**Title:** Characteristics and Formation of Eastern South Pacific Intermediate Water. 

**Running Title**: Eastern South Pacific Intermediate Water

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**Abstract.** Newly gathered hydrographic data from the Eastern South Pacific is combined with other high-quality data (mainly WOCE) to reassess the properties and boundaries of the Eastern South Pacific Intermediate Water (ESPIW); to date the ESPIW has been only poorly described. The ESPIW core is found off central and northern Chile, between the coast and 90˚W and 20-38˚S. Located at 50-400 m of depth, its temperature varies between 11-13˚C, salinity ranges from 34.1-34.3, and its sigma-t lies between 25.75-26.25 kgm$^{-3}$. ESPIW spreads with the subtropical gyre circulation and can be traced to at

least 150˚W. Formed through the process of subduction southeastward of the wind-driven gyre circulation, the ESPIW communicates surface properties of the waters off central Chile to tropical latitudes.

**Introduction**

The Eastern South Pacific Ocean (ESP) has a rich water mass structure, with waters originating from the equatorial/subtropical Pacific and the Southern Ocean. High saline Subtropical Surface Water (STSW) is formed to the south of about 5°S and to the north of the Subtropical Front, where evaporation greatly exceeds precipitation [Stramma et al., 1995]. Subantarctic Surface Water (SASW) is found to the north of the Subantarctic Front, and is carried northward in the Eastern South Pacific Ocean along the rim of the Subtropical Gyre. Here the Eastern South Pacific Transition Water (ESPTW), with temperatures increasing towards the Equator, is formed [Emery and Meincke, 1986]. Because of its subarctic origins, the ESPTW is low in salinity. However, between about 40-45ºS, there is high precipitation and fresh water runoff from the continent [Dávila et al., 2002] which contributes to create a pool of extreme low salinity of less than 34.0 [Strub et al., 1998] off southern Chile. This low salinity cell appears to extend westward from the coast of South America (> 150ºW), increasing slightly in salinity and creating a tongue of poorly salinated water south of the Suptropical Gyre. This low-saline tongue interrupts the normal low to high salinity gradient from the Antarctic convergence to the subtropics [Deacon, 1977]. Eastern South Pacific Central Water (ESPCW) determines the T-S properties of the thermocline north of the low salinity tongue and west of the ESPTW [Emery and Meincke, 1986; Tomczak and Godfrey, 1994]. Sprintall and

Tomczak [1993] compared surface temperature and salinity across the Subtropical Convergence (STC) of the South Pacific (30˚-45˚S) with the vertical temperature and salinity relationship of the Pacific Central Waters. Their results (their Figure 5) indicate that ESPCW most likely originates in the STC, and mainly in winter between 180˚ and 150˚W.

A shallow salinity minimum layer appears below the STSW [e.g. Reid, 1973; Blanco et al., 2001] and above the Equatorial Subsurface Water (ESSW) off central and northern Chile. High salinity and low oxygen characterize the ESSW. Antarctic Intermediate Water (AAIW) is found below the ESSW; low in salinity and high in dissolved oxygen content, it is formed in the ESP west of southern Chile [McCartney, 1977].

Emery and Meincke [1986] relate the shallow salinity minimum layer to Eastern South Pacific Intermediate Water (ESPIW), however, owing to a severe lack of data in the South Pacific and especially in the ESP, estimates of its properties and its boundaries could only be argued through an analogy with the North Pacific, namely the California Intermediate Water. Here, we follow the terminology of Emery and Meincke [1986] and also relate the shallow salinity minimum to ESPIW owing to its common formation history, which according to Tomczak and Godfrey [1994] defines a water mass**.**

In the beginning of the last decade, the World Ocean Circulation Experiment (WOCE) took place and more high-quality oceanographic data became available for the South Pacific. This data helped us to better understand the properties of ESPIW related to the shallow salinity minimum. Wijffels et al. [2001] detected an "offshore core of very low surface salinities (~34.1) (that) is connected to a shallow salinity minimum that penetrates westward to 95°W below the surface salinity maximum" of the STSW, along the zonal WOCE section P6 at 32º 30' S off central Chile. Tsuchiya and Talley [1998] analyzed the most eastern meridian hydrographic section in the Pacific Ocean along 88ºW (WOCE P19c). They identified a clear vertical salinity minimum at around 250 m between the Subtropical Front (34ºS) and 15ºS that was related to sigma-theta densities between 26.0 and 26.2 $kgm^{-3}$. The authors conclude that the shallow salinity minimum "appears to originate from (the) low-salinity surface water south of the Subtropical Front" and that it "can be explained in the framework of the ventilated thermocline theory of Luyten et al. [1983], as arising from subduction of low-salinity surface water from the south and east underneath the subtropical water by the wind-driven gyre circulation".

