

Enhanced Warming over the Global Subtropical Western Boundary Currents

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Subtropical western boundary currents are warm, fast flowing currents that form on the western side of ocean basins. They carry warm tropical water to the mid-latitudes and vent large amounts of heat and moisture to the atmosphere along their paths, affecting atmospheric jet streams and mid-latitude storms, as well as ocean carbon uptake¹⁻⁴. The possibility that these highly energetic and nonlinear currents might change under greenhouse gas forcing has raised significant concerns⁵⁻⁷, but detecting such changes is challenging owing to limited observations. Here, using reconstructed sea surface temperature datasets and newly developed century-long ocean and atmosphere reanalysis products, we find that the post-1900 surface ocean warming rate over the path of these currents is two to three times faster than the global mean surface ocean warming rate. The accelerated warming is associated with a synchronous poleward shift and/or intensification of global subtropical western boundary currents in conjunction with a systematic change in winds over both hemispheres. This enhanced warming may reduce ocean's ability to absorb anthropogenic carbon

dioxide over these regions. However, uncertainties in detection and attribution of these warming trends remain, pointing to a need for a long-term monitoring network of the global western boundary currents and their extensions.

The increase of carbon dioxide (CO₂) and other greenhouse gases in the atmosphere has been the major driver of surface warming of the Earth over the 20th century, a warming that is projected to continue in the foreseeable future⁸. The oceans take up both heat and CO₂, buffering this surface warming. The recent uptake of heat by the ocean⁹ has led to a significant increase in sea surface temperature (SST) in both the tropics and high latitudes, with to strong warming in the tropical Indian Ocean, and a weak warming over the deep water formation region in the high latitudes^{10,11}.

Studies so far have focused on tropical warming patterns^{8, 12-14} due to their profound influence on atmospheric deep convection and global atmospheric teleconnections. However, an important region with some of largest air-sea fluxes of heat, moisture and CO₂ in the world oceans is the convergence zone of extratropical western boundary currents. The poleward warm/salty subtropical western boundary currents meet equatorward flowing cold/fresh counterparts from the subpolar ocean, separate from the coast and extend eastward. These extensions form sharp thermal fronts fueling the midlatitude storms which are of vital importance in the climate system. Associated with wintertime heat loss, carbon is absorbed and sequestered into the ocean interior by the subduction and formation of mode water in these regions. Long air-sea equilibration timescales also lead to carbon sequestration downstream of the mode water formation regions.

Here we find a regionally accelerated warming since 1900 over the path of the subtropical western boundary currents in all the ocean basins, which far exceeds the globally averaged surface ocean warming rate (Fig.1). The global SST trends since 1900 are computed based on eight different datasets, including “analyzed” SST products that have been optimally interpolated or smoothed in both time and space (HadISST1, SODA, ERSSTv3b, Kaplanv2), “un-analyzed” SST datasets (HadSST2, Minobe/Maeda SST), and surface air temperature datasets (MOHMAT43, HadCRUT3) (See data descriptions in Methods section). Surface air temperatures

(MOHMAT43, HadCRUT3) are independently measured, and therefore may serve as cross-validation for trends derived from SST datasets. In the tropical Pacific, the center of action for the interannual El Niño-Southern Oscillation (ENSO) mode, the SST trend among these datasets differs significantly in sign and amplitude (Fig. 1), leaving a large uncertainty for the warming trend of the tropical Pacific¹⁵. However, in a sharp contrast, all analyzed SST datasets (HadISST1, SODA, ERSSTv3b, Kaplanv2) indicate a conspicuous warming trend over the path of the Pacific, Atlantic and Indian Ocean subtropical western boundary currents and their midlatitude extensions in both hemispheres (Fig. 1a-d). The magnitude varies regionally and is dataset-dependent, with a range of 0.8-1.8°C per century, or about two to three times the rate of the globally averaged SST trend (Fig. 1i). The accelerated warming trends over the global subtropical western boundary currents are also evident in the un-analyzed SST datasets (HadSST2, Minobe/Maeda SST) (Fig. 1g-h) and surface air temperature datasets (MOHMAT43, HadCRUT3) (Fig. 1e-f). In particular, both HadCRUTv3 and HadSST2 reveal a nearly uniform warming rate of approximately 1.5 °C per century over these western boundary current regions. Note that MOHMAT43, HadCRUT3, and HadSST2 data are independently measured based on different observational platforms or instruments¹⁵, so the consistency among different datasets suggests a robust process responsible for the accelerated warming over the global subtropical western boundary currents and their extensions. The magnitude of the warming trend varies with dataset but the ensemble mean of these eight datasets is a robust 1.2 °C per century over all the regions (Table 1).

