Pathways and Water Mass Properties of the Thermocline and Intermediate Waters in the Solomon Sea

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ABSTRACT

The semienclined Solomon Sea is the final passage in the equatorward transit of the South Pacific western boundary currents (WBCs) that play a key role in heat and mass budgets of the equatorial Pacific. The Solomon WBCs and their associated water properties are examined using data from two oceanographic cruises undertaken during the contrasting trade wind seasons: July 2012 and March 2014. The mean circulation and associated transports with uncertainties is determined from the cruise data using a unique configuration of an inverse box model formulated based on measured shipboard acoustic Doppler current profiler velocities. An intense inflow of 36 Sv is found entering the Solomon Sea in July–August 2012 that falls by 70% to 11 Sv in March 2014. Large differences are also found in the total transport partitioning through each of the major exit passages during each season. Different water masses are found in the WBC stream northeast of the Solomon Islands that are likely related to a northern stream of the South Equatorial Current. Within the Solomon Sea, isopycnal salinity gradients are gradually stronger than within the subtropical Pacific, likely induced by stronger diapycnal mixing processes. WBC pathways exhibit distinct water mass signatures in salinity, oxygen, and nutrients that can be traced across the Solomon Sea, associated with significant water mass modifications at the northern exit straits and south of the Woodlark Island.

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1. Introduction

The low-latitude western boundary currents (LLWBCs) of the southwest Pacific establish a major connection between the subtropics and the equator (McCreary and Lu 1994; Fine et al. 1994; Johnson and McPhaden 1999; Grenier et al. 2014). They cross the semienclosed Solomon Sea east of Papua New Guinea (PNG; Fig. 1a) before redistributing waters to the equatorial band, where LLWBCs are considered to be an important component of the equatorial Pacific water mass budget (Kleeman et al. 1999; Lee and Fukumori 2003). Any changes in mass transports or water mass properties from these LLWBCs could strongly affect the western Pacific with potential downstream effects on the eastern Pacific.

Within the CLIVAR Southwest Pacific Ocean Circulation and Climate Experiment (SPICE) program (Ganachaud et al. 2014), substantial efforts were carried out to understand the southwest Pacific ocean circulation and its influence on regional climate. The Solomon Sea was the focus of many studies, as it is the main pathway for the LLWBCs to reach the equator through a double system of currents (Melet et al. 2010a). At the northern exits of the sea, one stream flows through Vitiaz Strait (Fig. 1) to ultimately feed the Equatorial Undercurrent (EUC) or the equatorial current system, or the Indonesian Throughflow (ITF). Another stream exits the Solomon Strait (Fig. 1), providing a more direct connection with the equatorial region. Before SPICE, our knowledge of the circulation in the Solomon Sea was based on scattered in situ measurements from isolated ship transits. Recent modeling efforts (Melet et al. 2010a; Djath et al. 2014) and a 20-yr shipboard ADCP (S-ADCP) velocity climatology (Cravatte et al. 2011) provided a first description of the mean thermocline circulation and its seasonal variability across the Solomon Sea (Ganachaud et al. 2014).

To improve our understanding of the circulation in the Solomon Sea, two exploratory oceanographic cruises were undertaken during contrasted seasons through a France–U.S. collaboration as part of SPICE (Ganachaud et al. 2016, manuscript submitted to *Elementa*). The first cruise, named Pandora (27 June to 6 August 2012, R/V *L'Atalante*), combined physics, geochemistry, and biogeochemistry to explore the region (Fig. 1a). The second cruise, named MoorSPICE (28 February to 31 March 2014, R/V *Thomas G. Thompson*), focused on physics and biogeochemistry, partly repeated the July–August hydrographic sections and also carried out measurements in the Bismarck Sea, northwest of the Solomon Sea (Fig. 1b). The July–August 2012 cruise corresponded to the strong trade season whereas the March 2014 cruise was during weak trade season (Fig. 1c). Both

cruises were related with neutral phases of ENSO, as suggested by the near-zero Southern Oscillation index (SOI) values (red line, Fig. 1c).

In this study, we examine water mass pathways and properties in the Solomon Sea from hydrographic data collected during these two cruises. We use an inverse box model set up with S-ADCP velocities to infer a mean circulation during each cruise and to provide realistic transport estimates with a near-closed mass budget. The main questions addressed in this paper are 1) how do observed currents and associated water masses evolve within the Solomon Sea during the opposing strong and weak trades, 2) how typical were the currents with respect to climatology during July–August 2012 and March 2014, and 3) what are the transport partitions between the entrance and the exits of the Solomon Sea during both cruises?

To place this study into context, section 2 provides a detailed background on the current pathways and water properties feeding the Solomon Sea. The cruise data and climatological datasets are presented in section 3 along with the inverse box model description. Monthly climatologies show water masses around the Solomon Sea in section 4a, while water mass properties inside the Solomon Sea are described from the cruise data in section 4b. Current pathways and associated volume transports are shown for both cruises in section 5, and changes in water properties within the Solomon Sea are described in section 6. A summary and a discussion of our results are presented in section 7, followed by some perspectives.

2. Background: Currents and water masses feeding the Solomon Sea

Many studies describe the mean circulation in the Coral Sea (Sokolov and Rintoul 2000; Qu and Lindstrom 2002; Kessler and Cravatte 2013b) and Solomon Sea (Melet et al. 2010a; Cravatte et al. 2011). At thermocline level, the southwest Pacific LLWBCs (Fig. 1a) are fed by the westward zonal South Equatorial Current (SEC). One stream of the SEC bifurcates at the Australian coast into the northward-flowing Gulf of Papua Current (GPC) to feed the New Guinea Coastal Undercurrent (NGCU), with a maximum velocity core at $\sigma_\theta \sim 26.5$. Another stream of the SEC feeds directly into the North Vanuatu Jet (NVJ) and the NGCU as it flows equatorward inside the Solomon Sea. South of Woodlark Island (Fig. 1a), the NGCU splits into two branches that then remerge north of the archipelago, to then bifurcate again into two branches south of New Britain (Fig. 1a). The westward branch flows equatorward through the Vitiaz Strait while the eastward branch

FIG. 1. Shallow bathymetry at 100, 500, and 1000 m (brown shading); station positions (black dots); and repeat stations (yellow dots) along cruise tracks (gray background) during (a) the Pandora cruise (July–August 2012) and (b) the MoorSPICE cruise (March 2014). Red arrows in (a) denote the main thermocline currents in and around the Solomon Sea. In (b), the transects defining the boundaries of the inverse model are overlaid in red. The circled “V” and “S” represent Vitiaz and Solomon Straits, respectively, while “G” represents St Georges Channel. (c) ASCAT winds (m s^{-1}) averaged over the Solomon Sea basin from 2012 to 2014 (black arrows), overlaid by a 3-month moving average of the SOI (red line). Note the background shading during Pandora and MoorSPICE cruises.

forms the New Britain Coastal Undercurrent (NBCU). The NBCU splits to flow northward through St Georges Channel to form the St Georges Undercurrent (SGU) in the Bismarck Sea, and eastward through the Solomon Strait to form the New Ireland Coastal Undercurrent (NICU) east of New Ireland. Seasonal variations in the Solomon Sea are evident through strong wind stress anomalies, induced by the trade reversal (Hristova and Kessler 2012; Cravatte et al. 2011; Melet et al. 2010b). Sea surface temperature (SST) and sea surface salinity (SSS) variations are also associated with the seasonal cycle, with coldest and saltiest waters found in austral winter (Delcroix et al. 2014), inducing potential water mass modifications at the surface and deeper levels. Circulation and mass transports are expected to be modified at seasonal time scales; however, the scarcity of data so far has prevented the determination of the extent of these modifications.

