South Pacific Ocean dynamics redistribute ocean heat content and modulate heat exchange with the atmosphere

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Key Points:

- Wind-driven ocean adjustment explains much of the change in ocean heat content and the flux of heat to the atmosphere.
- The heat exchange attributed to the waves, after seasonality is removed, ranges from -9 to 21 W m^{-2}.
- The results suggest heat fluxes due to Rossby waves could be forecast to provide predictability on the heat exchange with the atmosphere.

Abstract

The correlation of global ocean surface temperatures with ocean heat content at interannual to decadal time scales shows wind-driven ocean circulation plays a fundamental role in the Earth's energy balance. Wind-driven baroclinic Rossby waves contribute to the adjustment of the ocean circulation to the winds modulating ocean heat content at mid-latitudes. Here we use observational records, a reanalysis and a Rossby wave model to quantify the contribution of the waves to the variations in air-sea heat flux. We find that Rossby waves crossing the South Pacific at 35ºS can explain up to 70% of the interannual variance of the heat flux. The heat exchange attributed to the waves, ranging from -9 to 21 W m^{-2}, has contributed to the multi-year increase in heat in the central Pacific. Heat fluxes due to Rossby waves could be forecast to provide predictability of this component of the heat exchange with the atmosphere.

Plain Language Summary

The interaction between heat stored in the ocean and the exchange of heat between the ocean and atmosphere is critical in the redistribution of heat in the climate system. Wind-driven oceanic Rossby waves are planetary-scale waves that propagate westward across ocean basins and modulate heat stored in the ocean. However, it is unclear how much of that ocean heat content modulated by the waves is transferred to the atmosphere. Here we use data and a theoretical model to quantify the heat exchange with the atmosphere brought by the Rossby waves in the South Pacific ocean. We find that the Rossby waves, at 35ºS, can explain up to 70% of year-to-year variance in the heat flux after the seasonal cycle is removed. The heat flux along the wave crests and througs ranges between -9 to 21 W m^{-2} and has contributed to the multi-year increase in heat flux in the central Pacific linked to the Chilean mega-drought.

1 Introduction

The Southern Hemisphere (SH) ocean has made the largest contribution to the observed increase in global ocean heat content (OHC) in recent decades (e.g., Purkey and Johnson, 2010; Roemmich et al., 2015) with most heat accumulating in the upper 300 m of the ocean (Levitus, et al., 2009; Lyman et al., 2010; Cheng et al., 2017). The warming pattern consists of an increase in ocean heat storage between 30 ˚- 45 ˚S where average sea surface temperatures have been increasing at a rate of over 0.1 ˚C per decade since the 1950s (Gille, 2002; Böning et al., 2008). Strengthening of the SH subtropical gyres has been linked to a positive trend in the wind stress curl (Gao et al., 2018; Roemmich et al., 2007) with the greatest heat gain in the South Indian and South Pacific oceans over the last decade (Roemmich et al, 2015). In particular, the largest change in heat content has been observed in the Southwest Pacific where subduction of heat by the mean circulation has increased with the continued strengthening of the gyre circulation due to increasing mid-latitude westerly winds (Cai, 2006; Wu et al., 2012). While interannual to decadal variations in OHC, ocean heat distribution and heat exchange with the atmosphere have been documented previously from observations and simulations (Trenberth and Stepaniak, 2004; Trenberth et al., 2016), the processes that modulate ocean heat storage and dominate the exchange with the atmosphere need to be identified and their contributions assessed to better understand climate variability and change (von Schuckmann et al., 2016).

Much of the ocean variability in the mid-latitude Pacific can be attributed to Rossby waves generated by the wind and coherently propagating westward (Bowen et al., 2006; Holbrook et al., 2011; Hill et al., 2011; Andres et al., 2012; Sasaki et al., 2013; Sun et al., 2021). In the Southwest Pacific, Rossby waves explain up to 60% of the observed sea surface height variance (Bowen et al. 2006) at annual or lower frequencies (Qiu and Chen, 2006), and barotropic Rossby waves also correspond with temperature and ocean heat transport convergence at multidecadal time scales (Bowen et al., 2017). Although Rossby wave signals have been identified in sea surface height and sea surface temperature, their role in determining the location and timing of heat exchange with the atmosphere has not been explored.