The enhanced warming trends suggest a globally synchronous change of the subtropical western boundary currents over the past century. One important process which may lead to these enhanced oceanic warming trends is a poleward shift of the midlatitude extensions of these boundary currents¹⁶⁻¹⁸. However, detecting human-induced changes in oceanic circulation has been severely hampered by a lack of direct long-term measurements. To assess the role of this process in affecting the warming trends, we use newly developed century-long oceanic reanalysis product SODA and the 20th Century Atmospheric Reanalysis (20CRv2) product (See

description in Methods section). The evidence of a poleward shift of the subtropical western boundary currents is seen in the SODA reanalysis. Over the Kuroshio Extension, for example, the mean current axis, defined as the latitude of the maximum eastward velocity, is around 34°N with an eastward velocity of 25cm s^{-1} (Fig. 2a), consistent with in-situ observations¹⁹. The eastward velocity displays a dipolar trend pattern with an intensification on the northern and a weakening on the southern flank of the mean current axis (Fig. 2a). This indicates a poleward shift of the Kuroshio Current by about $0.8^{\circ}\pm 0.4^{\circ}$ over the past century (Fig.2f) in association with the warming trend, suggesting a contribution from poleward warm water advection¹⁷. A similar dipolar trend pattern is also detected along the Gulf Stream extension (Fig.2b), whose axis undergoes a poleward shift by $1.4^{\circ}\pm 0.8^{\circ}$ (Fig.2g). In the Southern Hemisphere, the poleward axial shift is identified for the midlatitude extensions of the Brazil Current (Fig.2d,i), but less clear for the East Australian Current (Figs.2c,h) and the Agulhas Current (Figs.2e,j). Therefore, the enhanced warming over the Kuroshio Current, the Gulf Stream and the Brazil Current may be partly induced by the poleward axial shift of these western boundary currents.

Due to high nonlinearity of the western boundary currents and insufficient observations of both the winds and ocean temperatures during the early part of the 20th century, some uncertainties remain in the poleward axial shift of the western boundary currents revealed by SODA. To further validate these results, we examine changes in the large-scale wind stress over the 20th century in 20CRv2. Although the western boundary currents are not directly forced by the large-scale wind stress, the boundary between the subtropical and the subpolar gyres, in theory, is essentially set by the associated midlatitude zero wind stress curl line. Therefore, the zero-curl line may be taken as a proxy of the jet latitude although in reality the axis of the mean jets does not necessary follow the zero-curl line exactly. Over the past century, the zero-curl line averaged zonally across the basin has shifted poleward by about $3^{\circ}\pm 1.4^{\circ}$ over the North Pacific (Fig.3a) and $2.5^{\circ}\pm 1.0^{\circ}$ over the North Atlantic (Fig.3b). A

poleward shift of the zonally averaged zero-curl line by about $2^{\circ} \pm 0.6^{\circ}$ is also apparent over the South Atlantic (Fig.3d). The poleward shift tendency of the zero-curl line appears to be consistent with the sign of poleward shift in the axis of the Kuroshio Current, the Gulf Stream and the Brazil Current, but the amplitudes are different. In general, the poleward shift of these boundary currents is about 1° (Fig.2), which is somewhat smaller than that of the zero-curl line. Given the strong meridional temperature gradient in the convergence zones, the poleward migration of these boundary currents may lead to a large areal warming through advective changes in SST that are reinforced by strong air-sea heat exchanges. In the South Pacific and the South Indian Ocean, the latitude of the zonal extension of the boundary currents is set by the meridional extent of the coasts, and thus bears no relationship with the zero wind stress curl line (Fig.3c,e). Therefore, the accelerated warming in these two regions may not be associated with the poleward shift of the western boundary current axes.