A few studies have estimated net transports into the Solomon Sea. A net inflow was estimated at 30 Sv ($1 \text{ Sv} \equiv 10^6 \text{ m}^3 \text{ s}^{-1}$) over 0–2000 m from an August 2007 hydrographic cruise (Gasparin et al. 2012). The mean transport from repeated glider transects that transited across the Solomon Sea southern entrance was estimated at 15 Sv from the surface down to 700 m over 2007–11 (Davis et al. 2012). An Argo-based study from 2004 to 2011, which included data until 170°E because there are so few Argo floats into Solomon Sea, found a similar estimate of 19 Sv over 0–1000 m (Zilberman et al. 2013). From S-ADCP measurements (20–300-m depth range) and a single mooring with three current meters (at 354, 467, and 556 m) collected during the Western Equatorial Pacific Ocean Climate Studies (WEPOCS), Lindstrom et al. (1987, 1990) estimated transports through Vitiaz Strait at 8–14 Sv with a maximum velocity core around 200 m. This study suggested that the transport through Vitiaz Strait is a main source of the EUC, which was subsequently confirmed by the water properties analysis of Tsuchiya et al. (1989). Murray et al. (1995) estimated transports through Vitiaz Strait for the 50–800-m depth range, at 14.9–19 Sv from March 1992 to March 1993, with strong flows during June–August and weaker flows during September–March.

Water properties in the southwest Pacific exhibit strong signatures in salinity and oxygen that can be tracked along the LLWBCs from the Coral Sea to the equator through four main water masses. The South Pacific Tropical Water (SPTW), also referred to as the upper salinity maximum water in Qu and Lindstrom (2002), flows at the upper thermocline level ($\sigma_\theta \sim 24.5$) and originates in the southeast Pacific gyre (e.g., Kessler 1999; Hasson et al. 2013; Qu et al. 2013). Below the SPTW, two mode waters are identified with no vertical

extrema in temperature or salinity; rather, they are characterized by the thermostad typical of mode waters (Tomczak and Hao 1989; Grenier et al. 2014). The Subtropical Mode Water (STMW; $\sim\sigma_\theta = 25.5\text{--}26$; Roemmich and Cornuelle 1992; Qu et al. 2008) emanates from north of the Tasman Sea (Donguy and Henin 1977) and partly northeast of New Zealand (Tsuchiya 1981; Qu et al. 2008), and the Subantarctic Mode Water (SAMW; $\sim\sigma_\theta = 26.5\text{--}27$; McCartney 1977; Grenier et al. 2013) with quite high oxygen originates from the Southern Ocean by subduction north of the Antarctic Circumpolar Current (Hanawa and Talley 2001). A salinity minimum and an oxygen maximum identify the Antarctic Intermediate Water (AAIW) near $\sigma_\theta \sim 27.2$, with origins between 50° and 60°S (Qu and Lindstrom 2004).

3. Data and inverse model

a. Hydrographic cruise data

Both cruises and associated data processing are described in Ganachaud et al. (2016, manuscript submitted to *Elementa*); here we summarize the main features. During the July–August 2012 cruise (Pandora), hydrographic sections, including some repeat 28–36-h time series stations, were carried out. On stations, CTD O_2 sensors were used to measure temperature, salinity, and oxygen. Niskin bottles were used to collect water samples at specific depths to measure salinity, oxygen, and nutrients (nitrite, nitrate, phosphate, and silica). Overall, 83 stations were sampled, most to 2000 m depth (Fig. 1a). Currents were recorded during most profiles with a pair of lowered acoustic Doppler current profilers (L-ADCPs; RDI Instruments) attached to the CTD rosette (150 and 300 kHz, down- and up-looking with a vertical resolution of 16 and 10 m, respectively). Currents were also recorded along the ship track with two S-ADCPs (models RDI 0S-38 and 0S-150), with typical vertical ranges of 1300–1350 m and 300–350 m, respectively.

During the March 2014 cruise (MoorSPICE), 57 stations were surveyed, including some repeat 28–36-h time series, along CTD hydrographic sections that measured temperature, salinity, and oxygen (Fig. 1b), most to 2000 m or to 1000 m at the southern entrance. As in July–August 2012, discrete samples were carried out on station with Niskin bottles to measure salinity, oxygen, and nutrients. Currents were recorded at each station using a pair of down- and up-looking 300-kHz RDI L-ADCPs with vertical resolution of 8 m and a 0S-75 S-ADCP working in both broadband and narrowband modes that reached around 700 and 900 m, respectively.

In both cruises, the repeat stations (Figs. 1a,b) are used to estimate uncertainties in S-ADCP velocity data near

TABLE 1. Water masses and associated volume transports (Sv) during July–August 2012 [Pandora (P)] and March 2014 [MoorSPICE (M)]. Positive values are northward or eastward, negative values are southward or westward, and uncertainties are one standard deviation. Transport estimates do not entirely sum up, which is likely induced by diapycnal fluxes to deeper layers than 1000 m and residual noise.

Upper (σ_θ , kg m ⁻³)	Lower (σ_θ , kg m ⁻³)	Water mass	Southern entrance	St Georges–Solomon	Vitiaz	Woodlark–New Britain	Trobriand–Woodlark
Surface	24	TSW	P: 3.3 ± 0.4 M: -5 ± 0.3	2.4 ± 0.3 -6.7 ± 0.4	4.5 ± 0.1 2.2 ± 0.1	2.2 ± 0.2 1.5 ± 0.3	2.1 ± 0.2 -0.7 ± 0.2
24	26	SLW	P: 11.4 ± 0.3 M: 2.7 ± 0.4	6.3 ± 0.3 3.5 ± 0.3	3.4 ± 0.1 4.2 ± 0.1	1.8 ± 0.2 1.6 ± 0.2	3.1 ± 0.2 1 ± 0.2
26	26.9	SAMW	P: 12.2 ± 0.5 M: 8.7 ± 0.6	6.2 ± 0.5 3.8 ± 0.5	6.9 ± 0.1 3.1 ± 0.1	1.8 ± 0.3 5.6 ± 0.3	4.1 ± 0.2 1.4 ± 0.5
26.9	27.4	AAIW	P: 9.3 ± 1.4 M: 4.3 ± 1.4	3.8 ± 1.2 1.7 ± 1.2	4.6 ± 0.2 1.4 ± 0.2	5.8 ± 0.9 0.2 ± 1	-1.4 ± 0.8 0 ± 0.8
Surface	27.4		P: 36.2 ± 2.6 M: 10.7 ± 2.6	18.8 ± 2.3 2.2 ± 2.3	19.4 ± 0.4 10.9 ± 0.4	11.6 ± 1.7 8.8 ± 1.7	7.9 ± 1.7 1.7 ± 1.7

1000 m, associated with high-frequency natural variability (e.g., barotropic and baroclinic tides). Velocity uncertainties are lower than $\pm 5 \text{ cm s}^{-1}$ at most repeat stations during both cruises, except in July–August 2012 at Vitiaz Strait (repeat station 77), where observed velocity variability reached $\pm 10 \text{ cm s}^{-1}$, likely induced by the strong tides.

