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Dual overflows into the deep Sulu Sea

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[1] The Sulu Sea, isolated from the neighboring ocean below 570 m, is nearly isothermal below 1250 m but with a marked salinity increase with depth. The source of the deep Sulu Sea water has been attributed to South China Sea water overflowing the 570 m topographic sill of Panay Strait. However, the Panay overflow (estimated as 0.32 × 10^6 m^3/sec) is an unlikely source for the saltier water Sulu Sea deep water. We propose that deep Sulu Sea ventilation is derived from the south, from the Sulawesi Sea through Sibutu Passage. Sulawesi Sea water between 245 to 527 m, is mixed and heaved over the Sibutu Passage 234 m sill by the energetic tidal environment. Oxygen concentrations within the deep Sulu Sea suggest that the Sulawesi overflow is 0.15 × 10^6 m^3/sec, with a residence time of Sulu Sea deep water of 60 years. The deep tropical Sulu Sea has the unique distinction of being ventilated from two separate sources, whose ratio may fluctuate across a range of temporal scales, associated with regional thermocline depth changes. **Citation:** Gordon, A. L., Z. D. Tessler, and C. Villanoy (2011), Dual overflows into the deep Sulu Sea, *Geophys. Res. Lett.*, *38*, L18606, doi:10.1029/2011GL048878.

1. Introduction

[2] The relentless downward turbulent flux of buoyancy into deep ocean basins requires, for a quasi steady state condition, the replenishment of relatively dense deep water trapped within the confines of an isolated deep basin. In the archipelago stretching from Australia to southeast Asia, there are many isolated deep basins, each filled with different deep water depending on the mixing environment within the deepest passages linking the basin to the surrounding ocean stratification. The Sulu Sea (Figure 1) has been the focus of much attention in terms of its ventilation [*Quadfasel et al.*, 1990; *Tessler et al.*, 2010]; biogeochemistry, biodiversity and geochemistry [*Chen et al.*, 2006; *Nishida and Gamo*, 2007]; and paleo-climate studies [*Linsley*, 1996; *Rosenthal et al.*, 2003].

[3] The source of deep Sulu Sea ventilation is generally considered to be South China Sea water entering the Sulu Sea through the Mindoro and Panay Straits [*Broecker et al.*, 1986]. Recognizing that South China Sea overflow is not sufficiently dense to descend to the Sulu Sea floor, it has been suggested that the density is boosted by substantial addition of suspended sediment [*Quadfasel et al.*, 1990]. The Sulu Sea sedimentary record reveals the effect of episodic turbidity currents, possibly triggered by thermocline uplift in the South China Sea due to the passage of strong typhoons at intervals of several decades (on average 50 years), which may have enabled South China Sea water to ventilate the deep Sulu Sea [*Quadfasel et al.*, 1990]. Turbidity currents are effective ways to deliver shelf and slope sediments into the deep ocean, though their role in boosting the density of the descending fluid is not well established [*Meiburg and Kneller*, 2010]. It has also been suggested that during El Niño, when the South China Sea thermocline is uplifted, denser water can enter the Sulu via Mindoro Strait and so descend to greater depths [*Gamo et al.*, 2007], but as shown below the extend of the required uplift is not realistic.