Several new hydrographic sections were occupied between the Chilean coast (70ºW) and 110ºW (Easter Island), during 1999 and 2001 at various latitudes off central and northern Chile, and variable extension into the open ocean. These new transects especially cover the region of the core of ESPIW between the coast and about 90˚W, which only has been sampled sparsely during the 1960ies employing bottle casts only. This new data set, together with data starting from 1986, mainly stemming from the World Ocean Circulation Experiment, allow an analysis of the so far only partly described ESPIW, including its properties, its boundaries and its formation process.

**Data**

In this study only, but all on public data sites available, high-quality continuous CTD-profiles are used, between the Chilean coast and 153˚W, and between 5-40˚S.

ENOS, CIMAR and COOK cruises provide recent new original data. A listing of the data sources is given in table 1:

**Properties and Characteristics**

In the ESP, two intermediate water masses exist, namely, the dominating and deeper AAIW and the volumetrically smaller and shallower ESPIW. Both water masses are characterized by salinity minima. In its core region off central and northern Chile, the ESPIW can be defined and easily separated from AAIW as the absolute salinity minimum, a shallow salinity minimum layer between the STSW and the ESSW, which has lower salinities than the deeper AAIW (Fig. 1a and Fig. 1b, dotted dashed line). Within our data set, 149 stations qualify as core stations between the coast of Chile and 90ºW, and between 38ºS and 20ºS. No further core stations could be identified north of the latter latitude and west of 90ºW. The properties of the ESPIW were calculated within its core and are presented in Table 2. Average temperatures, around 12.1˚C with a standard deviation of 1.3˚C, significantly exceed those of the AAIW [Tsuchiya and Talley, Fig. 2, 1998]. The average salinity of 34.2 was associated with only a small standard deviation of 0.08, and was about 0.1 less saline than that of the underlying AAIW at these latitudes (Fig. 1b). The ESPIW outcrops at its southern boundary, at the southeastern edge of the suptropical gyre, between 33-38˚S and 88˚W and off the coast of central Chile (Fig. 2a) where its source water is found, namely the low salinity tongue of the southeast sector of the Pacific, from where it is apparently subducted [Tsuchiya and Talley, 1998], and injected into upper-intermediate depths below the mixed layer following the isopycnal surface of its own density, 25.95 ± 0.258 $kgm^{-3}$. The thickness of the ESPIW core layer is between 150-200 m shortly after subduction and it decreases in northwesterly directions (Fig. 2b). At the same time, its upper boundary deepens, reaching a maximum depth of 225 m along 88ºW between 25-30ºS (Fig. 2a). West of 88ºW and north of 20ºS, the ESPIW loses its quality as an absolute salinity minimum.

**Boundaries**

Owing to its shallow vertical position within the water column, the ESPIW core becomes part of the general subtropical gyre circulation, e.g. described by Tsuchiya [1982] and modeled by de Szoeke [1987]. It spreads northward and westward into the South Pacific Ocean. Vertical isopycnal mixing in its spreading path increases salinity within the layer, although it can still be easily identified as a relative shallow salinity minimum beyond 20ºS and 88ºW, with salinities only slightly higher than those of the AAIW (Fig. 1b, dotted line). However, it is amplified by the presence of the high saline ESSW just below the relative minimum. Further to the northwest, vertical mixing along its spreading path continues and completely erodes the relative shallow salinity minimum (Fig. 1b, dashed line). Nonetheless, ESPIW remains traceable. In the central South Pacific, e.g. 31.5ºS and 134.6ºW (Fig. 1b, solid line), the ESPCW forms a nearly straight line in the TS-Diagram presentation from low salinity and low temperature to high salinity and high temperature. In the northeastern part of the gyre, however, the TS-Diagram has the shape of a knee towards lower salinities within the sigma-t range of 25.75 to 26.5 $kgm^{-3}$ (Fig. 1b, dashed line) indicating the influence of another fresher source of water. Low salinity water is only found in the Antarctic sector of the South Pacific Ocean and within its low salinity tongue that stretches from the coast of South