Temperature, salinity, and oxygen profiles are filtered using a 5-m median to remove spikes. Velocity data from the narrowband 38-kHz S-ADCP during July–August 2012 and the narrowband 75-kHz S-ADCP in March 2014 are averaged every 10 min. Because S-ADCP profiles start at 50 m, they are extrapolated as a constant to the surface. To highlight the water property changes within the Solomon Sea (see section 6), hydrographic and S-ADCP data were averaged over potential density ranges (Table 1) encompassing the main water masses, defined in section 2.

b. Meteorological products

The Advanced Scatterometer (ASCAT) winds on a lateral resolution of 0.25° were spatially averaged over the Solomon Sea basin (6° – 10°S , 148° – 160°E) from January 2012 to December 2014. Monthly CPC Merged Analysis of Precipitation (CMAP) products at 2.5° lateral resolution were averaged over the Solomon Sea region (2° – 14°S , 146° – 164°E) during both cruises. A 3-month moving average of the SOI was used from January 2012 to December 2014.

c. Ocean climatology

The Monthly Isopycnal/Mixed-Layer Ocean Climatology (MIMOC) provides monthly mean salinity data at 0.5° lateral resolution over 81 standard pressure levels from the surface (0 dbar) to 1950 dbar (Schmidt et al. 2013). Maps are mostly based on Argo and shipboard data from 2007 to 2011, but they can relax back to historical

CTD measurements when no recent data are available. MIMOC uses a mapping scheme based on a fast marching algorithm, which improves property fields near the coasts and around the Solomon Islands.

d. Inverse box model

Inversion methods are used to infer synoptic current pathways and associated quantitative transports within an ocean volume (i.e., a box divided in layers along the z axis and bounded by hydrographic transects). The usual procedure (Wunsch 1996; Macdonald and Wunsch 1996; Ganachaud and Wunsch 2000) uses as an initial guess of geostrophic currents calculated between pairs of stations from a deep reference level. Then the inverse model is used to determine an adjusted flow with associated uncertainties, so that the flow conserves mass, salt, or heat to avoid large mass imbalances. This results in velocities and property transports with uncertainty estimates obtained directly from the hydrographic surveys.

MODEL CONFIGURATION

Our inverse box model uses the Gauss–Markov method (Wunsch 1996; Ganachaud and Wunsch 2000) along bounding hydrographic transects to adjust the flow and estimate errors of our diagnostics over 12 evenly spaced isopycnal layers from the surface to 1000 m (Table A1). Potential density surfaces that encompass main water masses found in the southwest Pacific (see section 2; Qu and Lindstrom 2002; Grenier et al. 2013; Gasparin et al. 2014) are grouped to calculate corresponding volume transport (Table 1). SPTW and STMW are grouped in a single layer, identified by Wyrki (1962) as the Subtropical Lower Water (SLW; $24 < \sigma_\theta < 26$). The model is set up to enforce mass, salt, heat, and silica conservations.

Calculation of geostrophic velocities is subject to biases from temporary displacements of isopycnals

due to internal waves. This noise is exacerbated in the Solomon Sea because of the high internal wave activity from tides (e.g., Melet et al. 2011; M. S. Alberty et al. 2016, unpublished manuscript) coupled with the low latitude. In addition, strong ageostrophic currents are expected in the narrow straits. To overcome this difficulty, we chose to use the gridded S-ADCP velocity profiles as our first guess and to allow a barotropic adjustment referenced to 1000 m depth through the inverse model; though necessarily the simplest, this barotropic adjustment is a realistic hypothesis. Locally, the required adjustment is relatively small, but nevertheless, its integral effect on coast-to-coast transport is important.

The inverse box model is bounded by three hydrographic transects enclosing the Solomon Sea and two transects crossing the midbasin, common to both cruises (Fig. 1b). A transect crosses the southern entrance of the Solomon Sea, with S-ADCP velocities rotated 346 degrees True (hereinafter °T) to be perpendicular to the transect. A second transect joins the St Georges Channel and Solomon Strait outflow passages (velocities rotated 359.9°T). At Vitiaz Strait, another transect crosses the outflow with S-ADCP velocities rotated 344°T. In the midbasin, a transect joins the Woodlark Island and New Britain with S-ADCP velocities first rotated 270°T (from 9° to 6°S) and then 242°T (from 6° to 5.5°S). A last transect joins the flow from Trobriand to Woodlark Islands, where S-ADCP velocities are rotated 203°T. During the March 2014 cruise, S-ADCP velocities do not reach 1000 m, so we used a merged velocity field based on S-ADCP in the upper ocean and L-ADCP at depths where S-ADCP velocities were not available, typically below 900 m. L-ADCP velocity profiles were compared with corresponding S-ADCP profiles at overlapping depths, and minor differences were found (0–1 cm s⁻¹). L-ADCP velocities were interpolated on the S-ADCP velocity grid using a Gaussian weighting function.

Freshwater transports are in the local mass balance: CMAP precipitation products provide estimates of 6 and 10 mm day⁻¹ over the area of the Solomon Sea, which correspond to mass fluxes of 0.01 and 0.016 Sv during the 2012 and 2014 cruises, that is, much smaller than uncertainties (Table 1). The Ekman component in the surface layer is partially included in the absolute S-ADCP currents, although an adjustment to the integral Ekman transport is allowed through the inversion. ASCAT winds during each cruise period were used to estimate a range for this Ekman adjustment (± 3 Sv).

A solution to the S-ADCP velocity adjustments, the reference velocities, and the advective and diffusive vertical transfers between the different box layers must be determined so that budgets in mass, salt, heat, and silica

are balanced in the upper 1000 m. Silica is conserved from the surface to 1000 m (layers 1–12) but not within individual layers. A priori uncertainties on mass were specified following Ganachaud et al. (2008), who used an inverse model to determine circulation in the Coral Sea. For both cruises, these uncertainties are detailed for each layer in Table A1. We set near the surface (i.e., layers 1–3) larger mass uncertainties (± 2 Sv), as higher residual mass variability is expected (Ganachaud 2003). Heat and salt are not conserved in these upper layers because of potential exchanges with the atmosphere. In the deepest layer 12 (>800 m), an allowance of ± 2 Sv permits possible exchanges with the deeper ocean. No conservation is applied to heat and salt in this last layer to allow exchange with the deeper ocean. To enforce heat and salt conservations, anomaly equations are used (Ganachaud and Wunsch 2000; Ganachaud 2003) associated with scaling factors (Table A1), which are determined experimentally to minimize the mass residuals between the initial and adjusted velocity fields.

Cross isopycnal transfers (w) are allowed with a priori values of $\pm 1 \times 10^{-3}$ cm s⁻¹ between layers 1 and 2 and $\pm 1 \times 10^{-4}$ cm s⁻¹ between the deeper layers, since larger vertical exchanges are expected near the surface than in deeper layers. A priori vertical diffusion coefficients (κ_z) are believed to be strong in the Solomon Sea (Melet et al. 2011; Olbers and Eden 2013), as it is strongly influenced by the South Pacific LLWBCs and rough topography. Thus, a κ_z range of adjustment was set to ± 10 cm² s⁻¹.

The range of adjustment for S-ADCP velocities is determined from repeat stations (yellow dots in Figs. 1a,b), except at Vitiaz Strait in July–August 2012, where variability is strongly impacted by tides (see section 3a). Thus, the velocity range is set to be the conservative value of ± 5 cm s⁻¹ for all transects during both cruises.

4. Water mass properties

a. MIMOC climatology

Monthly mean salinity over the southwest Pacific is shown for July and March (Fig. 2) to provide a climatological view of water masses entering and exiting the Solomon Sea at thermocline and intermediate levels. We overlay the corresponding salinity values from the cruise data (colored dots, Fig. 2).

In March and July, the SLW (Figs. 2a,b; $\sigma_\theta \sim 24$ –26), exhibits high salinity (>35.7) carried westward by the SEC from the high evaporation region (20°S, 120°W). These salty waters are spread out from the eastern Pacific to the Solomon Strait in July but are confined east of the Solomon Islands in March. In both seasons,

FIG. 2. Mean salinity climatology during (left) July and (right) March for (a),(b) SLW ($\sigma_\theta \sim 24\text{--}26$); (c),(d) SAMW ($\sigma_\theta \sim 26\text{--}26.9$); and (e),(f) AAIW ($\sigma_\theta \sim 26.9\text{--}27.4$) levels. Colored dots correspond to measured salinity during each July–August 2012 and March 2014 cruise. Note the choice in salinity scale used for each potential density range.

the direct NVJ pathway carrying more salty waters (Kessler and Cravatte 2013b) is not distinguishable once in the Solomon Sea. Fresher waters coming from the eastern Pacific are tracked across the Coral Sea (south of 15°S) to the GPC before entering into the Solomon Sea. Downstream, the NGCU and the SGU carry fresh waters into the Bismarck Sea with lower salinity in July than March.

