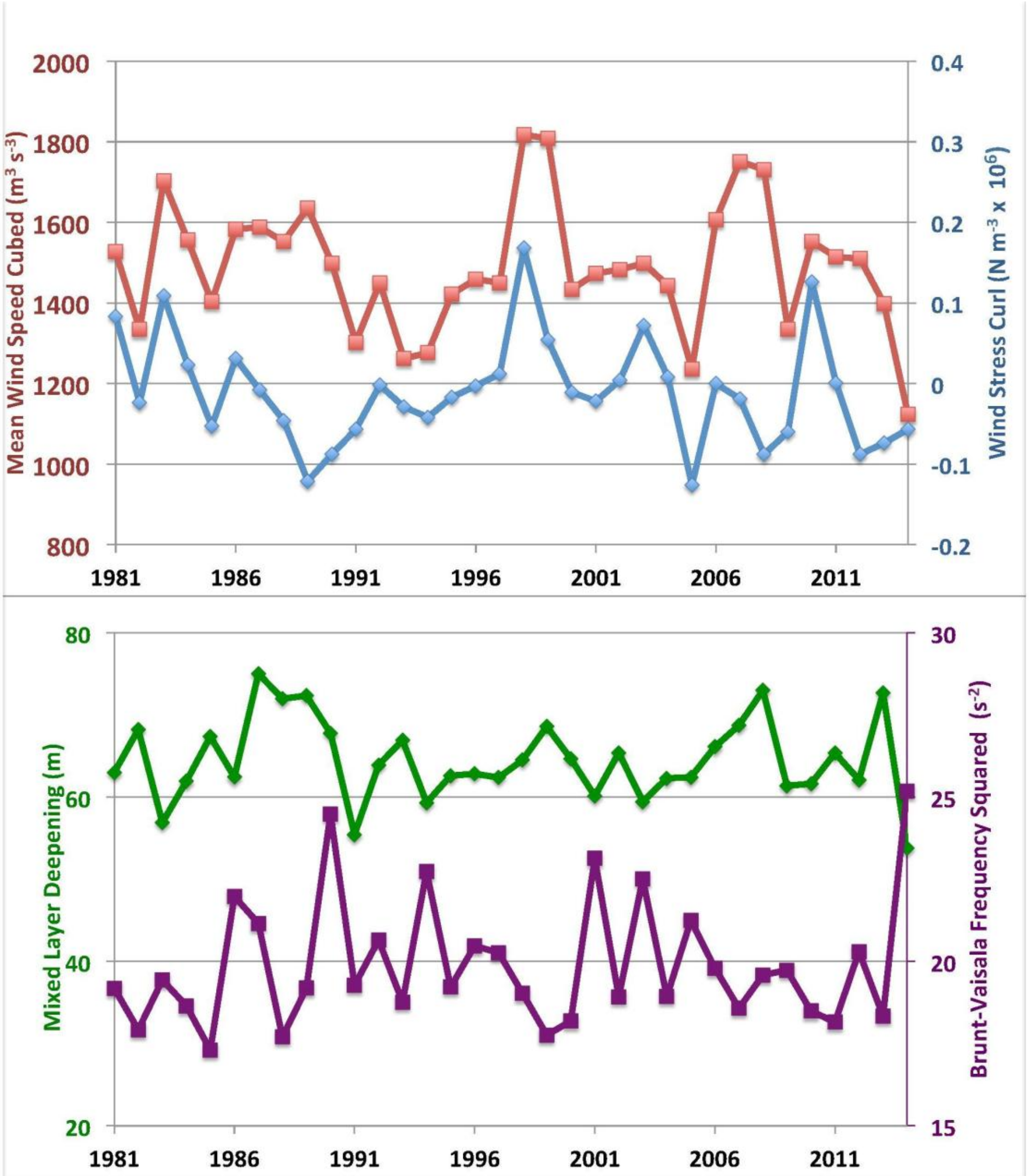

Fig. 3 (Top) Time series of seasonal mean (October-January) wind speed cubed (red) and wind stress curl (blue) for the area of 50-40 °N, 150-135 °W. **(Bottom)** Time series of mean seasonal mixed layer deepening (September to February; green) and stratification at the base of the mixed layer (February; purple) for the area of 50-40 °N, 150-135 °W. The years refer to January-February values.