In this study we investigate the link between large-scale wind-driven ocean dynamics, ocean heat storage and heat exchange with the atmosphere by showing that changes in ocean circulation influence the heat released into the atmosphere via fluctuations in oceanic heat storage. Using a linear Rossby wave model we show that the wind-driven circulation redistributes OHC at 35 ˚S in the South Pacific Ocean via Rossby waves and the change in heat content creates anomalies that modulate heat exchange with the atmosphere. We express this relationship in terms of variance explained and quantify how much heat could be potentially released to the atmosphere over the transit of a Rossby wave. We show that even over just a decade, wind-driven ocean adjustment can explain much of the change in OHC and plays a non-negligible role in the flux of heat to the atmosphere.

2 Materials and Methods

2.1. Data

Argo-derived subsurface temperature was used to compute 0-2000m depth-integrated OHC. We used the Roemmich-Gilson Optimal Interpolation (Roemmich & Gilson, 2009) which consists of monthly values over 58 pressure levels from the surface down to 2000m referenced to the period 2006-2020 and mapped onto a 1 $^{\circ}$ longitude and latitude grid.

We computed time series of the sea level anomalies (SLAs) centered at 35°S using mapped satellite observations of the sea surface height with a spatial resolution of 0.25 $^{\circ}$ in latitude and longitude distributed by the Copernicus Marine Environment Monitoring Service (CMEMS). To focus on the signals due to ocean circulation we subtracted the global mean sea level trend (GMSL; Nerem et al., 2018). This minimises sea level changes due to changes in total ocean water mass and to density changes due to global average thermal expansion.

The heat flux data used in this study are the monthly net upward surface heat fluxes from UCAR/NCAR – Geoscience Data Exchange. The fluxes are calculated as the residual between the vertically integrated atmospheric divergence of energy and the downward radiation through the top-of-atmosphere and they are calibrated with global ocean constraints (Fasullo and Trenberth, 2022). This record goes from 2000 to the end of 2017 and has a spatial resolution of 0.7 $^{\circ}$ in latitude and longitude. Improved formulations in this product have led to estimated accuracies, on basin scales lengths, of better than ±10 W m^{-2} (Trenberth and Fasullo, 2018).

We remove the seasonality in the OHC, SLA and heat flux. While this removes propagating waves with characteristic annual frequencies, it does preserve the low frequency baroclinic Rossby waves. For all timeseries the seasonal cycle was removed by subtracting the average monthly means of the variables. A 3-month running mean was applied to further remove intra-annual frequencies.

2.2. The 1.5-layer reduced gravity model

To investigate the link between wave dynamics and the time varying changes of the heat fluxes we use a linear baroclinic Rossby wave model for an inviscid fluid moving in a rotating frame. The model, based on the linear vorticity equation, has been extensively used to investigate the upper ocean response to wind driven Rossby waves (Bowen et al., 2006; Qiu and Chen 2006; Holbrook et al., 2011; Polito and Sato, 2015; Jin et al., 2018). The model uses the long-wave approximation and assumes that friction and nonlinear processes are negligible. The model has 1½ layers with an active upper layer of depth h and a motionless bottom layer of infinite depth. The stratification is represented by the difference in uniform density (Δ) between the layers defining the reduced gravity $g^{'} = g\frac{\rho}{\rho o}$ where g is the gravity acceleration and $_{0}$ is a reference density. The propagating signals have a zonal wave phase speed for the first-mode baroclinic Rossby wave,

C_R (Chelton et al., 1998), and are analysed at 35°S across the South Pacific gyre. We use a latitude-dependent *g'* following Qiu and Chen (2006) and a frictional damping parameter = 2000 day^{-1} that acts to dissipate the signals. To force the model, we use the monthly means of the surface wind stress at 0.25° resolution in both latitude and longitude from the European Centre for Medium-Range Weather Forecasts ERA5 Reanalysis from 1993 to 2021. The surface wind stress, , forces the interface between the upper and bottom layer (the pycnocline) to move vertically by Ekman pumping resulting in sea level anomalies of opposite sign and proportionally less magnitude than *h*. With these simplifications, conservation of momentum and mass become:

$$\frac{\partial h}{\partial t} - C\mathrm{R}\frac{\partial h}{\partial x} = -\frac{g^{'}\mathrm{curl}}{\rho 0\mathrm{gf}} - \epsilon h.$$

$= -\frac{\rho}{\rho \mathrm{o}} h.$

The model also uses the mean SLA for 1993 (the first year of the altimeter record) as an initial condition and the observed SLA at the easternmost longitude of the South Pacific near the coast of Chile as an eastern boundary condition.