At the SAMW level (Figs. 2c,d; $\sigma_\theta \sim 26\text{--}26.9$), both seasons show salty waters (>34.9) carried by the GPC to feed the NGCU and ultimately the Solomon Sea. These salty waters originating from north of New Zealand are also carried westward by the northern stream of the SEC

and are found in the Bismarck Sea. Fresh waters enter the Coral Sea ($\sim 13^\circ\text{--}15^\circ\text{S}$), emanating from the eastern Pacific. MIMOC climatological fields appear to be too smooth to allow inference of detailed pathways, but the salty NGCU is clearly visible in the July–August 2012 cruise data.

At the intermediate level (Figs. 2e,f; $\sigma_\theta \sim 26.9\text{--}27.4$), fresh waters related to the AAIW salinity minimum are observed within the Coral Sea. They are not traceable inside the Coral Sea, and their signature vanishes as they flow equatorward. Conversely, AAIW is traced inside the Solomon Sea with both July–August 2012 and March 2014 cruise data. Salty waters (>34.53) are observed

northeast of the Solomon Islands and in the Bismarck Sea during both seasons.

Thus, in the MIMOC climatology major differences are found between both seasons at the SLW near Solomon Strait, where northeastern salty waters seem to enter the Solomon Sea during March and not in July. In contrast, there is not much difference at SAMW and AAIW levels in the MIMOC climatology. As expected, MIMOC does not agree well with the cruise data within the Solomon Sea, since only a few scattered profiles were available in the region before the two SPICE cruises.

b. July–August 2012 and March 2014 cruises

During both cruises, the SPTW identified as a salinity maximum (Figs. 3c,d) is found at $\sigma_\theta \sim 24.5$ within the Solomon Sea. During both cruises, salty waters are observed at the eastern entrance of the Solomon Sea, carried by the direct NVJ, and also northeast of Bougainville Island. The western Solomon Sea has less saltier waters during both cruises at the southern entrance where the NGCU flows into the Solomon Sea (dark red, Figs. 3c,d). These less salty waters, which exhibit a deeper salinity maximum (below $\sigma_\theta = 24.5$), are found in Vitiaz Strait and St Georges Channel, as we will discuss further in section 6. Nutrients (see Fig. S1 in the supplemental material) exhibit common features between both cruises. Nitrate (Figs. S1a,b) and phosphate (Figs. S1c,d) concentrations range from 10 to 15 and 0.4 to $0.8 \mu\text{mol kg}^{-1}$, respectively, and silica (Figs. S1e,f) is $<10 \mu\text{mol kg}^{-1}$. Below the SPTW, the STMW ($\sigma_\theta \sim 25.5$ –26) is observed (Figs. 3c,d) with similar temperature, salinity, and nutrient characteristics between both cruises. Below $\sigma_\theta = 26$, waters with temperatures from 8° to 10°C (Figs. 3c,d) and with high oxygen ($>160 \mu\text{mol kg}^{-1}$; Figs. 3e,f) are identified as the SAMW during both cruises with similar nutrient concentrations.

Near $\sigma_\theta = 27.2$, a salinity minimum (<34.6 , Figs. 3c,d) and an oxygen maximum (~ 150 – $200 \mu\text{mol kg}^{-1}$; Figs. 3e,f) identify the AAIW during both cruises, except northeast of Bougainville Island, where saltier waters associated with low oxygen, high phosphate, and high nitrate are found. These waters emanate from the equatorial region, where Bostock et al. (2010) identified the Equatorial Pacific Intermediate Water (EqPIW) with higher salinity, phosphate, and nitrate and lower oxygen compared with other intermediate waters. Northeast of Bougainville Island, similar silica concentrations to those found by Bostock et al. (2010) (20 – $100 \mu\text{mol kg}^{-1}$) were measured during both cruises. Tracer signatures indicate that the EqPIW is older than both AAIW and the North Pacific Intermediate Water (NPIW), suggesting a formation of the EqPIW by diapycnal mixing with older upwelled waters as the Pacific Deep Water

(Bostock et al. 2010). Both Θ – S and Θ – O_2 diagrams (Fig. 3) reveal strong erosion of the extrema as the water masses flow across the Solomon Sea with significant differences between both cruises, as investigated below in section 6.

5. Pathways and integrated transports

In this section, the main currents and their associated volume transports are detailed across the Solomon Sea during the two SPICE cruises. Reference velocity adjustments through the inversion at 1000 m are presented (Fig. 4, top panels), and are much smaller than the a priori velocity uncertainties of $\pm 5 \text{ cm s}^{-1}$ (see section 3d).

a. Southern entrance of Solomon Sea in austral winter 2012

The estimated July–August 2012 velocity field reveals strong currents across the southern entrance section to the Solomon Sea (Fig. 4a), associated with a surface-to-1000-m volume transport of 36 Sv (Table 1), which is in the upper range of previous estimates (Kessler and Cravatte 2013a). Waters between $24 < \sigma_\theta < 26.9$ (SLW and SAMW) and below $\sigma_\theta = 26.9$ (AAIW) represent 65% (~ 24 Sv) and 26% (~ 9 Sv), respectively, of this transport estimate (Table 1). The striking feature is a strong NGCU confined against PNG (~ 18 Sv; Table A2), with a main core located at 500 m (Fig. 4a). East of the NGCU, the direct NVJ flows into the Solomon Sea (~ 8 Sv; Table A2), centered on $\sigma_\theta = 25.5$ (~ 200 m), before merging with the NGCU south of Woodlark Island (Figs. 1a,b). On the eastern part, a southward current (5 – 10 cm s^{-1} ; Fig. 4a) is observed at 159° – 160°E between 400 and 1000 m, which suggests waters flowing out of the Solomon Sea along the Solomon Islands.

b. Interior pathways in austral winter 2012

A surface-to-1000-m volume transport is estimated at 12 Sv (Table 1) between Woodlark and New Britain Islands, largely as a result of the westward current across the section except along the New Britain coast, where an eastward flow is observed (Fig. 4e). Below the surface, the most striking feature is the sharp and intense eastward flowing NBCU (~ 28 Sv; Table A2) confined along the New Britain coast (north of 6°S ; Fig. 4e). A strong westward flowing NGCU is identified (7.5° – 8.4°S ; Fig. 4e) with a high-velocity core located at 500 m (16 Sv; Table A2), a similar magnitude and depth to the NGCU as it enters across the southern entrance (northward flow south of 155°E in Fig. 4a). A recirculation is also identified through an eastward flow sandwiched between Woodlark and the NGCU. Farther north, a westward flow is observed centered on $\sigma_\theta = 27$ ($\sim 6.5^\circ\text{S}$), likely

FIG. 3. Hydrographic stations during (a) Pandora and (b) MoorSPICE. Shown are the Θ - S diagrams during (c) Pandora and (d) MoorSPICE and Θ - O_2 diagrams during (e) Pandora and (f) MoorSPICE, respectively. Note expanded inset for Θ - S diagrams. Color corresponds to locations as indicated in legends and maps in (a) and (b).