America towards the central Pacific between 40-45˚S, whose more eastern part has previously been identified as the source of the ESPIW. In order to estimate the ESPIW boundaries, or the geographic region it influences, the average salinity within the sigma-t range of 25.75-26.25, the sigma-t range estimated for its core, was computed for all stations available between the coast of South America, 5-40˚S and 153˚W (Fig. 2c). The ESPIW boundaries reflect the gyre circulation and mark its most western boundary at about 150˚W between 10-17˚S.

**Formation**

The ESPIW formation region can be linked to the outcrop of the shallow salinity minima established by observations (Fig. 2a; 33-38˚S), and the region south of it, where the low salinity cell of the ESP is found. Tsuchiya and Talley [1998] already suggested that the lower-salinity water found to the south of the subtropical gyre is the apparent source of the shallow salinity minimum in the eastern subtropical South Pacific, likely through subduction. A requirement for subduction to take place is the presence of negative Ekman pumping (downward) above the outcrop region and equatorwards of it [Pedlosky, 1998].

Ekman pumping velocity [Tomczak and Godfrey, 1994; Equation 4.2] is computed from monthly mean wind stress curl estimates based on ERS1/2-AMI scatterometers, provided by Ifremer/Cersat. The horizontal resolution of their gridded data set is 1˚ by 1˚ in latitude and longitude. Monthly Ekman pumping velocity was computed for August 1991 to July 1999, and the 8- year average for the ESP is presented in Figure 1c. Highest downward velocities, exceeding $2\times10^{-6}$ $ms^{-1}$ (which equals 63 $myr^{-1}$) are found off central Chile and in the eastern subtropical gyre.

The temperature range of the ESPIW core was found to be between 11-13˚C. The geographical locations of this temperature band are derived from NOAA's Satellite Active Archive 50 km Sea Surface Temperature product for January (shown in blue) and September (shown in red) 2002, and are added to Figure 1c. In January (austral summer), the band is located far to the south, namely between 45-48˚S, and only exposed to weak Ekman pumping. It advances equatorwards to 34-40˚S east off central Chile until September (austral winter), which corresponds to a progression of about 5cm/s, accompanied by a deepening of the mixed layer depth due to surface cooling. Here, the 11-13˚C sea surface temperature band reaches the outcrop zone of the absolute salinity minima, and enters a region of strong downward Ekman pumping between the coast of Chile and 90˚W, thereby triggering subduction and formation of the ESPIW.

**Discussion**

The depth of the shallow salinity minimum layer related to ESPIW deepens from its outcrop region towards the west and the north, as well, which concurs well with the theory of subduction presented by Pedlosky [1998]. The thickness of the layer thins towards the north, owing to conservation of potential vorticity [Keffer, 1985], but it also thins towards the west, indicating isopycnal mixing. The temperature range of the ESPIW core, 11-13˚C, is slightly higher than that stated by Emery and Meincke [1986], who specified its temperature between 10-12˚C. Salinity is within the range (34.0-34.4) given by Emery and Meincke [1986], although the range found for this study, 31.1-31.3, was much narrower. The main difference lies in the depth range of this water mass, which is between about 50-400 m; Emery and Meincke placed it below 500 m. The boundaries of ESPIW at least can be traced till 150˚W which is in good agreement with Reid's [1973] estimates, and hence ESPIW communicates surface properties of the waters off central Chile far west into the subtropical gyre. Further, it appears that in Reid's [1973] plates salinities are somewhat lower, possibly indicating a climate shift.