[4] The PhilEx program [*Gordon and Villanoy*, 2011] provides new information about deep Sulu Sea ventilation. The South China Sea links to the Sulu Sea are the channel composed of the Mindoro Strait (sill 440 m) and Panay Strait (sill 570 m), and the Balabac Strait (sill 132 m, Figure 1). PhilEx stratification and currents observations at the Panay Strait sill at 11.3°N and 121.9°E between June 2007 and March 2009 reveal a strong overflow into the Sulu Sea between 400 m to 570 m depth, derived from approximately 400 m within the South China Sea [*Tessler et al.*, 2010]. Sulu Sea stratification indicates that the overflow does not descend below 1250 m in the Sulu Sea, but rather settles above higher salinity deep water [*Tessler et al.*, 2010]. The mean observed overflow transport at the sill is 0.32 Sv (Sverdrup, Sv = 10^6 m^3/sec) with a standard deviation 0.13 Sv, leading to an 11 years residence time in the 570 to 1250 m Sulu layer. As the Panay overflow estimate is based on a single ADCP mooring with extrapolation to the sidewalls using ship based ADCP data, with there is a fair amount of uncertainty, estimated as 50% if not greater (see *Tessler et al.* [2010] for cross channel extrapolation methods and error estimates). *Lermusiaux et al.* [2011] using the MIT Multidisciplinary Simulation, Estimation, and Assimilation System (MSEAS) model finds a Panay sill overflow of 0.68 Sv, twice that determined by *Tessler et al.* [2010], with a 50% uncertainty. The exact value for Panay overflow would naturally affect the residence time of the Sulu Sea 570–1250 m layer. In this study we offer a hypothesis for the source of the saline water within the Sulu Sea below 1250 m, the limit of the Panay overflow ventilation.

2. Sulu Sea Deep Water Stratification

[5] The deep Sulu Sea potential temperature (θ°C) is nearly isothermal with a weak minimum observed near 2800 m (Figure 2). The minimum is more discernable in the PhilEx data in the southern Sulu Sea (Figure 1), dropping slightly below 9.890°C. The potential temperature increases to 9.893°C towards the sea floor. At 1000 m there is a broad salinity minimum of 34.45, below which the salinity increases to 34.47 at the temperature minimum, increasing to 34.474 at the sea floor (Figure 2a). The θ/S scatter (Figure 2b)

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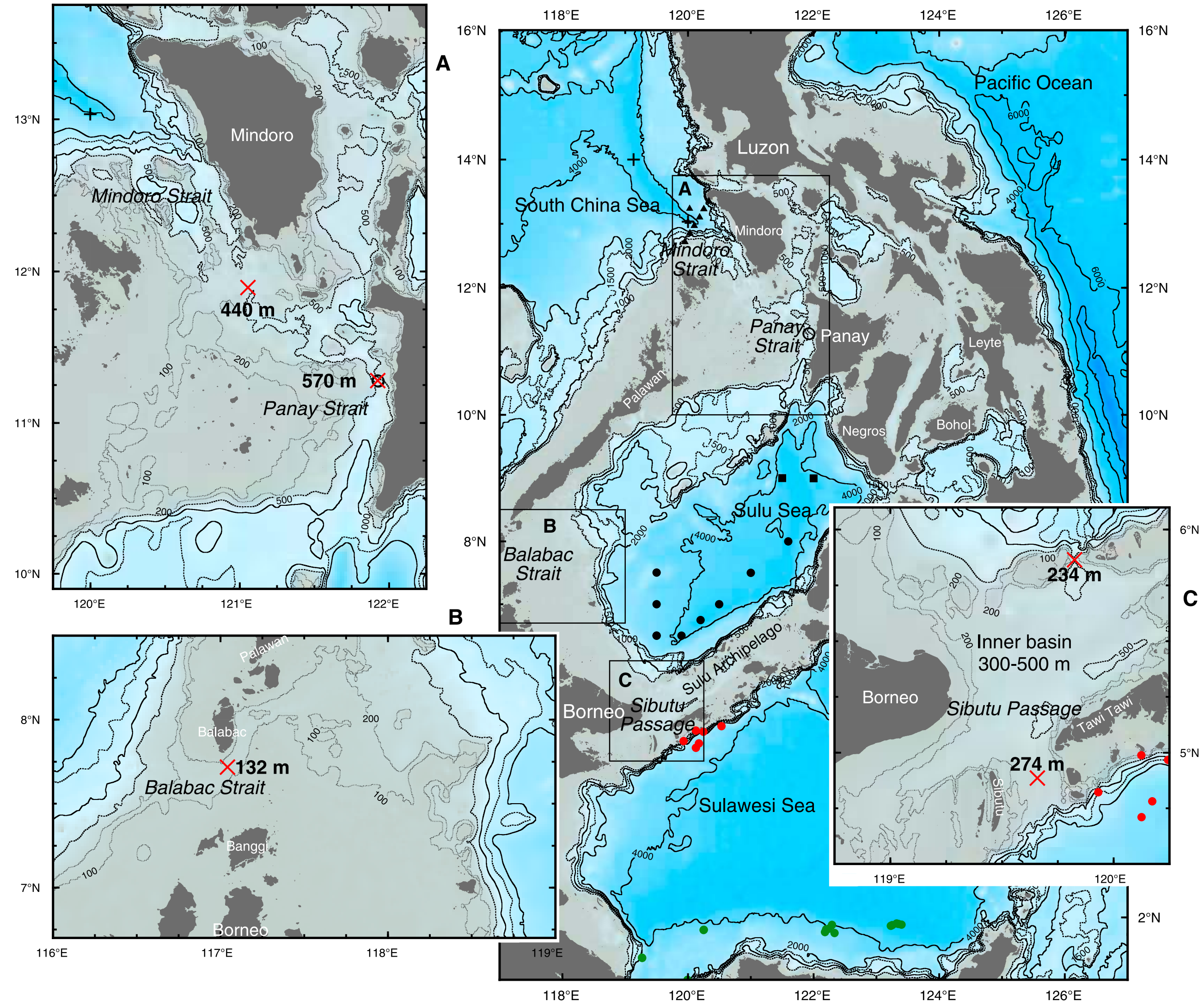