FIG. 4. The top part of each panel shows the difference between estimated and initial reference velocities at 1000 m (solid line). (left) July–August 2012 and (right) March 2014 estimated zonal cross-section S-ADCP velocities (a),(b) at the southern entrance of the Solomon Sea; (c),(d) between St Georges Channel and Solomon Strait; (e),(f) between New Britain and Woodlark Islands; (g),(h) between Trobriand and Woodlark Islands; and (i),(j) at Vitiaz Strait. Positive values indicate northward and eastward directions, and overlaid white lines indicate potential density anomaly (kg m^{-3}).

resulting from another recirculation confined to the northern part of the basin. Between Trobriand and Woodlark Islands (Fig. 4g), we estimated a northward flow of 8 Sv (Table 1), with a strong current along the Trobriand coast. A southward flow centered on $\sigma_\theta = 25.5$ is observed near Woodlark Island.

c. Northern outflow pathways in austral winter 2012

Across the St Georges–Solomon transect (Fig. 4c), the estimated volume transport reaches 19 Sv (Table 1), with ~ 8 Sv flowing through St Georges Channel and ~ 11 Sv across Solomon Strait (Fig. S2c). Near 67% (12.5 Sv) of the total integrated transport is found between $24 < \sigma_\theta < 26.9$, while 20% (~ 4 Sv) is attributed to the AAIW (Table 1). Above 150 m, transports are estimated to be 2 Sv and are associated with a persistent anticyclonic eddy, observed by altimetry as present during the whole austral winter 2012 cruise in Solomon Strait (Ganachaud et al. 2016, manuscript submitted to *Elementa*). At St Georges Channel, the northward SGU (Fig. 4c, west of 153°E) transports ~ 6 Sv between $24 < \sigma_\theta < 26.9$ (Table A2), with two velocity cores of $\sim 40 \text{ cm s}^{-1}$. At Solomon Strait (Fig. 4c, east of 153°E), a strong NICU is found at this density range, transporting equatorward ~ 6 Sv (Table A2). The eastern part of Solomon Strait shows a southward current centered on $\sigma_\theta = 27$ (153.5°–154.5°E) entering the Solomon Sea. This current potentially feeds westward into the interior Solomon Sea, or perhaps contributes to the southward current found at the southern entrance (Fig. 4a). Below $\sigma_\theta = 27$, a core of weak velocities ($0\text{--}10 \text{ cm s}^{-1}$) exits Solomon Strait at 154°E. These transport estimates and current structures are consistent with previous studies (Melet et al. 2010a; Cravatte et al. 2011).

At Vitiaz Strait, a high-velocity core of $90\text{--}110 \text{ cm s}^{-1}$ is found at 200 m (Fig. 4i), consistent with previous studies (Lindstrom et al. 1990; Murray et al. 1995; Cravatte et al. 2011). Near 53% (~ 10 Sv) of the total volume transport (Table 1), is found between $24 < \sigma_\theta < 26.9$. Above 150 m and at the AAIW density range, we found a similar contribution of almost 25% (4.5 Sv; Table 1) to the total volume transport, leading to a total estimate of 19 Sv across the strait, which is also consistent with previous estimates (Lindstrom et al. 1990; Murray et al. 1995; Cravatte et al. 2011). Thus, the circulation during July–August 2012 is slightly stronger, but close to the mean conditions.

d. Southern entrance of Solomon Sea in austral summer 2014

During March 2014, the volume transport fell by 70% to 11 Sv across the southern entrance, compared to the

austral winter 2012 cruise (Table 1), although there were quite similar contributions from waters encompassing the SLW and SAMW (near 70%) and the AAIW (25%). The NGCU is less intense and extended to the surface (Fig. 4b, west of 155°E), with a transport almost halved (~ 10 Sv; Table A2) in comparison with austral winter 2012.

The direct NVJ appears to be impacted by surface eddies (Fig. 4b, east of 156°E) and fell to 4 Sv (Table A2), as it flows deeper than in austral winter into the Solomon Sea ($\sigma_\theta \sim 26.5$). Above 150 m, the estimated transport is -5 Sv, implying a southward outflow likely induced by persistent cyclonic eddies (Fig. 4b, 156°–157.5°E; east of 159°E), which have been also identified through satellite altimetry (Ganachaud et al. 2016, manuscript submitted to *Elementa*). Farther east near 160°E, a southward current ($0\text{--}10 \text{ cm s}^{-1}$) is observed as during winter 2012, suggesting a downstream inflow along the Solomon Islands.

e. Interior pathways in austral summer 2014

In March 2014, a weaker total volume transport is estimated at 9 Sv (Table 1) between Woodlark and New Britain Islands. The westward NGCU core is slightly less intense but extends down to 800 m depth (Fig. 4f) and is associated with a similar transport (~ 16 Sv; Table A2) to that during July–August 2012. The eastward NBCU is weaker and appears to be less confined against New Britain, and its transport is 14 Sv, half that found in the austral winter cruise (Table A2), with a high-velocity core centered on $\sigma_\theta = 26.5$. Moreover, opposite surface currents are observed along New Britain in March 2014 compared with July–August 2012. Across the transect between Trobriand and Woodlark Islands, we also observe opposite surface currents compared with July–August 2012 (Fig. 4h), associated with a negligible northward transport (Table 1).

f. Northern outflow pathways in austral summer 2014

At St Georges Channel, volume transports are almost halved (~ 4 Sv; Fig. S2d) compared to that found in austral winter, with minor contributions of the surface and AAIW layers. Most of the northward outflow is carried by the SGU (~ 4 Sv; Table A2) between the SLW and SAMW. Across Solomon Strait, a strong surface inflow is found above 150 m, estimated at -6 Sv (Fig. S2d). Volume transports fell to -2 Sv (Fig. S2d) across the Solomon Strait, where the NICU transports northward ~ 3 Sv (Table A2) and ~ 1 Sv is associated with the AAIW (Fig. S2d).

As during July–August 2012, Vitiaz Strait exhibits high velocities (90 cm s^{-1}) at 200 m (Fig. 4j), but the total volume transport was almost halved to 10.9 Sv (Table 1). Near 70% (~ 7 Sv) of this estimate is found

FIG. 5. Mean currents from nonadjusted S-ADCP velocities (arrows) colored by salinity during (left) July–August 2012 and (right) March 2014 for (a),(b) SLW ($\sigma_\theta \sim 24$ –26); (c),(d) SAMW ($\sigma_\theta \sim 26$ –26.9); and (e),(f) AAIW ($\sigma_\theta \sim 26.9$ –27.4) levels.

between the SLW and SAMW, while unlike during austral winter, surface waters and the AAIW have only minor contributions (20% and 13%, respectively).

6. Water mass modifications across Solomon Sea

In this section we focus on salinity, silica, and nitrate distributions vertically averaged within density ranges encompassing the SLW ($24 < \sigma_\theta < 26$), the SAMW ($26 < \sigma_\theta < 26.9$), and the AAIW ($26.9 < \sigma_\theta < 27.4$). Oxygen patterns are similar to salinity with anti-correlated values during both cruises, except for the SAMW (see supplemental materials, Fig. S3). Phosphate distributions are similar to nitrate and so are not shown.

a. The SLW ($24 < \sigma_\theta < 26$)

In July–August 2012, fresh (Fig. 5a), oxygenated (Fig. S3a) waters are associated with the upper NGCU confined along the PNG coast and its streams (SGU and NICU) across and out of the Solomon Sea. Low silica (Fig. S4a) is also associated with the NGCU from its

southern entrance and along its pathway toward Vitiaz Strait, while higher silica is found along the SGU and NICU streams and northeast of Bougainville Island. Saltier waters with lower oxygen and higher silica are carried into the Solomon Sea by the direct NVJ and merge with the NGCU south of the Woodlark Island. These salty waters are significantly eroded by lateral and vertical mixing along their equatorward pathways, with the lowest salinities (< 35.5) found at Vitiaz Strait. Northeast of Bougainville, salty and poorly oxygenated waters are carried by the westward-flowing SEC, but do not seem to intrude into the Solomon Sea. Similarly in March 2014, fresh (Fig. 5b) and oxygenated (Fig. S3b) waters are associated with the upper NGCU, but with higher salinity and oxygen values than those of July–August 2012. The NGCU salinity gradually increases (~ 0.05) as it flows equatorward, likely induced by isopycnal mixing with salty waters coming from Solomon Strait or the southern entrance at $\sim 158^\circ\text{E}$. Silica (Fig. S4b) exhibits similar distributions to that during July–August 2012 along the NGCU and the direct NVJ pathways.