Another important process which may also potentially lead to these enhanced oceanic warming trends is an intensification of the western boundary currents, which can transport more warm tropical water into the cold midlatitude oceans, augmenting the warming there. The changes in the amplitudes of the subtropical western boundary currents may be inferred from the changes in the surface wind stress curl, although nonlinear vorticity dynamics also plays a role. In each of the southern subtropical oceanic gyres, the anticyclonic wind stress curl has intensified over the past century (Fig.3c-e), which may accelerate the interior equatorward flow and thus the poleward western boundary currents. It has been suggested that intensification of the East Australian Current (Fig.2c,h), as manifested in an acceleration of the southern supergyre over the past decades, is caused by climate change-induced increases in the westerly wind^{5,18}. In the Northern Hemisphere, however, the wind stress curl appears to have weakened or changed little in the subtropical North Pacific and the North Atlantic, respectively. Therefore, the enhanced warming over the western boundary currents in the Northern Hemisphere may not be associated with the changes in the

amplitudes of the subtropical wind stress curl. There is a possibility that this connection works well at decadal timescales, but less so for long-term trends due to additional buoyancy forcing effects in a warming climate.

The poleward shift of the zero-curl line and/or intensification of the subtropical wind stress curls are further supported by other atmospheric reanalysis products despite some notable inter-product discrepancies (see Methods section). Analysis of observational data over the past decades has also revealed a widening of the Hadley Cells²⁰ and an associated poleward shift of westerly winds in both hemispheres^{21,22}, which has been attributed to increasing greenhouse gas concentrations in the atmosphere. These atmospheric changes over recent decades are largely in the same direction as the centennial trends identified in our analysis of the surface wind stress curl. A poleward expansion of the oceanic subtropical gyres in both hemispheres has been supported by climate model simulations with increasing greenhouse gas concentrations⁷.

Although the trends in the 20th century are consistent with projections from climate models, an issue arises as to the extent to which the detected trends are associated with natural climate variability, particularly at decadal timescales. To address this issue, we assess the trends in two separate periods: 1900-1949 and 1950-2008. In the early period, enhanced warming can be found over the Kuroshio Current, the Gulf Stream and the Agulhas Current regions in most of datasets, while the warming over other subtropical western boundary current regions is marginal (Table 1 and Supplemental Fig.S1). The poleward shift is evident for the Kuroshio Current and the Brazil Current, but an equatorward shift, opposite to the long-term trend, is found for the Eastern Australia Current and the Agulhas Current (Supplemental Fig.S2). These results are perhaps not surprising given that greenhouse gas forcing in the early period is not strong, and some of the induced changes do not rise above the background of natural variability. In the later period, the enhanced warming is seen over all southern ocean western boundary current regions (Table 1 and Supplemental Fig.S3), consistent with the intensification trend of the southern subtropical western boundary currents (Supplemental Fig.S4) and the wind stress

changes (Supplemental Fig.S5). However, both the Kuroshio Current and the Gulf Stream display a trend towards an equatorward shift. For the Kuroshio, this equatorward shift is likely attributable to the mid-1970s North Pacific decadal climate shift¹⁶. Thus, in the later period despite the stronger greenhouse gas forcing, decadal variability could still substantially modulate the long-term trends in some ocean basins, such that the long-term trend can be different from decadal trends in both amplitude and sign (Supplemental Fig.S6). Nevertheless, For centennial time scale trends, influences from decadal variability diminish, and systematic enhanced warming is detected along the path of all western boundary currents, making it unlikely to be a reflection of decadal climate variability.