Figure 1. The Sulu Sea and passages to the South China Sea and Sulawesi Sea. The symbols denote positions of temperature and salinity profiles used in the construction of Figures 2 and 3: the green solid circles in the southern Sulawesi Sea are from the Arlindo program 1993–1994 [*Ilahude and Gordon*, 1996]; the red solid circles are at the southern entrance to the Sibutu Passage are from ROV CTD (Conductivity, Temperature, Depth) measurements during October 2007 Inner Space Speciation Expedition, http://oceanexplorer.noaa.gov/explorations/07philippines); the black symbols are CTD were stations obtained during the PhilEx 2007-09 program [*Gordon and Villanoy*, 2011]; the stations in the southern Sulu Sea (black solid circles) were obtained in March 2009. The insets show the passages leading into the Sulu Sea, with the sill depths marked by the red X and depths [*Smith and Sandwell*, 1997].

shows that salinity in the deep Sulu Sea below ~1250 m extends well above the salinity at the Panay sill within the 9° to 10°C layer.

[6] The dissolved oxygen concentration (Figure 2a) decreases from 1.4 ml/l at the salinity minimum to 0.92 ml/l at the potential temperature minimum, below which it remains within the 0.85 to 0.90 ml/l range with slightly higher oxygen values (also slightly cooler water) below the temperature minimum in the southern Sulu Sea. The Panay Strait overflow oxygen concentration range from 1.7 to 2.0 ml/l, about 0.4 ml/l above the Sulu Sea layer ventilated by the Panay overflow. Using the 11-year residence time [*Tessler et al.*, 2010] the oxygen consumption rate in the 570 to 1250 m depth range is 0.035 ml/l-year, about 1.6 times that of the >3000 m deep water of the Sulu Sea [*Gamo et al.*, 2007; if the Panay overflow is twice that found by *Tessler et al.* [2010], as implied by the MSEAS model [*Lermusiaux et al.*, 2011], the 570–1250 m residence time is halved and the oxygen consumption rate doubles to 0.070 ml/l-year]. Decreased oxygen consumption with depth is expected as the ‘rain’ of organic material is depleted with increasing depth.