b. The SAMW ($26 < \sigma_\theta < 26.9$)

During both cruises, the NGCU can be tracked within the Solomon Sea through salty and oxygenated waters with low silica and nitrate (Figs. S4c,d and Figs. S5c,d, respectively), confined along the PNG coast. Salinity decreases as the SAMW flows northward during both cruises, in particular south of Woodlark Island, where strong mixing might occur. Northeast of Bougainville Island, fresh and poorly oxygenated waters associated with high silica and nitrate are also found, suggesting a distinct water mass likely emanating from the equatorial region and carried by the SEC.

c. The AAIW ($26.9 < \sigma_\theta < 27.4$)

At the intermediate level and during both cruises, the lower NGCU carries the AAIW salinity minimum (Figs. 5e,f) with high oxygen (Figs. S3e,f), low silica and nitrate signatures (Figs. S4e,f and Figs. S5e,f, respectively) from its southern entrance to its separation south of Woodlark Island. Further north in the mid-basin, where the two NGCU streams rejoin, salinity and silica increase as the AAIW flows toward Vitiaz Strait. After the bifurcation of the NGCU south of New Britain, relatively high salinity is found at St Georges Channel and Solomon Strait. The striking feature is the strong contrast between the interior of the Solomon Sea and waters outside of Solomon Strait, northeast of Bougainville Island. AAIW is exiting through Vitiaz, but cannot be detected through Solomon Strait. Salty and poorly oxygenated waters are observed, with high silica ($>50 \mu\text{mol kg}^{-1}$; Fig. S4e,f) and nitrate ($>30 \mu\text{mol kg}^{-1}$; Fig. S5e,f). As suggested in section 4b, these distinct water properties are clearly related with the EqPIW emanating from the northern branch of the SEC in the eastern Pacific.

7. Discussion

a. Overview of our results

This paper provides a first snapshot of the South Pacific LLWBCs over the upper 1000 m during two contrasted seasons through a key region connecting the subtropics and the equator: the Solomon Sea. From two cruises, we depict the main pathways, associated transports, and water mass properties of the LLWBCs through the Solomon Sea. The July–August 2012 cruise sampled during the strong phase of the trade season, while the March 2014 cruise coincided with the opposite weak trade season. We implemented a new inverse box model configuration using measured S-ADCP velocities and basic conservation requirements to estimate at the cruise scale, velocities, transports, and related uncertainties.

In July–August 2012, we estimate a surface-to-1000-m transport of 36 Sv across the southern entrance with a major contribution from the NGCU, confined along the PNG coast and ~ 50 km wide. At the northern exits, we estimate 19 Sv through Vitiaz Strait, 8 Sv through St Georges Channel, and 11 Sv across Solomon Strait. At the thermocline level, salty waters from the SLW are found, with the freshest waters and low nutrients (nitrate, phosphate, and silica) observed within the equatorward NGCU pathways, confined along the PNG coast. Vitiaz Strait had lower salinity than at the southern entrance of the NGCU (~ 0.05), suggesting an erosion of the salinity maximum as the NGCU flows across the Solomon Sea. Below, the SAMW carries the intense NGCU core associated with salty and oxygenated waters along the PNG coast. At the intermediate level, the AAIW is a prominent feature characterized by a salinity minimum and relatively high oxygen. The water properties in the AAIW are eroded as it flows equatorward along the PNG coast within a narrower NGCU (width ~ 25 km).

In March 2014, the surface-to-1000-m estimated transport is 11 Sv across the southern inflow, again with a major contribution of the NGCU. Transports are 11 Sv across Vitiaz Strait, while ~ 4 Sv exits St Georges Channel. A strong surface inflow is found at Solomon Strait, leading to a total transport estimated to -2 Sv across the strait. These transport estimates do not sum up exactly with small volume imbalances at the southern entrance and across the St Georges–Solomon transect that are lower than transport uncertainties (see Table 1). At the thermocline level, both cruises exhibit freshest SLW at the southern entrance, where the NGCU enters into the Solomon Sea. The SAMW shows similar water properties to that during July–August 2012, but associated with a weaker NGCU. At the intermediate level, lower velocities are found in comparison with July–August 2012, especially at the southern entrance of the NGCU and at Vitiaz Strait. Salinity and nutrient distributions within the Solomon Sea appear to be similar to those found during July–August 2012, where an erosion of the salinity minimum (~ 0.05) is detected along the NGCU equatorward pathways.

Transports from the inversion technique provide realistic mean estimates during the two SPICE cruises, but it is worth comparing with plain geostrophy and adjusted and nonadjusted S-ADCP (Table A3). Across the southern entrance, the surface-1000-m cumulative geostrophic transport referenced to 1700 m is 30 Sv in July–August 2012. Nonadjusted S-ADCP transport is 31 Sv, partly including the negligible Ekman transport, with a difference compared to the adjusted S-ADCP transport of 5 Sv. In March 2014, the surface-to-1000-m geostrophic transport is also referenced to 1700 m (no data at deeper

depths) but reaches only 3 Sv, which represents $\sim 30\%$ of both S-ADCP estimates. Nonadjusted S-ADCP transport is 9 Sv, again with negligible Ekman and a difference of 2 Sv in adjusted transport. The gap between geostrophy and S-ADCP transports is the result of unaccounted transports of 7 Sv between the PNG coast and the first station, where the narrow NGCU carries most of the inflow.

b. How representative are the observed currents during both cruises with respect to climatology?

A strong transport variability was revealed between the two SPICE cruises that occurred during opposite seasons, especially at the surface and thermocline levels. This current seasonality inside the Solomon Sea has been discussed by Melet et al. (2010a,b), Cravatte et al. (2011), and Hristova and Kessler (2012), and our results are quite consistent with their findings. The seasonality results from a combination of basinwide forcings with different phasings, including equatorial dynamics, remotely forced Rossby waves, and monsoon winds. At the exit of Solomon Strait, the current variability is driven both by the annual cycle of the EUC and by remotely forced Rossby waves arriving east of the Solomon Islands. At the entrance of the Solomon Sea, the equatorward inflow seasonal variability is driven by the SEC transport variability south of 10°S , driven by a spinup and spindown of the subtropical gyre at annual time scales (Kessler and Gourdeau 2007). In March, the subtropical gyre spins down, leading to a decreased NVJ transport and a weaker flow entering into the Solomon Sea, consistent with what is observed during the MoorSPICE cruise. In contrast, the SEC arriving at the latitude east of the Solomon Strait is stronger, implying a weaker NICU, weaker currents exiting the Solomon Strait, and a weaker NBCU. A weaker Vitiaz transport is also expected, in part due to the monsoon winds and in part due to mass balance. The opposite situation is observed in July–August 2012 during the Pandora cruise, with a stronger inflow through the southern entrance and a stronger NGCU, NBCU, and NICU.

At the thermocline level (100–300 m), our results are also in good agreement with Cravatte et al. (2011), who observed a strengthening of the NGCU and its branches within the Solomon Sea during JJA and a weakening in DJF from observations. A modeling study (Melet et al. 2010a) has shown quite similar results, but with smaller seasonal variations and larger transport estimations in the straits.