We conclude that the enhanced warming over the global subtropical western boundary currents in the 20th century might be attributable to the poleward shift of their midlatitude extensions and/or intensification in their strength. It should be noted that uncertainties remain large in terms of quantifying, detecting, and attributing the enhanced warming trends, due to a lack of long-term observations of the western boundary currents and to varying algorithms used in SST reconstructions among reanalysis products. Some additional mechanisms, for example, the enhanced upstream land warming may also contribute to the warming over the western boundary current regions. The estimated errors of these calculated trends presented here are also probably underestimated without explicitly taking into account these uncertainties. Nevertheless, the results highlight the importance of century-long datasets in detecting climate change signals. To detect future changes with confidence, a long-term monitoring network of western boundary current systems that builds on existing programs²³ is needed, particularly in regions of accelerated warming.

Methods

SST trends

Eight datasets are used for calculating global SST trends: Hadley Center Sea Ice and SST version 1 (HadSST1)²⁴; National Oceanic and Atmospheric Administration Extended Reconstructed SST version 2 (ERSSTv2b)²⁵; Kaplan Extended SST version 2 (Kaplanv2)²⁶; Simple Ocean Data Assimilation (SODA) SST product²⁷; Hadley Center SST version 2 (HadSST2)^{28,29}; night-time marine air temperature (NMAT) from Meteorological Office Historical Marine Air temperature version 4 (MOHMAT43)²⁴; and air temperature from Hadley Center/Climate research Unit Temperature version 3 variance-adjusted (HadCRUT3)³⁰. A detailed description of these datasets (except SODA) can be found in Deser et al.¹⁵ and cited references. Among these datasets, MOHMAT43, HadCRUT3, and HadSST2 are independent, and others may differ in quality-control and bias correction procedures.

The linear trends are calculated from 1900-2008 monthly anomalies using the method of least-squares with statistical significance assessed using a Student's-t test. Following Deser et al.¹⁵, we use a 24-month per decade threshold as the sampling criterion, but results are not sensitive to this criterion. This restriction together with the consistency with independently measured marine air temperatures is used to assess the realism of the SST trends¹⁵.

Wind Stress Trends

The 20th Century Atmospheric Reanalysis product, designated as 20CRv2, contains the synoptic-observation-based estimate of global tropospheric variability spanning from 1871 to 2008 at 6-hourly temporal resolution and 2° spatial resolution. The product is derived using observations of synoptic surface pressure and prescribing monthly SST and sea-ice distributions as boundary conditions for the atmosphere³¹. To assess the trends of the wind stress in the 20CRv2 atmospheric reanalysis dataset, we conducted an inter-comparison with the National Center for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR) Reanalysis (1950-2009), the European Centre for Medium-Range Weather Forecasts

(ECMWF) ERA40 Reanalysis (1957-2002) , and the newly constructed WASWind (Wave and Anemometer-based Sea-surface Wind) dataset (1950-2009), in which the bias in the ship-based measurements of sea surface winds due to an increase in anemometer height has been corrected³². Over the past half century, the wind stress curl in all these data displays an upward trend in the southern subtropical oceans with the poleward-shifted zero line more pronounced over the Atlantic-Indian ocean sector (Supplemental Fig.S5). In the northern subtropics, the changes of the wind stress curl in the North Pacific are not significant in all these data, while in the North Atlantic the wind stress curl is intensified in 20CRv2, NCEP/NCAR and ERA40 but not in WASWind. The insignificant changes of the wind stress in the North Pacific may be partly attributable to the opposite effect of the mid-1970s North Pacific decadal climate shift, which leads to a cooling in the North Pacific and an equatorward migration of the zero wind stress curl line¹⁶. Indeed, the widening of the Hadley Cells²⁰ and associated poleward shift of westerly winds over recent three decades have been documented from both satellite observations and model simulations^{21,22}. It should be noted the errors shown here are probably underestimated without explicitly taking into account uncertainties in different reconstructions. To further assess the robustness of the estimated trends, the ensemble mean and the standard deviation of trends derived from these four datasets are calculated. The ensemble mean displays an upward trend in global subtropical wind stress curl, except the subtropical North Pacific. The poleward shift of the zero-curl line is more evident in the south Atlantic and Indian Ocean sectors.