3. Sulu Sea Bottom Water Source

[7] A single, steady overflow source of South China Sea water over the Panay Strait sill would induce a homogeneous volume within the sub-sill Sulu Sea. The Panay overflow reaches only to 1250 m within the Sulu Sea [*Tessler et al.*, 2010], below which the Sulu Sea salinity is too high to be derived from the South China Sea. To match the Sulu Sea bottom salinity the Panay Strait overflow would have be

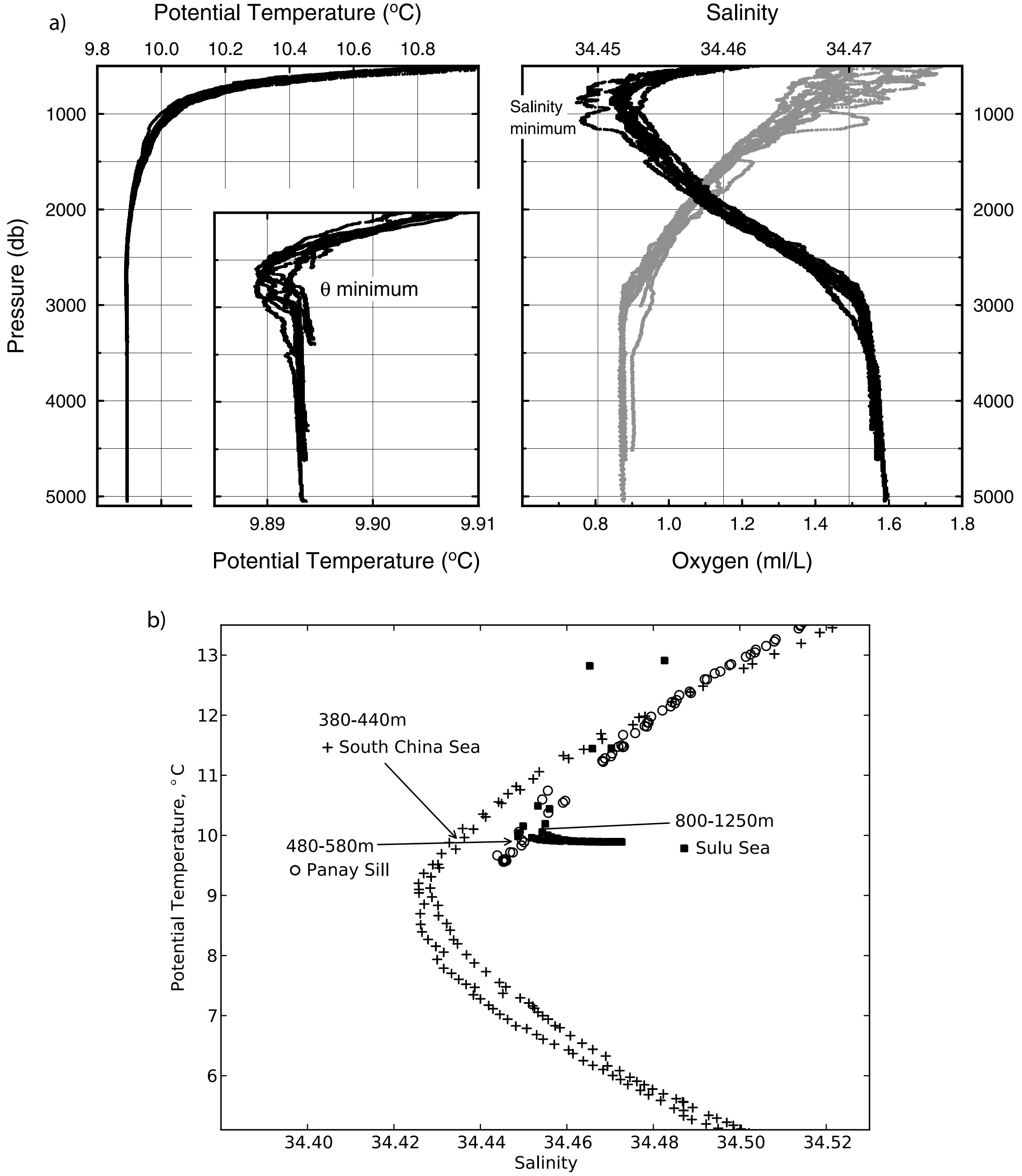

Figure 2. (a) Deep Sulu potential temperature, salinity and oxygen profiles from PhilEx data >500 m within the Sulu Sea, shown in Figure 1. The inset on the left shows expanded potential temperature >2000 m. (b) Deep Sulu potential temperature and salinity relationship [*Tessler et al.*, 2010]. The Sulu Sea bottom water is 34.474. The depths marking the approximate temperature at the Panay sill within Panay Strait is shown for the three regions: South China Sea (+), Panay sill (open circles), and in the northern Sulu Sea (black boxes) (Figure 1).

derived from the 12°C horizon of the South China Sea, well above the deep Sulu Sea potential temperature of 9.9°C. The 6°C isotherm within the South China Sea has sufficiently high salinity to provide the Sulu Sea bottom water, but it's too cold to explain the Sulu deep water, and its depth within the South China Sea is 800 m, 360 m below the 440 m Mindoro sill depth [*Tessler et al.*, 2010]. As the South China Sea near the Mindoro Strait portal displays weak tides, as shown by models that assimilate TOPEX/POSEIDON altimetry data [*Zu et al.*, 2008] this possibility is not tenable. The lack of strong tides also precludes the likelihood that the Sulu Sea bottom water θ/S values can be derived by blending a rather thick water column layer (208 and 830 m) of South China Sea water at the northern end of Mindoro Strait (Figure 3a). The narrow and shallow (132 m sill) Balabac Strait pathway (Figure 1) blocks access of the required South China Sea water into the deep Sulu Sea. The PhilEx CTD data obtained in the small basin between the Mindoro and Panay sills do not reveal the required thermohaline characteristics to provide the observed Sulu Sea bottom water.

