Linking northeastern North Pacific oxygen changes to upstream surface outcrop variations

Sabine Mecking and Kyla Drushka

Applied Physics Laboratory, University of Washington, 1013 NE 40th St, Seattle, WA 98105 (mecking@uw.edu)

Introduction

The North Pacific thermocline was one of the first regions where large variations in oceanic O_2 concentrations were observed and linked to ventilation changes (Andreev and Kusakabe, 2001; Ono et al., 2001; Watanabe et al., 2001; Emerson et al., 2004). Several mechanisms responsible for the observed variability in thermocline O_2 content have been suggested (Whitney et al., 2007; Sasano et al., 2018). Here, we investigate the hypothesis that changes in outcrop location/area of the densest outcropping isopycnals (including cessation of outcropping) may be causing O_2 variations in the thermocline downstream (Emerson et al., 2004; Mecking et al., 2008; Kwon et al., 2016).

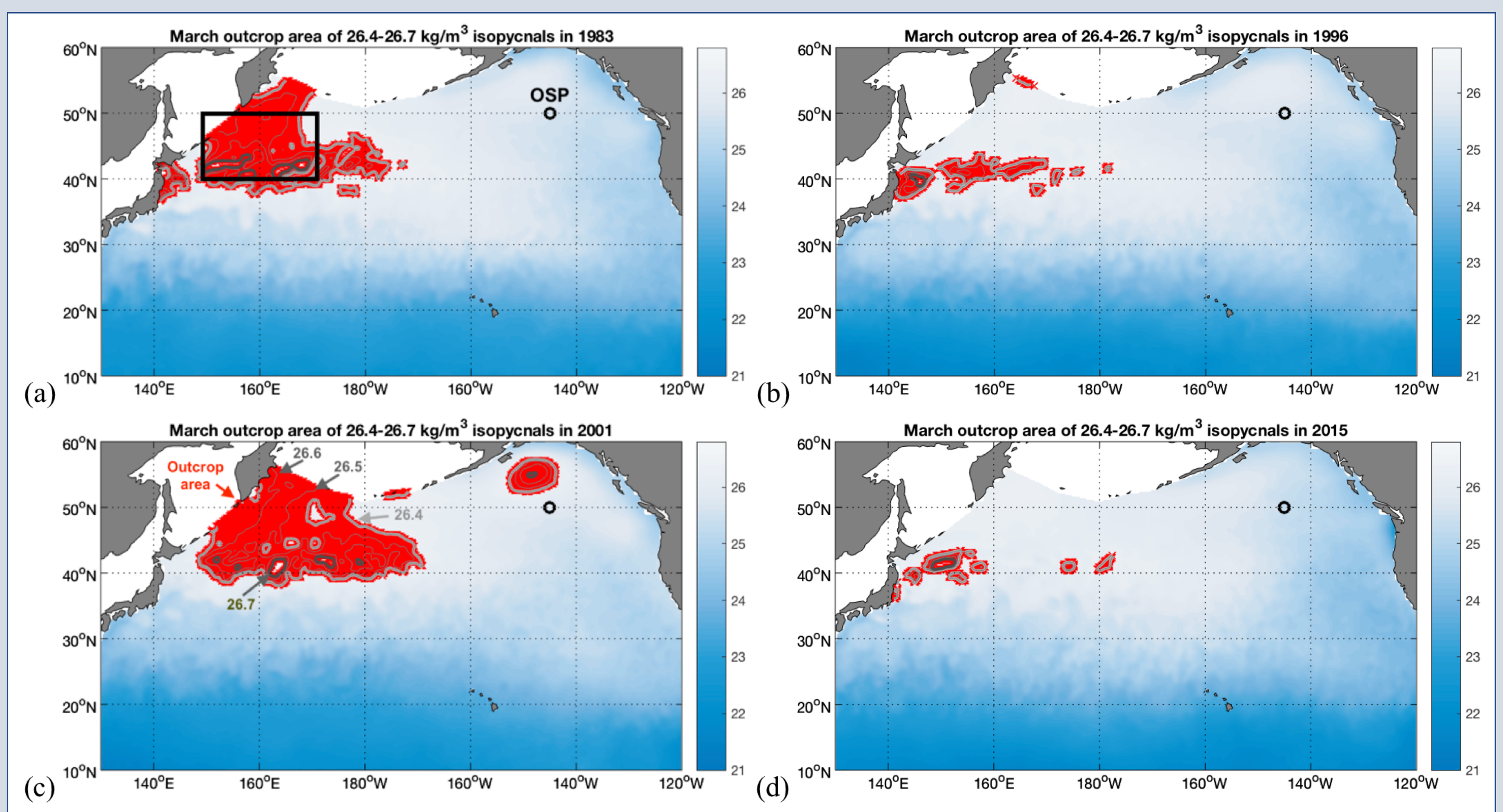

Figure 1. Examples of maxima (a, c) and minima (b, d) of March outcrop areas of the σ_θ = 26.4–26.7 kg m^{-3} isopycnal range: (a) 1983, (b) 1996, (c) 2001, and (d) 2015. Dataset used is EN4-OISST. Color shading and color bar show surface potential density anomalies (σ_θ), with anomalies in the σ_θ = 26.4–26.7 kg m^{-3} range indicated by red markers. Contour lines also show σ_θ outcrops as labeled in (c). Location of OSP (50°N, 145°W) is marked by an open black circle. Area used for northwestern North Pacific SST, SSS, and surface density averaging (Figs. 6&7) is outlined by a black box in (a).

Data

Sea surface temperature (SST), salinity (SSS), and density

– EN4: 1°x1°, similar to WOD, use T & S at 5m, 1900–2020 (Good et al., 2013)
– OISST: 1/4°x1/4°, SST from satellite & in situ, 1982–2020 (Reynolds et al., 2007)
– EN4-OISST: created from en4 SSS (interpolated to1/4°x1/4°) & OISST, 1982–2020

Oxygen (O_2) measurements in ocean interior

– Ocean Station P (OSP) timeseries: 50°N, 145°W, 1956–2020 (Whitney et al., 2007)
– *GO-SHIP repeat hydrography at 152ºW (P16), 47ºN (P1), for comparison (not shown here)*

Pacific Decadal Oscillation (PDO) Index (Mantua et al., 1997)