To find the signals associated with Rossby waves, we average the variables along wave characteristics determined by a constant wave speed C_R. The time span of this average is the mean transit time between 60°W and 170°W.

2.3. Calculation of the Variance

We use the variability in the model SLA to explain the variability in the heat flux. The variance is calculated for 2004-2014 (when both timeseries overlap) with a linear regression model where the coefficient of determination is

$\mathrm{r}^2 = 1\text{-} \frac{\mathrm{SSres}}{\mathrm{SStot}}$

where $\mathrm{SS}_{\mathrm{res}}$ is the variance of the residuals (the sum of the squared difference between the observations and the linear fit) and $\mathrm{SS}_{\mathrm{tot}}$ is the total variance (the sum of the squared difference between the observations and the mean of the observations). The slope and the error of this linear fit is then used to model heat flux based on Rossby wave dynamics.

We report statistical coefficients at a 95% confidence level. The significance is calculated using the effective number of degrees of freedom from the autocorrelation function where the decorrelation time for the wave characteristics is 15 months (2× e-folding time) and a two-tailed t-test (Emery and Thomson, 2001; Von Storch and Zwiers, 2001).

4 Results

4.1. Ocean Heat content modulation and exchange with the surface by wind-driven wave dynamics

Maps of the extended SH winter season (May to September) averaged SLAs from 2009 to 2015 show a shift in positive anomalies from the eastern to the western mid-latitudes in the South Pacific, indicative of westward propagating signals (Figure 1). We want to estimate how much heat is exchanged between the ocean and the atmosphere as the SLA and associated OHC anomalies propagate across the basin. Here, we use a Rossby wave model to investigate changes in OHC in association with wind-driven ocean adjustment. We hypothesize that OHC changes are modulated by signals propagating on the thermocline and the changes in temperature change the heat entering the mixed layer and exchange with the atmosphere.