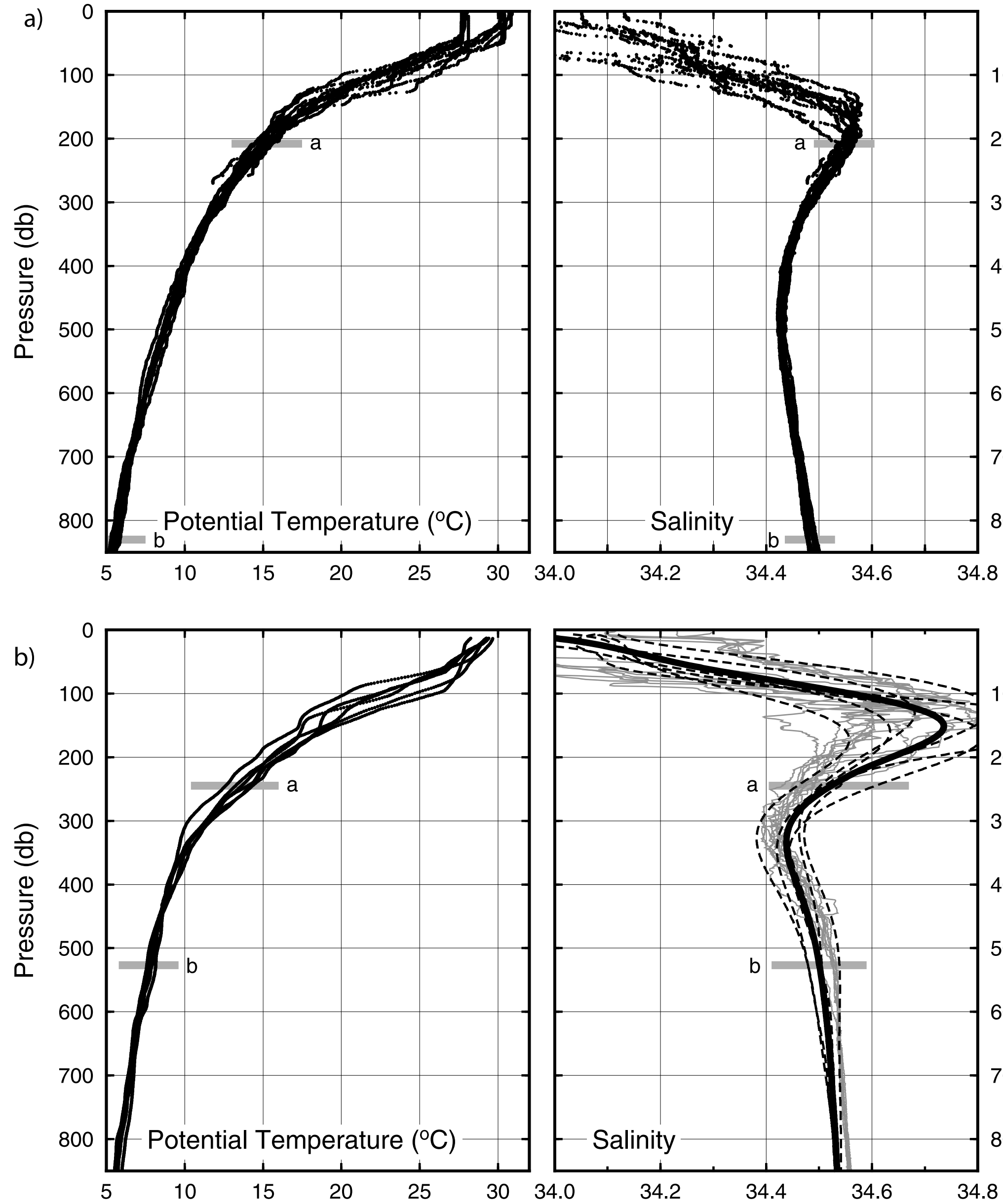

Figure 3. (a) South China Sea potential temperature and salinity profiles for the upper 850 m from PhilEx CTD stations at the northern entrance of Mindoro Strait (Figure 1). Blending the water column from 208 to 830 m, between the 'a' and 'b' indicators, matches Sulu bottom water θ/S (9.89°C; 34.47). (b) Potential temperature and salinity profiles for the upper 850 m at the southern entrance to the Sibutu Passage based on the ROV data (red dots shown in Figure 1). Blending of water column from 245 to 527 m, between the 'a' and 'b' indicator, matches Sulu bottom water θ/S (9.89°C; 34.47). The ROV salinity profiles (dashed line) have been smoothed by a least-squares polynomial fit to remove outlier data point. The mean salinity profile (solid black line), is used to determine the position of the 'blended' water column. For comparison the Arlindo station (green dots in Figure 1) salinity profile are shown as gray lines.

We therefore infer that the bottom water of the Sulu Sea is not derived from the South China Sea.

[8] A more plausible hypothesis for producing the Sulu bottom water is that it is derived from the Sulawesi Sea (Figure 3b) via Sibutu Passage, the deepest access of Sulawesi Sea water to the Sulu Sea. The Sibutu Passage sill is 234 m near the northern edge of the strait, 274 m at the southern sill, with an intervening basin of 500 m (Figure 1) [*Smith and Sandwell*, 1997]. The Sibutu Passage separates very different tidal regimes of the Sulu Sea from the Sulawesi Sea [*Apel et al.*, 1985]. Differences in amplitude and phase causes strong oscillatory tidal currents across Pearl Bank (the region immediately east of the 234 m sill shown in Figure 1, bottom left inset), leading to flow of warm water into the Sulu Sea from the south, which depresses the depth of the thermocline. This trough propagates northward as a series of waves called solitons into the Sulu Sea. Section 2.06, the Sibutu Passage entry in the Sailing Directions for Southeast Asia [*Defense Mapping Agency*, 1993], reads: "Overfalls, 150 miles long and between 3/4 to 1 mile wide, may be encountered in the Sulu Sea during spring tides. Breaking waves of up to 3 m have been reported in the