Oceanic current trends

The oceanic current trends are calculated based on the century-long SODA reanalysis product²⁶, which is based on the Parallel Ocean Program (POP) ocean model with an average horizontal resolution of 0.4° longitude \times 0.25° latitude and with 40 vertical levels. Temperature and salinity profiles are assimilated and include the recent release of the World Ocean Database 2009 (WOD09). Assimilation is carried out sequentially using a 10-day update cycle with model error covariances determined

from a simulation that does not include assimilation. The surface boundary conditions are taken from 20CRv2.

To assess whether SODA captures variability of western boundary currents, we select two sections across the Kuroshio Current and the Gulf Stream where the transport has been routinely measured. Across the Pollution Nagasaki (PN line) section of the Kuroshio Current over the East China Sea, repeat hydrographic surveys have been conducted on a quarterly basis by the Japan Meteorological Agency since the mid-1950s. For the Gulf Stream, the transport of the Florida Current between Florida and the Bahamas near 27°N has been collected from calibration cruises and calibrated cable voltages since early 1980s. The transports of the Kuroshio Current across the PN line, which is calculated from geostrophic balance, and the Florida Current are superimposed over these from SODA (Supplemental Fig.S7). The agreement is reasonably good, with a correlation of 0.6 and 0.65 (statistically significant at the 95% confidence level) for the Kuroshio Current and Florida Current during the observed period, respectively.

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Table 1: Mean SST warming trends and standard deviations of global and regional subtropical western boundary currents over different periods ($^{\circ}\text{C}$ per century) for eight different datasets.

Period	Global mean	Kuroshio Current	Gulf Stream	East Australian Current	Brazil Current	Aguhlas Current
1900-2008	0.62±0.14	1.29±0.30	1.02±0.37	1.30±0.23	1.28±0.15	1.40±0.40
1900-1949	0.60±0.18	1.33±0.25	2.31±0.15	0.90±0.15	1.13±0.18	1.71±0.20
1950-2008	0.71±0.22	1.10±0.31	0.90±0.30	1.37±0.23	1.93±0.28	1.31±0.42

Figure Captions

Figure 1: Global SST trends over the 1900-2008 period. (a-h) SST trends for various datasets. The corresponding global mean SST trend has been subtracted. White grid boxes denote insufficient data, and grey boxes indicate trends that are not statistically significant at the 95% confidence level. (i) SST trends averaged over the midlatitude extensions of the subtropical western boundary currents in each dataset (labels (a)-(h) stand for different dataset). Black error bar denotes the 95% confidence interval. Boundary current regions include the Kuroshio Current (KC) (25°E-150°E, 25°N-38°N), the Gulf Stream (GS) (75°W-45°W, 38°N-48°N), the Eastern Australian Current (EAC) (150°E-165°E, 44°S-34°S), the Brazil Current (BC) (58°W-35°W, 48°S-35°S) and the Agulhas Current (AC) (25°E-60°E, 45°S-35°S). The unit for SST trends is °C per century. GM stands for global mean.

Figure 2: Trends of eastward velocity across the extensions of the subtropical western boundary currents from SODA (1900-2008). Left panel: Depth-latitude profile of mean (contours) and trend (1900-2008, color). Units for mean and trend are m s^{-1} and m s^{-1} per century, respectively. Right panel: Latitudinal distribution of depth-weighted average eastward velocity in upper 500-m. Red and blue curves denote $\text{mean} \pm \text{trend} * N/2$ (N is the length of data used for trend analysis), respectively. Shading indicates the 95% confidence interval of the trend. The eastward velocity is zonally averaged over the Kuroshio Current (140°E-180°E), the Gulf Stream (290°E-320°E), the East Australian Current (150°E-160°E), the Brazil Current (295°E-320°E), and the Agulhas Current (21.25°E-40°E), respectively.

Figure 3: Trends of zonally averaged wind stress curl over each ocean basin in 20CRv2 (1900-2008). Red and blue curves denote $\text{mean} \pm \text{trend} * N/2$ (N is the length of data used for trend analysis), respectively. Negative (positive) values in the Northern (Southern) Hemisphere imply equatorward flow in the interior ocean that must be compensated by poleward flow in the western boundary. The units are 10^{-7}N

m^{-3} . Shading indicates the 95% confidence interval of the trend.