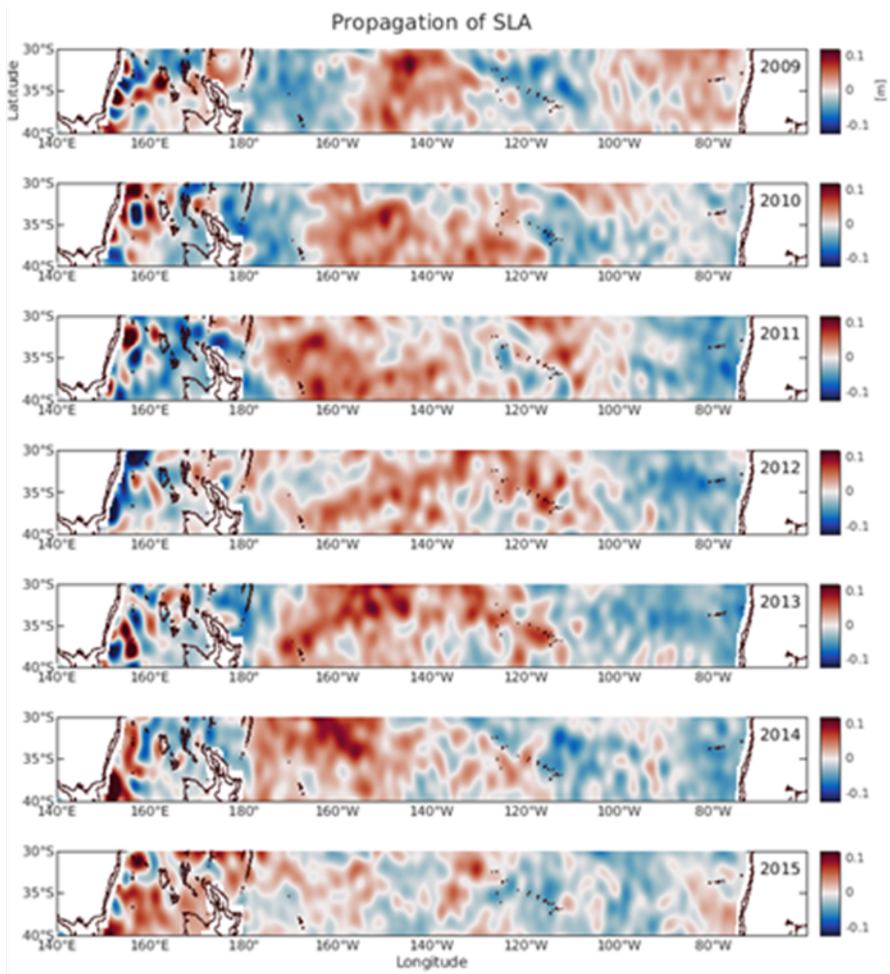


Figure 1. Maps of SLAs for the Southern Hemisphere extended winter season (May to September) from 2009 to 2015 illustrating SLAs propagating from east to west at mid-latitudes in the South Pacific.

SLAs are simulated at 35 ˚ S, the central latitude of the South Pacific domain. The modeled and observed SLAs are displayed in time-longitude plots and show wave characteristics (dashed lines) with similar spatiotemporal patterns (Figure 2a, 2b). OHC at 35 ˚ S also shows a westward propagating pattern (Figure 2c). Despite the relatively short record, OHC still captures the warm propagating signal from 2009 to 2015. The net upward heat flux is also plotted in time-longitude (Figure 2d) and shows the places where the atmosphere gains (loses) heat from (to) the ocean often coincide with the positive (negative) OHC anomalies and high (low) sea level produced by the Rossby wave crests (troughs). Much of the largest heat gain by the atmosphere in the central to western South Pacific in 2014, coinciding with increased OHC and SLAs, can be explained by a wind-driven Rossby wave crossing the South Pacific between 2009 and 2016.

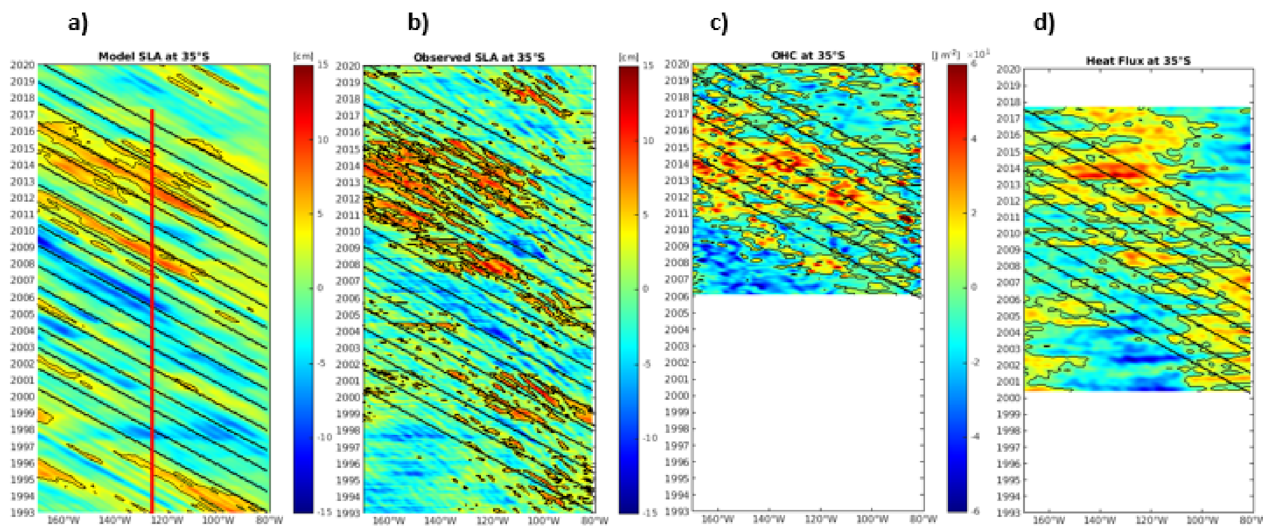
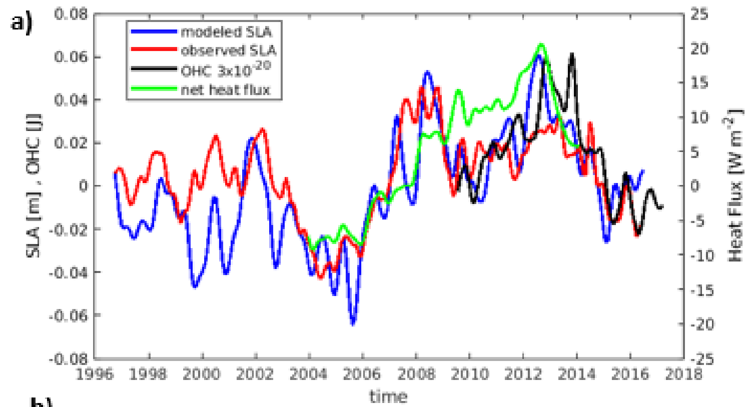
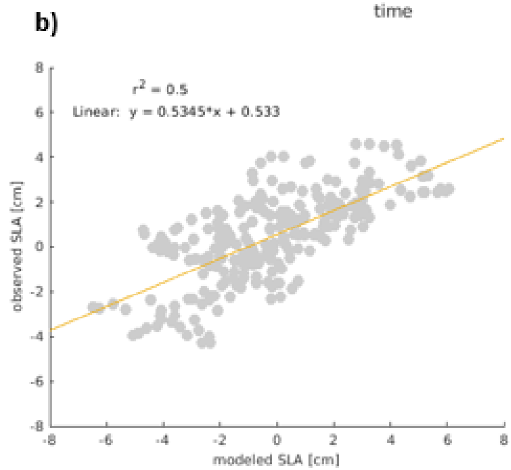