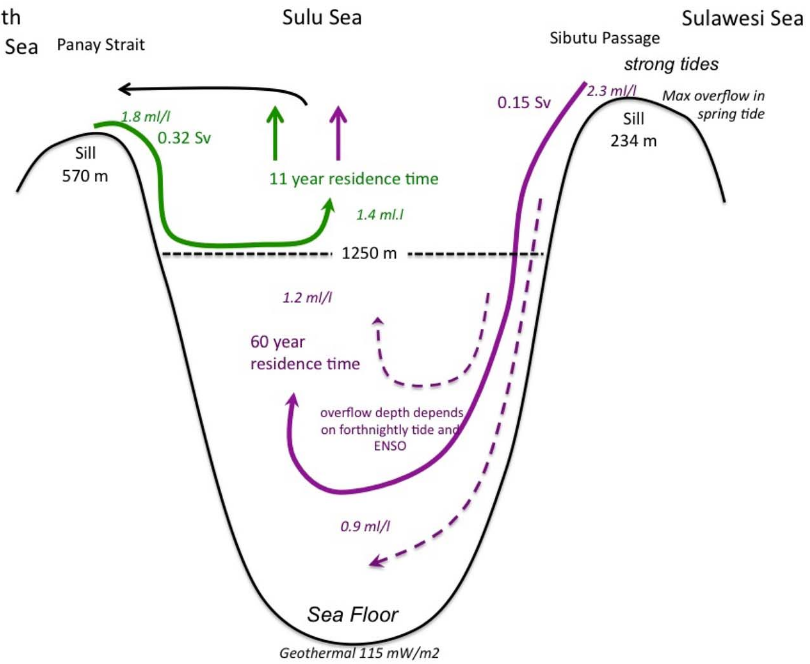

Figure 4. Schematic of the proposed Sulu dual ventilation environment, with the source of the deeper ventilation derived from the Sulawesi Sea via Sibutu Passage and the shallower ventilations drawn from the South China Sea via Panay Strait. The 11-year residence time for the 570–1250 m layer is based on Panay overflow of 0.32 Sv [*Tessler et al.*, 2010]. As the uncertainty is ~50%, with the overflow value likely to be an underestimate, the residence time may be less than 11-years. The residence time below 1250 m is based on the oxygen consumption rates given by *Gamo et al.* [2007].

overfalls. The overfalls appear to be generated by tidal action in Sibutu Passage, where the tides at each end of the passage are about 4 hours out of phase, resulting in a series of waves being formed, 6 miles from crest to crest, moving NNW across the Sulu Sea towards Palawan."

[9] Potential temperature and salinity data from CTD sensors attached to an ROV during the October 2007 Inner Space Speciation Expedition (http://oceanexplorer.noaa.gov/explorations/07philippines) in the northern Sulawesi Sea, close to the southern entrance to the Sibutu Passage, indicate that blending the Sulawesi Sea water of a less than 300 m slab (from 245 to 527 m, Figure 3b) produces the observed Sulu Sea bottom water θ/S characteristics. The lack ROV oxygen data, prohibits the use of those to estimate residence time within the deep Sulu Sea. The archival T/S data in the Sulawesi Sea are sparse and of poor quality. However, the Arlindo 1993 and 1994 CTD stations obtained in the southern Sulawesi Sea [*Ilahude and Gordon*, 1996], which match closely with the ROV profiles near Sibutu Passage (Figure 3b) have oxygen data. The Arlindo data oxygen concentration within the Sulawesi 245 to 527 m depth slab is 2.28 ml/l. As the bottom oxygen in the Sulu Sea is 0.85 ml/l, using the oxygen consumption rate of 0.022 ml/l yr^{-1} (0.97 μMol.kg-year) [*Gamo et al.*, 2007] indicates a residence time in the deep Sulu Sea of 60 years.