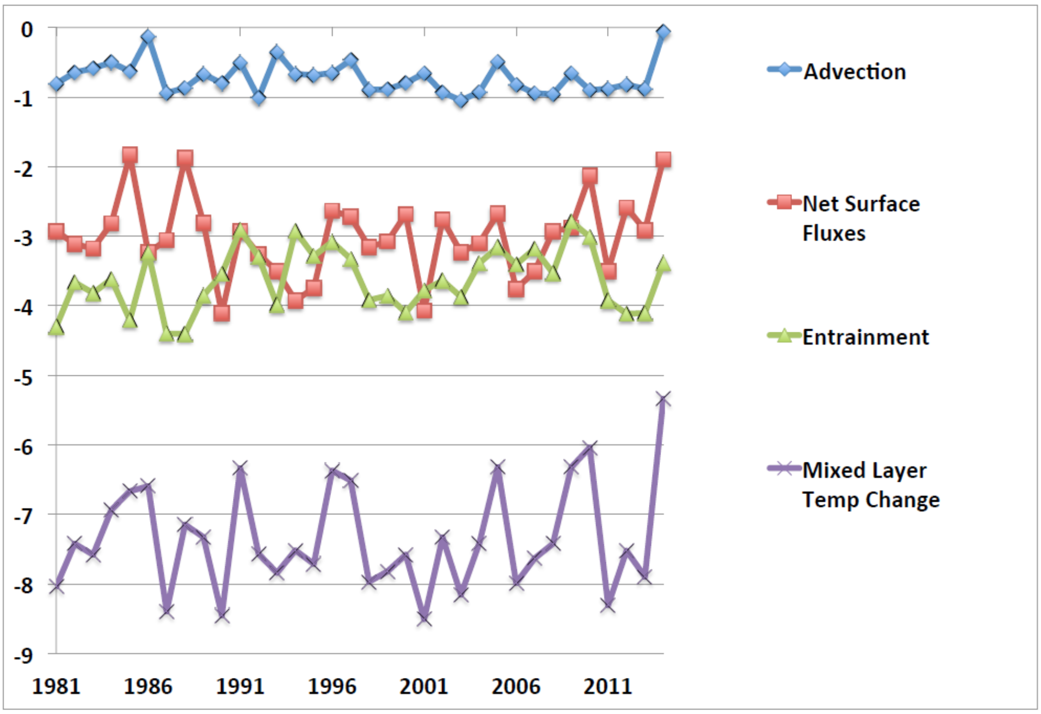

Figure 4. Seasonal values of the mixed layer temperature change from September to February for the area of 50-40 °N, 150-135 °W (°C; purple) and budget terms contributing to this temperature change. The black arrow points to the value for 2013-14. Budget terms include horizontal advection (blue), net surface heat fluxes (red) and entrainment (light green). Values represent degrees (C) of temperature change associated with the individual terms.

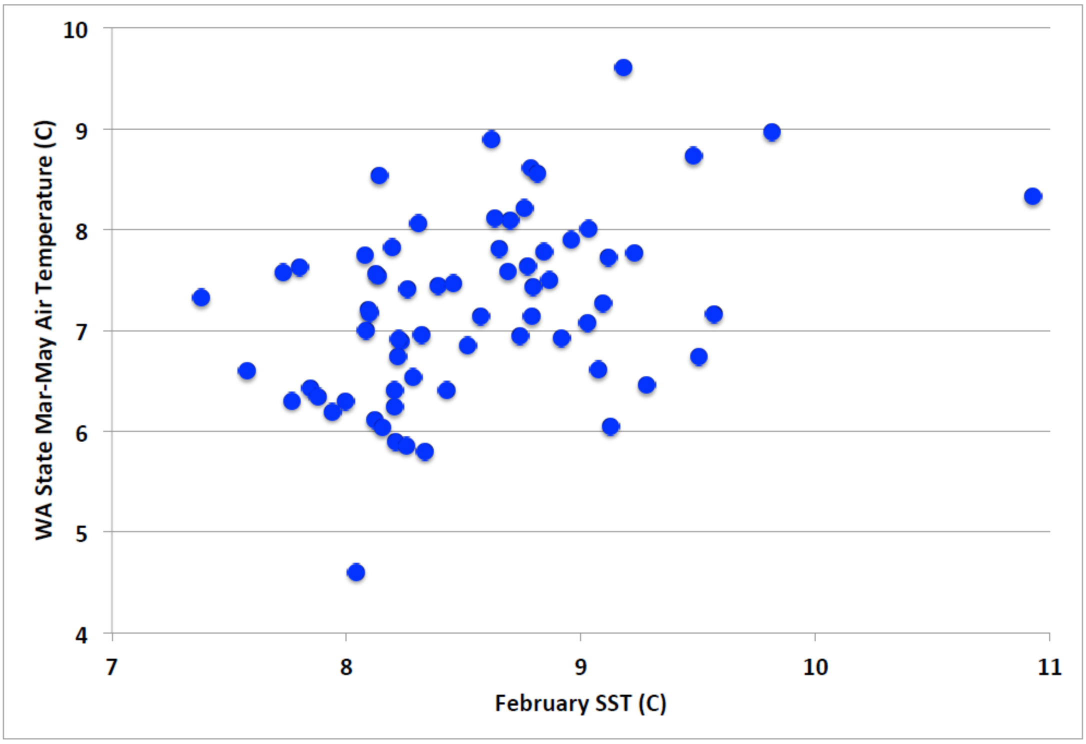

Figure 5. March-May air temperatures in Washington state (°C; y-axis) versus February sea surface temperature (°C; x-axis) averaged for the area of 50-40 °N, 150-135 °W. The year of 2014 is represented by the dot near the right-hand border of the figure.