Figure 2. Hovmöller diagrams at 35°S of **a)** modeled and **b)** observed SLA, **c)** OHC anomalies and **d)** net upward heat flux anoma
where positive is atmosphere heat gain (all deseasoned). Wave characteristics are the lines of equal slope representing the westw
propagating signals (spaced lines every 15 months for display purposes). The vertical red line intersecting the dashed lines in **a)** m
the reference time for the average of the variables along each wave characteristic.

We estimate how much of the heat redistribution and atmospheric exchange results from westward propagating signals by taking averages along the wave characteristics. The observed and modeled SLA and the heat flux have similar interannual changes. OHC changes also have a similar variation but over the shorter time of the Argo observations. A linear regression of the model SLA and the observed SLA shows that Rossby wave dynamics at 35 ˚ S explain 50% of the variance in SLA ($r^2 = 0.5$) (Figure 3b). Similarly, the modeled SLA explains 70% of the variance ($r^2 = 0.7$) in net upward heat flux (Figure 3c).





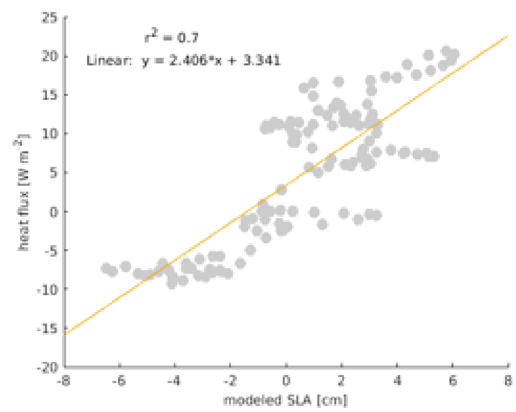


Figure 3. a) Averages of model SLA observed SLA, OHC and heat flux along the wave characteristics at 35°S (each slanted line in Figure 2) plotted at the midpoint time of the characteristic (red line in Figure 2). The OHC has been multiplied by 3×10^{-20} for display purposes. **b)** Scatter plot of the model SLA and observed SLA at 35°S for each wave characteristic. **c)** Similarly, for the model SLA and the heat flux. The equations are the linear fit between model and observations of SLA and heat flux, respectively.