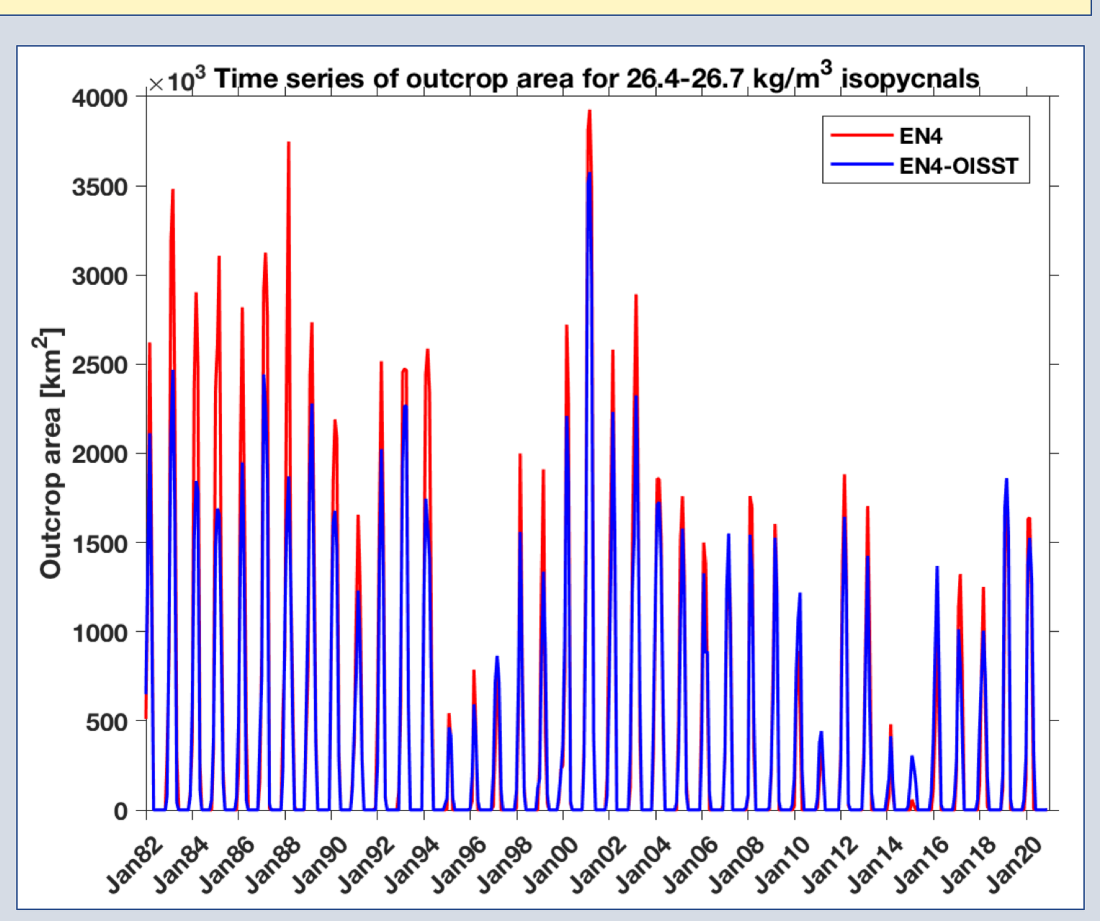

Figure 2. Time series of the surface outcrop area of the σ_θ = 26.4–26.7 kg m^{-3} isopycnal range in the North Pacific from 1982–2020. The blue line is based on surface density from the 1/4° EN4-OISST dataset, and the red line is based on surface density from the 1° EN4 dataset. The peaks in the outcrop area occur just after January (shown on the x axis) of each year, usually in March. There are distinct March minima in 1995–1997, 2011, and 2014–2015 compared to the March outcrop area in the years before and after with a distinct March maximum in 2001 in particular. Despite the 2001 maximum, the EN4 and EN4-OISST datasets both show a declining trend in the σ_θ = 26.4–26.7 kg m^{-3} outcrop area from 1982–2020.

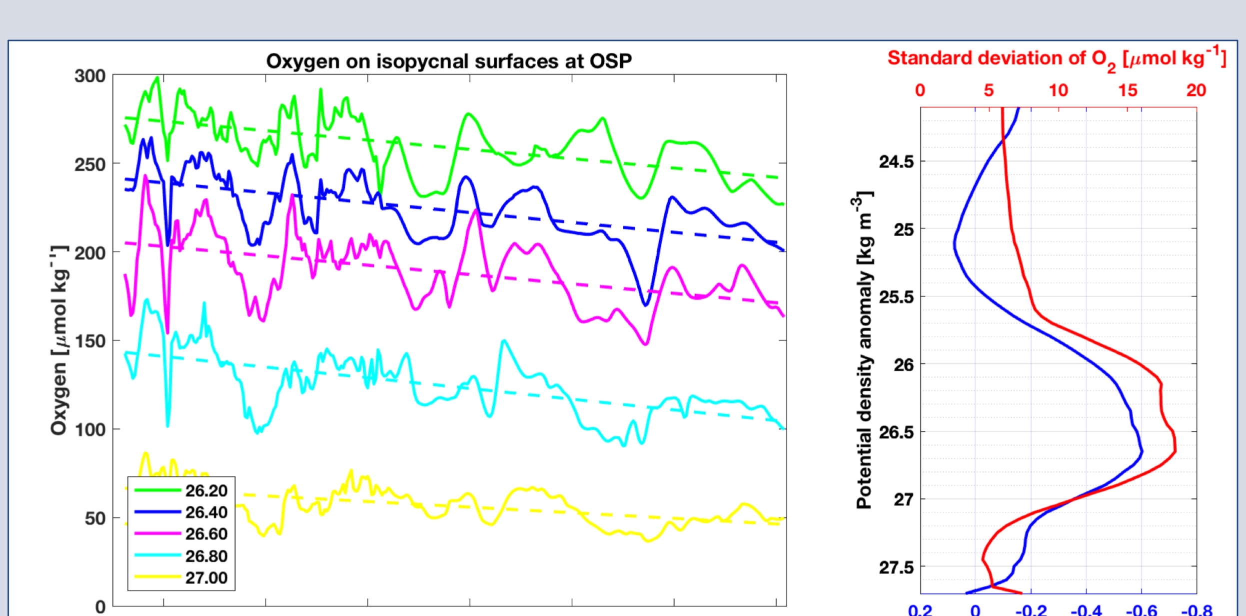

Figure 3. (a) Time series of O_2 at OSP (see location in Fig. 1) on σ_θ = 26.2–27.0 kg m^{-3}. Linear trends of O_2 on each isopycnal are shown as dashed lines. (b) Profiles of linear O_2 trends (blue) and of standard deviation of the O_2 variations (red) on isopycnals at OSP, with maxima near σ_θ = 26.6 kg m^{-3} as also found using repeat hydrography (Mecking et al. 2008). Data used are objectively mapped O_2 data at OSP. Maxima in declining O_2 trends at OSP have also been reported near this density by Whitney et al. (2007; σ_θ = 26.5 kg m^{-3}) and Crawford and Peña (2016; σ_θ = 26.7 kg m^{-3}), each using slightly different methodologies. This confirms that large decadal variations and declining trends in O_2 occur on isopycnals near the bottom of the ventilated thermocline.