At interannual time scales, a 2007–11 glider time series (Davis et al. 2012) and numerical simulations (Melet et al. 2013) indicated large LLWBC transport variations, as strong as the mean. In the model and the repeated

glider transects, ENSO is identified as the main driving factor of the interior flow (direct NVJ) associated with increasing transports during El Niño and decreasing transports during La Niña. Previous studies (Melet et al. 2010b, 2013) suggest a correlation factor of -0.8 between peak ENSO phase and peak transports with a 3-month lag through the Solomon Sea at the surface and the upper thermocline. Neutral phases of ENSO even existed 3 months prior to both cruises (Fig. 1c), suggesting little ENSO influence on our transport estimates. Moreover, a modeling study (Melet et al. 2010a) inferred that transports through Vitiaz Strait are hydrodynamically constrained by bathymetry, especially during El Niño conditions (Melet et al. 2013); thus, enhanced transports were mainly found at the Solomon Strait exit, although this may have been dominated by the transient eddy phenomena during the cruises. Our results might suggest a less effective hydrodynamic constraint, as Vitiaz transports change by 100% between the cruises.

At higher frequency, large transport variations were observed at the southern entrance of the Solomon Sea from the 2007–11 glider time series over 0–700 m (see Fig. 2 of Davis et al. 2012) and a high-resolution model (see Fig. 7h of Djath et al. 2014) over 0–300 m. Within the Coral Sea, Kessler and Cravatte (2013a) highlighted the influence of mesoscale eddies in generating large current fluctuations and potential aliasing in cross-section transport estimates. A modeling study (see Fig. 12 of Hristova et al. 2014) identified small and intense surface eddies during JJA while larger and much weaker ones were found during DJF, such as the large and persistent cyclonic eddies found in March 2014 at the southern entrance, which strongly impact our transport estimate ($>50\%$ of the total 0–1000-m transport).

Thus, our transport estimates through an inversion model during both SPICE cruises appear to be mostly representative at seasonal time scales rather than at interannual time scales. The July–August 2012 cruise is related with JJA conditions whereas the March 2014 cruise is associated with DJF conditions.

c. How water mass properties within the LLWBCs evolve across the southwest Pacific?

Water masses entering the Solomon Sea from the Coral Sea exhibit different characteristics at different depth levels. They undergo significant transformations as shown in section 6, through mixing processes during their transit across the Solomon Sea. A modeling study (Melet et al. 2011) attributed these water mass transformations mostly to diapycnal mixing ($\sim 60\%$) rather than isopycnal mixing. In our model, vertical diffusivity estimates (κ_z) are not statistically significant to be realistic, and our results are mostly descriptive. A study based on CTD/L-ADCP data

from the two SPICE cruises (M. S. Albery et al. 2016, unpublished manuscript) investigates the strength of diapycnal mixing and its causes in the Solomon Sea.

1) EQUATORWARD PATHWAYS OF THERMOCLINE WATERS

At the upper thermocline ($\sigma_\theta \sim 24.5$), two branches of SPTW can be traced across the Coral Sea from the subtropics (Gasparin et al. 2012, 2014; Grenier et al. 2013; Kessler and Cravatte 2013b) with a salinity gradient $\sim 7 \times 10^{-5} \text{ km}^{-1}$ (170°E – 100°W ; Johnson and McPhaden 1999). A SPTW branch with high salinity and relatively high oxygen originates from the subtropical central South Pacific around 20°S (Grenier et al. 2013). It enters into the Coral Sea north of Vanuatu, then flows within the direct NVJ to ultimately reach the Solomon Sea. A fresher SPTW branch with higher oxygen is formed by subduction in the subtropics around 30°S (Qu and Lindstrom 2002). It flows westward within the North Caledonian Jet (NCJ) into the Coral Sea (Gasparin et al. 2011) before feeding the GPC and ultimately the NGCU south of the Louisiade Archipelago. In our results, the two SPTW branches with their distinct signatures appear to merge south of Woodlark Island, inducing significant water mass modifications. During July–August 2012, the fresher and highly oxygenated SLW is carried along the NGCU pathways to the exiting straits with water property modifications (see section 6a) and is associated with a similar salinity gradient ($\sim 1 \times 10^{-4} \text{ km}^{-1}$) to that found across the subtropics. The salty waters carried by the direct NVJ are associated with a marginally stronger salinity gradient ($\sim 2 \times 10^{-4} \text{ km}^{-1}$) between the southern entrance and the Solomon Sea exits (Vitiaz, St Georges, and Solomon Straits). In March 2014, fresh NGCU waters exhibit a lower salinity gradient ($\sim 4 \times 10^{-5} \text{ km}^{-1}$) than during July–August 2012, suggesting weaker mixing processes associated with the NGCU at the thermocline level. The salty direct NVJ also exhibits lower salinity gradients ($\sim 5 \times 10^{-5} \text{ km}^{-1}$) between the southern entrance and the Solomon Sea exits, likely induced by mixing with surface waters caused by surface transient eddies (see section 5d).

2) EQUATORWARD PATHWAYS OF MODE WATERS

Below the thermocline, the SAMW is carried equatorward within the LLWBCs from the southeastern Pacific near $\sigma_\theta = 27.07$ with low salinity and high oxygen signatures (Grenier et al. 2013). Kessler and Cravatte (2013b) observed these water mass signatures entering the Coral Sea at $\sigma_\theta = 26.5$, corresponding to the 13°C waters, emanating northeast of New Zealand (Tsuchiya 1981; Qu et al. 2009). Across the subtropics, these 13°C waters are strongly related with the SAMW and the

Eastern Subtropical Mode Water (ESTMW) through diapycnal mixing (Qu et al. 2009) and a salinity gradient $\sim 2 \times 10^{-5} \text{ km}^{-1}$ (Johnson and McPhaden 1999). They exhibit higher salinity and higher oxygen as they flow equatorward within the LLWBCs across the Coral Sea to the southern entrance of the Solomon Sea. Our results exhibit significant water mass transformations (see section 6b) as the 13°C waters flow across the Solomon Sea. In July–August 2012, the salty NGCU gets fresher along its equatorward pathways, with a stronger salinity gradient than across the subtropics from the southern entrance and Vitiaz Strait ($\sim 1 \times 10^{-4} \text{ km}^{-1}$). The salinity gradient from the entrance and northeast Solomon Sea exits (St Georges Channel and Solomon Strait) is 10 times higher than across the subtropics ($\sim 2 \times 10^{-4} \text{ km}^{-1}$), which is likely caused by strong diapycnal mixing south of Woodlark Island. In March 2014, the NGCU gets also fresher as it flows equatorward, but with lower salinity gradients that fall by 70% from the southern entrance and Vitiaz Strait and by 50% between the southern entrance and northeast exits. Hence, the weak NGCU that flows into the Solomon Sea in March 2014 is associated with less water mass transformation along its pathways across the Solomon Sea.

3) EQUATORWARD PATHWAYS OF INTERMEDIATE WATERS

At the intermediate level, the AAIW identified as a salinity minimum with high oxygen can be tracked along $\sigma_\theta = 27.2$ from the subtropical gyre to the Coral Sea before reaching the LLWBCs (Qu and Lindstrom 2002; Gasparin et al. 2012; Grenier et al. 2013; Kessler and Cravatte 2013b), with a salinity gradient $\sim 1 \times 10^{-5} \text{ km}^{-1}$ (Johnson and McPhaden 1999). Previous studies based on scattered observations (Tsuchiya 1991; Qu and Lindstrom 2004) tracked this salinity minimum (<34.5) within the Solomon Sea and beyond the equator without strong modifications. In our results, the AAIW undergoes significant transformations (see section 6c) through the erosion of its extrema in salinity and oxygen. During both cruises, the AAIW carried equatorward by the NGCU exhibits higher salinity gradients than across the subtropics ($\sim 3 \times 10^{-5} \text{ km}^{-1}$) from the southern entrance to Vitiaz Strait. However, the salinity gradient between the southern entrance and the northeast exits increased by 70% in March 2014, potentially induced by a salty inflow from the EqPIW. Furthermore, the AAIW layer shows significant mass transports across the Solomon Sea with significant variations between the July–August 2012 and the March 2014 cruises. Downstream in the Bismarck Sea, Zenk et al. (2005) found a mean AAIW velocity core ($\sim \sigma_\theta = 27.2$) near 20 cm s^{-1} from float observations over 1996–98.