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**Figure captions**

**Figure 1. a)** Salinity along 80˚W. ESPIW outcrops, related to the shallow salinity minimum, at the southern end of the transect (right), is subducted at 32.5˚S and spreads northward at depths between 150-250 m, below the STSW and above the ESSW. Data stem from September/October 2000 (austral winter), CIMAR-6. **b)** TS-Diagrams. The dotted-dashed line represents an ESPIW core station, featuring its absolute shallow salinity minimum with salinities of 34.1 and temperature of 12˚C (33.00˚S and 73.53˚W). The dotted line shows the ESPIW as a relative shallow salinity minimum just outside of its core (26.99˚S and 87.99˚W). The dashed line represents a knee-shaped station, with the ESPIW mixed into the upper-intermediate layers (23.00˚S and 103˚W). The solid line represents ESPCW (31.51˚S and 134.62˚W). The asterisk denotes AAIW at 50˚S and 88˚W. **c)** Ekman pumping velocity in the ESP. Average Ekman Pumping computed for August 1991 to July 1999. Units are in $10^{-6}$ $ms^{-1}$. SST, derived from satellite data, is included in the figure: Solid red line is 13˚C, September 2002. Dashed red line is 11˚C, September 2002. Solid blue line is 13˚C, January 2002. Dashed blue line is 11˚C, January mean 2002.

**Figure 2. a)** Upper depth of ESPIW core layer and **b)** layer thickness. Depth is given in meters. In b), the dashed line corresponds to the outcrop of the shallow salinity minimum (=0 m of figure a). Contours south of the dashed line refer to the thickness of the low salinity surface layer. **c)** Boundaries of ESPIW. Average salinity within the sigma-t layer 25.75-26.25 $kgm^{-3}$.

**Table 1**. Research cruises included in this study.

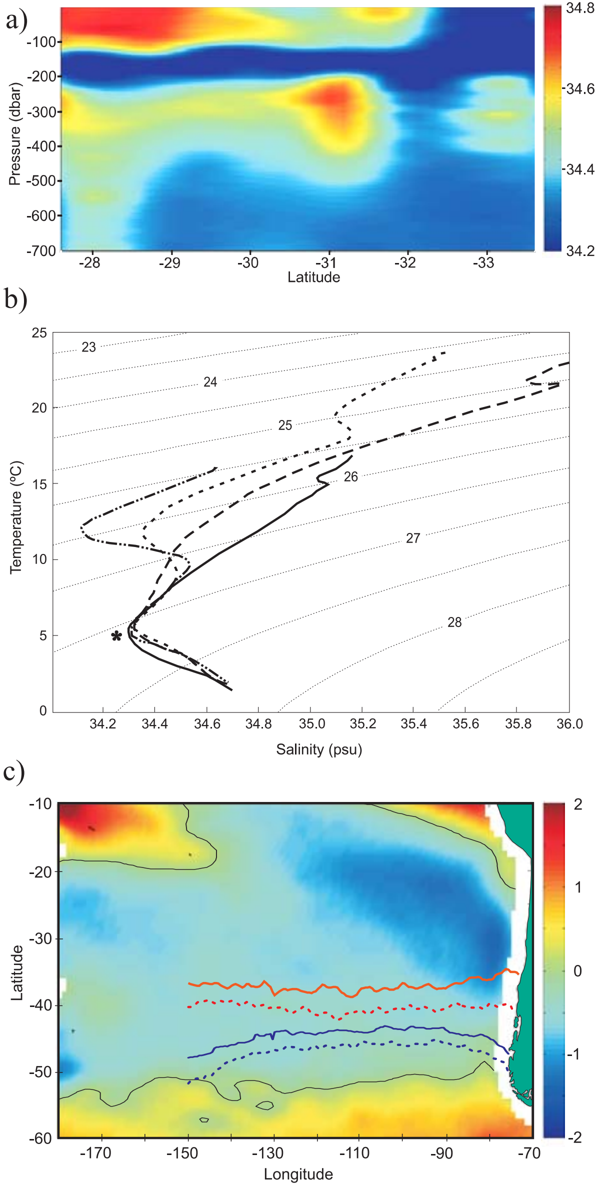
**Table 2.** ESPIW Core. Mean properties and standard deviation.