Acknowledgments

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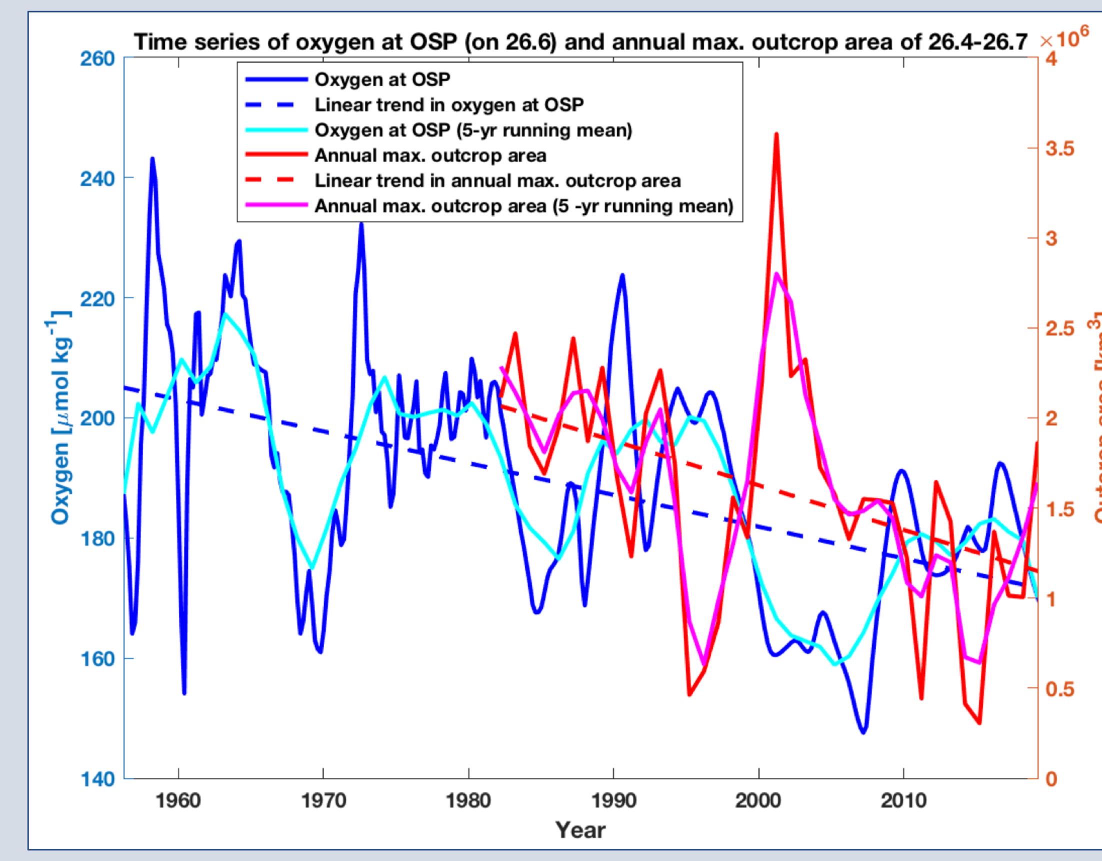
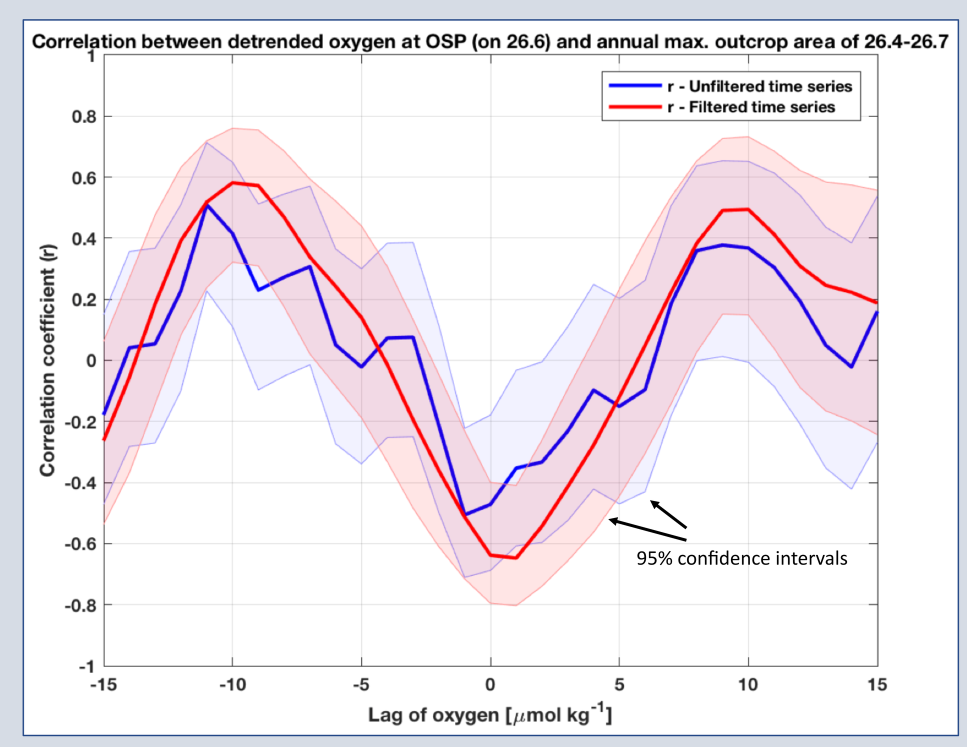
Figure 4. Time series of O_2 on σ_θ = 26.6 kg m^{-3} at OSP (solid blue line) and of annual maximum outcrop area of σ_θ = 26.4–26.7 kg m^{-3}, used as a proxy for ventilation, based on the EN4-OISST dataset (solid red lines). Also shown are the data filtered with a 5-year running mean (solid cyan and magenta lines, respectively) and the linear trends in each time series (dashed blue and red lines, respectively). Noticeably, a strong minimum in O_2 in 2005–2007 lags the minimum in annual maximum outcrop area in 1995–1997 by about a decade. Such a lag is expected, assuming it takes about 10 years for surface waters from the outcrop area in the northwestern North Pacific to reach OSP on σ_θ = 26.6 kg m^{-3}.