The heat flux for the period 2000 to 2017 ranges from -92 to 98 W m^{-2}, with a standard deviation of 23 W m^{-2}. Once averaged along the characteristics the range reduces to -9 to 21W m^{-2} and the standard deviation reduces to 9 W m^{-2}. The fitted heat flux, based on the equation in Figure 3c applied to the modeled SLA accounts for 10.5% of the total variance or 70 % of the variance of the heat flux averaged along the characteristics.

5 Conclusions

We find that Rossby waves contribute to the interannual variations in heat exchange between the ocean and atmosphere. Averaging the heat flux along wave characteristics removes interannual variability from the atmosphere and shows much of the variability in heat flux can be explained by Rossby waves. We find Rossby waves can explain about 10% of the total interannual variance in heat flux.

The correspondence between the model and observed SLA and OHC indicate that wind driven Rossby waves propagate large OHC anomalies across the basin over many years modulating the heat exchange with the atmosphere. The largest heat flux signal in the observations is a large loss of heat from the ocean to the atmosphere in the central subtropical South Pacific (Figure 2) where Garreaud et al. (2021) find, in a series of simulations, that surface temperature trends contribute to the severity of the Chilean mega-drought. Our results suggest that oceanic Rossby waves, through heat transfer to the upper ocean and atmosphere, are likely modulating weather patterns across the Southern Hemisphere.

Previous studies have linked regional changes in OHC with ocean dynamics and air-sea interactions regionally and globally. Jin et al. (2018) used reanalysis data and an ocean general circulation model to investigate OHC decadal variability and concluded that heat storage in the eastern Indian Ocean is modulated by thermocline fluctuations due to Rossby waves. Gao et al. (2018) focused on the global ocean south of 30˚S to show that a large contribution to the increasing trend in upper OHC is from wind driven thickening and warming of subantarctic mode water. A similar result was found by Kolodziejczyk et al., (2019) where positive trends in OHC are correlated to increasing thickness of isopycnal layers of mode water. In the South Atlantic Ocean, Leyba et al., (2019) found that an intensification of the western boundary component of the South Atlantic subtropical gyre drives the confluence of subantarctic and subtropical waters. The increasing upper OHC leads to larger latent and sensible heat exchange from the ocean to the atmosphere. While identifying where in the ocean the largest air-sea fluxes occur is fundamental to determine the state of the climate (Roberts et al., 2017; Trenberth et al., 2019), the ubiquitous nature of planetary waves and their influence on heat fluxes over multi-spatiotemporal scales is very relevant. For example, Zhang et al. (2021) showed that long-lasting marine heat wave events in the tropical Indian Ocean are maintained by the downwelling of oceanic Rossby waves. Our results show that the propagation of OHC anomalies results in a mean heat flux along Rossby wave characteristics of magnitude comparable to air-sea fluxes driven by marine heat waves (5 Wm^{-2}; Croning et al., 2019). Therefore, large-scale planetary waves determine thermocline depth fluctuations sustaining long-term heat storage and playing a significant role in air-sea heat exchange.

Here we show the connection between OHC and heat exchange directly forced by wind driven ocean dynamics from a relatively simple linear model and a short observational record. Our results suggest that heat fluxes due to Rossby waves could be forecast to provide predictability in heat exchange between the ocean and atmosphere.

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Data Availability Statement

This study used freely available data. The heat fluxes are the product from the

Clouds and Earth's Radiant Energy Systems and Energy Balanced And Filled: CERES-EBAF https://www.cgd.ucar.edu/cas/catalog/newbudgets/index.html and made freely available at GDEX https://gdex.ucar.edu/dataset/282_fasullo/file.html under the file name ERAI.EBAF4.1_FS.200003-201712_new.nc. Subsurface temperature data were from the Roemmich-Gilson Optimal Interpolation. These data were collected and made freely available by the International Argo Program and the national programs that contribute to it and available at https://sio-argo.ucsd.edu/RG_Climatology.html. The Argo Program is part of the Global Ocean Observing System. The altimeter satellite data (SLA) are available at Copernicus Marine Environment Monitoring Service (CMEMS; https://resources.marine.copernicus.eu/product-detail/SEALEVEL_GLO_PHY_CLIMATE_L4_MY_008_057/INFORMATION/).

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