**Table 1: Research expeditions included**

| Expedition | Year | Transect (along) | From | To |
|---|---|---|---|---|
| | | | | |
| ENOS-5 | 2001 | 26.3˚S | Chile | 75˚W |
| ENOS-5 | 2001 | 27.6˚S | Chile | 75˚W |
| ENOS-5 | 2001 | 29.0˚S | Chile | 75˚W |
| ENOS-5 | 2001 | 30.3˚S | Chile | 75˚W |
| ENOS-5 | 2001 | 31.6˚S | Chile | 75˚W |
| CIMAR-6 | 2000 | 27˚S | Chile | 80.5˚W |
| CIMAR-6 | 2000 | 33˚S | Chile | 82.0˚W |
| CIMAR-6 | 2000 | 80˚W | 33.6˚S | 27.6˚S |
| COOK-2 | 2000 | 20˚S | 71˚W | 85.0˚W |
| CIMAR-5 | 1999 | 27˚S | Chile | 110˚W |
| SONNE 102 | 1995 | 35.25˚S | Chile | 86˚W |
| SONNE 102 | 1995 | 28.25˚S | Chile | 86˚W |
| WOCE P14r | 1995 | 38˚S | Chile | 82˚W |
| WOCE P21 | 1994 | 17˚S | Peru | 152˚W |
| WOCE P18 | 1994 | 103˚W | 40˚S | 5˚S / 110˚W |
| WOCE P19 | 1993 | 88˚W | 40˚S | 5˚S / 85˚W |
| WOCE P17 | 1992 | 135˚W | 40˚S | 5˚S |
| WOCE P6 | 1992 | 32.5˚S | Chile | 152˚W |
| WOCE P16 | 1991 | 152˚W | 40˚S | 5˚S / 153˚W |
| WODATA | 1986 | 15˚S | Peru | 110˚W |

**Table 2: ESPIW Core**

| | Mean | STD |
|---|---|---|
| Temperature (ºC) | 12.15 | 1.36 |
| Salinity | 34.219 | 0.085 |
| Oxygen (micromol/kg) | 199.866 | 45.214 |
| Sigma-t (kg/m$^3$) | 25.945 | 0.258 |


a)
Pressure (dbar)
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b)
Temperature (ºC)
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26
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28
*
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34.6
34.8
35.0
35.2
35.4
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35.8
36.0
Salinity (psu)
c)
Latitude
-10
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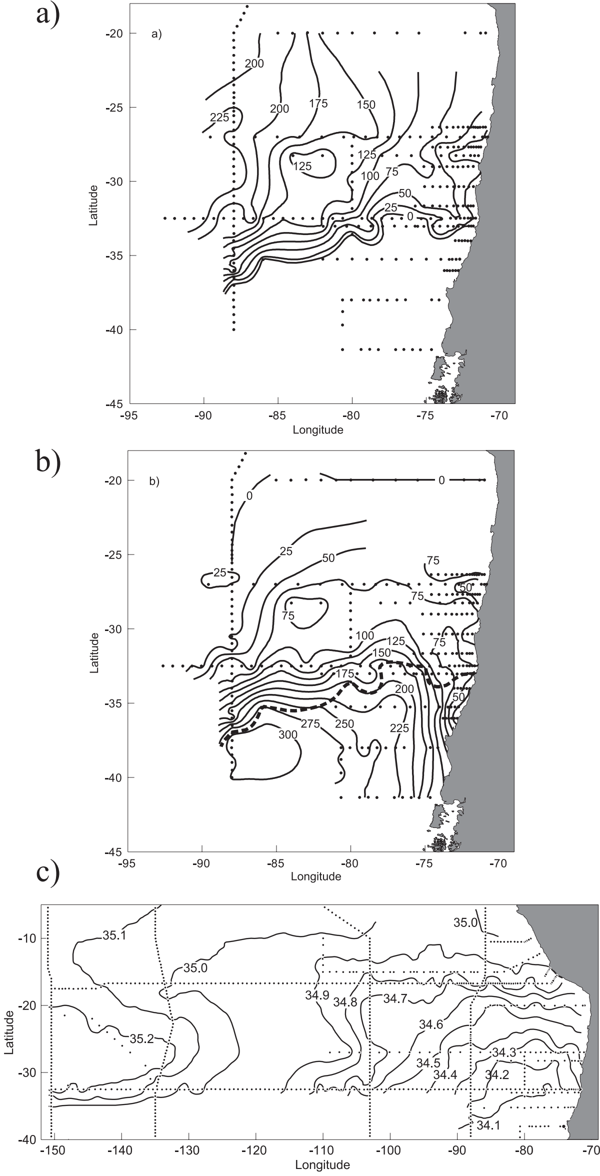
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