← **Figure 5.** Lagged correlations between detrended time series of O_2 on σ_θ = 26.6 kg m^{-3} at OSP and of annual maximum outcrop area of σ_θ = 26.4–26.7 kg m^{-3} from EN4-OISST: using unfiltered time series data (blue line) and time series data filtered with a 5-year running mean (red line). Maximum correlation values (r) for filtered data are 0.50 at a +10-year lag and 0.59 at a −10-year lag in agreement with ~10 year travel time (assuming bi-decadal cycles).

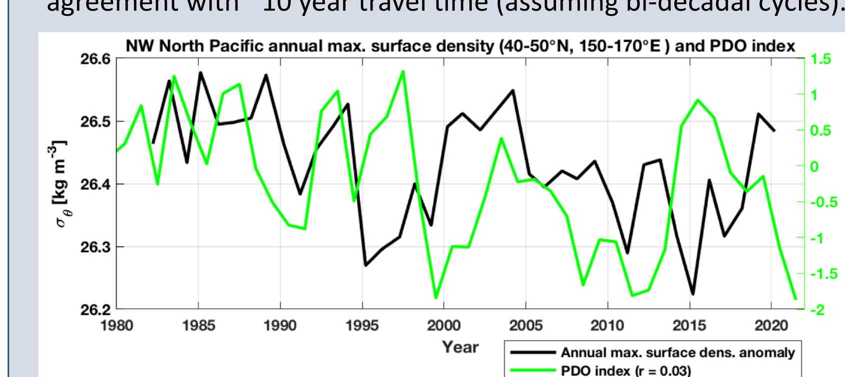


Figure 6. Annual maximum surface σ_θ averaged over 40–50°N, 150–170°E (see box in Fig. 1a) and annually averaged PDO index. Time series track each other e.g. 1999–2005, but show opposite variations e.g. 1995– 1999 & 2013–2018, resulting in a correlation close to 0.