[10] The volume of the Sulu Sea below 1250 m is 3.2×10^{14} m^3. With the 60 year residence time the Sulawesi Sea overflow into the deep Sulu Sea via Sibutu Passage is estimated as 0.15 Sv. The Sibutu Passage overflow added to the 0.32 Sv Panay overflow [*Tessler et al.*, 2010] indicates a total ventilation into the sub-sill Sulu Sea of 0.5 Sv.

[11] The MSEAS simulation [*Lermusiaux et al.*, 2011; *Haley and Lermusiaux*, 2010] to the Philippine seas for the February-March 2009 period provides model support for the Sibutu Passage source of bottom Sulu Sea ventilation. The Sibutu Passage simulation portrays strong tidal velocities, with periods of overflow into the deep Sulu Sea modulated by fortnightly tide. They find that the Panay Strait overflow provides salinities around 34.47 to 34.52 while Sibutu Passage overflow is slightly saltier, 34.5 to 34.55. The modeled Sulawesi Sea below 700 m upwells to 200 m to mix within the Sibutu Passage before entering the Sulu Sea [*Lermusiaux et al.*, 2011].The tidally active shallow Balabac Strait is not portrayed in the model as a ventilation source of the deep Sulu Sea [*Lermusiaux et al.*, 2011].

4. Discussion and Conclusions

[12] Mindoro Strait, which provides access of South China Sea to the Panay Strait and Sulu Sea, is not as tidally active as the Sibutu Passage region [*Zu et al.*, 2008]. Additionally, none of the PhilEx cruises observed water cold and salty enough within the Mindoro and Panay Straits to deliver the required θ/S properties to the deep Sulu Sea.

[13] We propose that the Sibutu Passage overflow is achieved in 'surges' of subsill water from the Sulawesi side of the Sulu archipelago lifted to sill depths by tides. This water mixes with shallower water within Sibutu Passage. The Sibutu Passage, albeit shallower than the Panay Strait sill, is able to deliver a denser inflow due to strong tidal uplift of the pycnocline. This effect would be greatest during spring tide. The Sulawesi source most commonly spreads across the Sulu Sea near 2500–3000 m depth, inducing a θ-min at that depth (which is more pronounced in the southern Sulu Sea), below which the θ increases to the sea floor, but is stabilized by increased salinity with depth, so it seems not to

be a product of geothermal heating (which would not cause the increasing salinity with depth), but rather the nature of the deep ventilation (Figure 4).

[14] The Sulawesi Sea thermocline stratification is stronger than that of the South China Sea. Whereas the 21°C isotherm is about 120 m in both the South China and Sulawesi Seas, the 10°C isotherm is at 325 m in the Sulawesi and 420 m in the South China Sea (Figures 3a and 3b). This enables tidal uplift in the Sulawesi Sea to be more effective in injecting dense water into the Sibutu Passage.

[15] The deep Sulu Sea is ventilated from two sources, the Panay Strait and the Sibutu Strait (Figure 4). The northern source allows South China Sea water to ventilate the Sulu Sea from 570 m to 1250 m, and the southern source allows Sulawesi Sea to enter and descend to the 2800 m θ-min and occasionally, during strong El Niño events when the regional pycnocline is shallower and dense water more in reach of the topographic sills, to the bottom of the Sulu Sea. The dual ventilation source of the Sulu Sea leads to a unique deep stratification: while the deep temperature is 9.9°C, once below 1250 m the salinity increases to the sea floor. It is hypothesized that the ratio of the competing overflows into the deep Sulu Sea will change in their relative importance with ENSO and longer periods that alter the Pacific thermocline configuration (do the dual sources duel for dominance?). As Sulu Sea sediment cores have been used to investigate the glacial/inter-glacial climate, assuming a single ventilation source from the South China Sea, perhaps their interpretations need to be reconsidered.

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