TABLE A1. Potential density layers used to construct the inverse box model, which constraints on mass and silica budgets and dimensionless scaling factor applied to the heat and salt anomaly equations (see text for details; NC = not constrained) during July–August 2012 and March 2014 cruises. P and M abbreviate Pandora and MoorSPICE.

Layer	Upper (σ_θ , kg m ⁻³)	Lower (σ_θ , kg m ⁻³)	Mass (Sv rms)	Heat scaling	Salt scaling	Silica (kmolSi s ⁻¹)
1	Surface	22.5	2	NC	NC	NC
2	22.5	24	2	NC	NC	NC
3	24	25.5	2	0.4	0.05	NC
4	25.5	26	1	0.4	0.05	NC
5	26	26.5	1	0.4	0.05	NC
6	26.5	26.7	1	0.4	0.05	NC
7	26.7	26.9	1	0.4	0.05	NC
8	26.9	27	1	0.4	0.05	NC
9	27	27.1	1	0.4	0.05	NC
10	27.1	27.2	1	0.4	0.05	NC
11	27.2	27.3	1	0.4	0.05	NC
12	27.3	27.4	2	NC	NC	NC
Top to 1000 m	Surface	27.4	3	NC	NC	P: ± 147 M: ± 171

They estimated corresponding transports across hydrographic sections (October–November 1996) at 5 Sv into the western Bismarck Sea (near 146°E) and 2 Sv into the eastern Bismarck Sea (near 148°E). These estimates are consistent with our upstream results during July–August 2012, as shown in [section 5](#). From a ~ 1.5 -yr mooring time series (near 2.5°S, 142°E; from October–November 1996 to March 1998) and model results, [Zenk et al. \(2005\)](#) also found the NGCU vertically extended to the AAIW depth level and was associated with significant seasonal variations. Another mooring study ([Kawabe et al. 2008](#)) in the same area from 1998 to 2002 confirmed the NGCU seasonality at the AAIW depth level with high velocities during austral winter and weak velocities during austral summer. This is consistent with our results that suggest a reduced NGCU transport of almost 50% at the southern entrance of the Solomon Sea in March 2014.

Thus, our results show significant water mass transformations within the Solomon Sea, as they flow equatorward in the southwest Pacific LLWBC system. Salinity gradients within the Solomon Sea appear to be higher than across the whole subtropics from the Coral Sea to the eastern Pacific (170°E–100°W). These water mass transformations, mostly found south of Woodlark Island and likely induced by diapycnal mixing, impact downstream water masses through the NGCU, which is a main source to equatorial waters ([Tsuchiya et al. 1989](#); [Fine et al. 1994](#); [Grenier et al. 2011](#)).

4) WATER MASSES NORTHEAST OF BOUGAINVILLE ISLAND

One of the striking results from both cruises is the strong differences between water masses exiting Solomon Strait near New Ireland and those carried along the Bougainville eastern coast, as shown by tracers (see

[section 6](#)). In July–August 2012, geochemical tracers such as aluminum, manganese, and iron also suggest these differences ([Ganachaud et al. 2016](#), manuscript submitted to *Elementa*). During the two SPICE cruises, waters east of Bougainville are likely emanating from the equatorial Pacific, carried by the westward SEC or perhaps by an as-yet-unobserved northwestward Solomon Islands Coastal Undercurrent (SICU) found in a model study ([Melet et al. 2010a](#)). In March 2014, these equatorial Pacific waters are flowing into the Solomon Sea at the surface and intermediate level (see S-ADCP velocities, [Fig. 4d](#)). In July–August 2012, they do not seem to intrude into the Solomon Strait [see S-ADCP velocities in [Fig. 4c](#) and water properties in [Fig. S9](#) in [Ganachaud et al. \(2016](#), manuscript submitted to *Elementa*)]. Waters exiting through Solomon Strait are likely flowing directly northwestward, without influencing waters farther east.

d. Relation with the WWV

Warm waters ($T > 20^\circ\text{C}$) are found above 150 m depth ($\sigma_\theta = 24$) within the Solomon Sea, corresponding to the Tropical Surface Water (TSW; [Table 1](#)). As described in [section 5](#), the two SPICE cruises depict a strong transport variability associated with these warm waters carried equatorward by the LLWBCs. This study highlights the crucial contribution of these LLWBCs for the warm water volume (WWV) recharge/discharge (e.g., [Melet et al. 2013](#); [Hu et al. 2015](#)) with potential impacts on eastern equatorial heat fluxes.

e. Limitations and perspectives

Our analysis based on two oceanographic cruises is limited in many ways, giving a mean representation of

TABLE A2. Main currents across the Solomon Sea and associated volume transports (Sv) during July–August 2012 (Pandora) and March 2014 (MoorSPICE). Positive values are northward or eastward, and negative values are southward or westward. P and M abbreviate Pandora and MoorSPICE.

Main currents	Spatial extent	Upper (σ_θ , kg m ⁻³)	Lower (σ_θ , kg m ⁻³)	Transport estimates (Sv)
At the southern entrance:				
New Guinea Coastal	154°–155°E	24	27.4	P: 18
Undercurrent (NGCU)	154°–155°E	Surface	26.9	M: 12
North Vanuatu Jet (NVJ)	155°–159°E	24	26	P: 8
	155°–156°E	24	26	M: 4
Across Woodlark and New Britain Islands:				
New Guinea Coastal	7.5°–8.4°S	24	27.4	P: 16
Undercurrent (NGCU)	7.5°–8.4°S	24	27.4	M: 16
New Britain Coastal	5.4°–6.1°S	Surface	27.4	P: 28
Undercurrent (NBCU)	5.4°–6.1°S	24	27.4	M: 14
Across St Georges Channel and Solomon Strait:				
St Georges	152.35°–153°E	24	26.9	P: 6
Undercurrent (SGU)	152.35°–153°E	24	26.9	M: 4
North Ireland Coastal	153°–153.75°E	24	26.9	P: 6
Undercurrent (NICU)	153°–153.75°E	24	26.9	M: 3
Across Vitiaz Strait:				
New Guinea Coastal	147.58°–147.88°E	Surface	27.4	P: 19
Undercurrent (NGCU)	147.58°–147.88°E	Surface	27.4	M: 11

the ocean circulation whereas currents, such as the NGCU, are heavily influenced by transient eddies. To address this, and more generally the time variability, nine subsurface moorings were deployed in St Georges Channel and Vitiaz and Solomon Straits in July–August 2012, then recovered and redeployed during the March 2014 cruise before a final recovery in August 2015. These moored data will be used to assess the current variability and heat and salt fluxes through the exit straits of the Solomon Sea in a future study.

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APPENDIX

Constraints and Volume

Constraints used to configure the inverse model are summarized in Table A1. Transport estimates by major

TABLE A3. Volume transport estimates (Sv) across the southern entrance transect from three methods—geostrophy, direct ADCP, and adjusted ADCP through inversion—during July–August 2012 (Pandora) and March 2014 (MoorSPICE). Positive values are northward and P and M abbreviate Pandora and MoorSPICE.

	Geostrophy (reference level at 1000 m)	Geostrophy (reference level at 1700 m)	Geostrophy (reference level at 1800 m)	Nonadjusted ADCP (before inversion)	Adjusted ADCP (after inversion)
P	17	30	31	31	36 ± 2.6
M	4	3	—	9	11 ± 2.6

currents within the Solomon Sea are provided in [Table A2](#). Integrated transports from geostrophy, from direct ADCP, and after inversion across the southern entrance are provided in [Table A3](#).

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