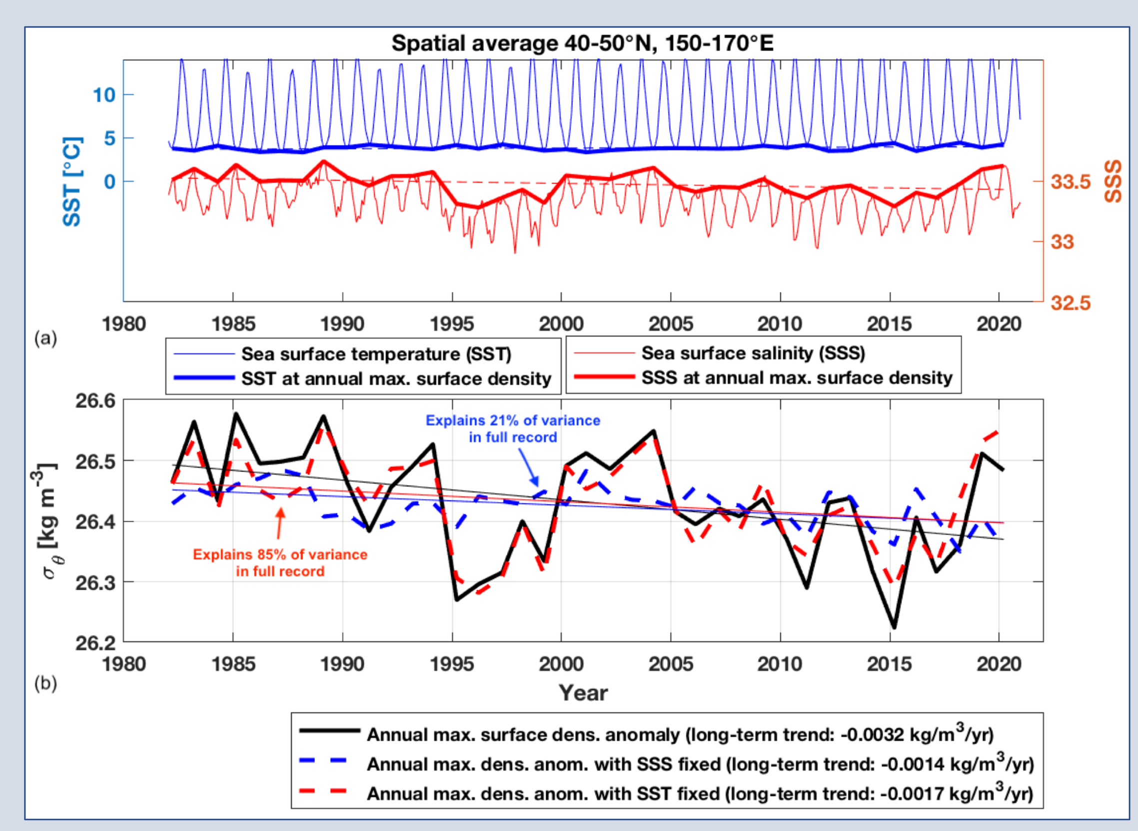


Figure 7. (a) SST (bold blue line) and SSS (bold red line) at annual maximum surface σ_θ and (b) annual maximum surface σ_θ (bold black line) and contributions from SST (dashed blue line; with SSS fixed at mean annual cycle during density calculation) and SSS (dashed red line; with SST fixed) in the northwestern North Pacific (averaged over 40–50°N, 150–170°E; see Fig. 1a for area). The dashed red line (SST fixed) and dashed blue line (SSS fixed) in (b) explain 85% and 21% of variance of the full record, respectively, indicating that SSS has a much larger contribution to surface density variability. In terms of the long-term linear density decrease (solid black line), the SSS-based trend (red solid line) and the SST-based trend (blue solid line) contribute about equally. Dataset used is the EN4-OISST dataset.

Summary & Conclusions

– The size of the annual maximum σ_θ = 26.4–26.7 kg m^{-3} outcrop area is used as an indicator of how much ventilation is occurring at the bottom of the ventilated thermocline. This is compared to O_2 on σ_θ = 26.6 kg m^{-3} where large O_2 variations occur at OSP.
– A correlation is found with a lag that approximately matches the travel time of water from the northwestern North Pacific to the northeast (10 years). A correlation between surface density variations and the PDO (defined by SST variability) is not as clear.
–SSS appears to dominate over SST in causing decadal changes in surface density whereas SSS and SST contribute about equally to long-term declining density trends.

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