Dramatic impact of the South China Sea on the Indonesian Throughflow

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[1] Using OGCM experiments with and without the South China Sea throughflow, it is shown that this throughflow plays an important role in generating the subsurface maxima in the meridional velocity of the Makassar Strait throughflow. The maximum in the southward flow is located at subsurface around 110 m in the control run, whereas that exists near the surface without the South China Sea throughflow. This results in 0.18 PW difference in the southward heat transport by the Makassar Strait throughflow, suggesting that the South China Sea throughflow may play an important role in climate variability of the Indo-Pacific region. Furthermore, the South China Sea throughflow, which undergoes a seasonal variation with a maximum in boreal winter, significantly influences the simulated seasonal variation in the Makassar Strait throughflow. Citation: Tozuka, T., T. Qu, and T. Yamagata (2007), Dramatic impact of the South China Sea on the Indonesian Throughflow, Geophys. Res. Lett., 34, L12612, doi:10.1029/2007GL030420.

1. Introduction

[2] The Indonesian Throughflow plays an important role in the global climate variability on seasonal to millennial timescales as it transports large amount of heat from the Pacific Ocean to the Indian Ocean. Not only does it modulate the temperature and salinity distribution and oceanic circulation of the Indian and Pacific Oceans [Hirst and Godfrey, 1993; Lukas et al., 1996; Schneider, 1998], but also influences the seasonal upwelling and currents along the southern coast of Sumatra and Java [Du et al., 2005; Iskandar et al., 2006], the interannual SST variability associated with ENSO events [Lee et al., 2002], the decadal modulation of Indian Ocean Dipole events [Tozuka et al., 2007], and even the global thermohaline circulation [Gordon, 1986; Shriver and Hurlburt, 1997].

[3] One interesting feature observed by recent mooring observations in the Makassar Strait, which is the major pathway of the Indonesian Throughflow, is the strong vertical shear in the meridional current profile [Gordon et al., 2003]. The mean surface current is southward with the magnitude of 0.35 m s⁻¹, and the maximum of 0.43 m s⁻¹ exists at a depth of 160 m [Susanto and Gordon, 2005]. This profile has a significant impact on the heat transport of the Indonesian Throughflow [Frances et al., 2002; Song and Gordon, 2004] as the suggested transport-weighted temperature was at least 9°C colder than earlier estimates.

[4] Gordon et al. [2003] attributed this current profile to regional winds over the Java Sea. They claimed that the northwesterly monsoon wind during boreal winter drives buoyant, low-salinity Java Sea surface water into the southern Makassar Strait, generating a northward pressure gradient that inhibits the southward flow near the surface. On the other hand, Qu et al. [2005] recently suggested that the South China Sea throughflow (SCST), a cyclonic circulation around Philippines-Borneo that is forced by the large-scale wind of the tropical Pacific, affects the near surface flow in the Makassar Strait and leads to the subsurface maximum in the southward current of the Makassar Strait. The latter was drawn from high-resolution OGCM results, which showed a northward “relative” surface current (relative to 100 m) traced back to the Luzon Strait. However, this hypothesis has never been discussed quantitatively; this is the main motive of the present study.

[5] As a first step toward understanding the importance of the SCST in the Indonesian Throughflow and climate variability of the Indo-Pacific region, we have conducted two experiments with and without the SCST in an OGCM. The content is organized as follows. A brief description of the OGCM used in this study is given in the next section. In Section 3, we discuss the role of the SCST on the vertical structure and seasonal variation of the Makassar Strait throughflow. The final section summarizes the main results. An impact on the thermal structure of the South China Sea is also discussed.

2. OGCM

[6] The ocean general circulation model (OGCM) used in this study is based on version 3.0 of the Modular Ocean Model (MOM3.0), which has been developed at the National Oceanic and Atmospheric Administration (NOAA)/Geophysical Fluid Dynamics Laboratory (GFDL) and the basic equations are given by Pacanowski and Griffies [1999]. Our model covers the global ocean from 65°S to 65°N. The horizontal resolution varies from 0.4° in the region 92°E-140°E, 16°S-30°N to 2° in the outer region (Figure 1). The horizontal resolution is not very high, but it is enough to capture the major features of the SCST and the Makassar Strait throughflow. Also, we plan to couple the same OGCM to an atmospheric general circulation model (AGCM) for coupled model studies on the importance of the SCST. There are 25 vertical levels with 11 levels in the upper 180 m. The bottom topography and coastlines adopted in this model are based on 5-min Earth Topography...
(ETOP05) dataset. The lateral eddy viscosity and diffusivity are based on the formula given by Smagorinsky [1963]. Near the southern and northern boundaries (poleward of 61 S and 61 N), the values of these coefficients are increased steadily so that the damping time scale reaches one day at 65 S and 65 N. The temperature and salinity are relaxed to the annual mean climatology [Levitus and Boyer, 1994; Levitus et al., 1994] within the sponge layer so that artificial wall effects are reduced. The vertical eddy viscosity and diffusivity are calculated using the parameterization of Pacanowski and Philander [1981].

Two experiments are conducted in the present study. For both experiments, the model is spun up for 11 years by the annual mean wind stress and surface heat flux data from the NCEP/NCAR reanalysis data [Kalnay et al., 1996]. The initial condition is the annual mean climatology [Levitus and Boyer, 1994; Levitus et al., 1994] with no motion. Also, the sea surface temperature (SST) and salinity are restored to the annual mean climatology with the relaxation time scale of 30 days. Then, the model is further integrated for 10 years using the monthly mean wind stress and surface heat flux data from the NCEP/NCAR reanalysis data and the model SST and SSS are restored to the monthly mean climatology. Outputs from the last four years are analyzed here. The SCST is allowed in a Control Run (CTRL), whereas it is prohibited by closing Luzon Strait, Taiwan Strait, Mindoro Strait, and Karimata Strait in a No South China Sea Throughflow Run (NOSCST).

3. Results

Prior to investigating the circulation in the South China and Indonesian Seas, it is necessary to check the validity of the present model results. Figure 2 shows the annual mean whole-column integrated volume transport through important straits. We note that it is rather difficult to obtain mean transports through these straits in observation because of the high variability of the currents and the complicated coastline and topography of the strait. Also, the model flow tends to be weaker than observations as the...
resolution of the present OGCM requires relatively large viscosity for numerical reasons. However, the simulated transport through the Luzon Strait is 3.6 Sv, which is in agreement with estimates by the hydrographic observation (6 ± 3 Sv) [Tian et al., 2006] and Godfrey’s [1989] Island Rule (4.2 Sv) [Qu et al., 2000]. The simulated transport through the Makassar Strait is 4.6 Sv, which is somewhat smaller than prior observational estimates [e.g., Susanto and Gordon, 2005]. The weaker Makassar Strait throughflow may result in overestimation of the SCST impact, but the qualitative results presented in this study should not change. Finally, the simulated transports through the Lombok Strait, Ombai Strait, and Timor Passage are 2.0 Sv, 1.8 Sv, and 2.4 Sv, respectively, in reasonable agreement with prior observational estimates of 2.6 ± 0.8 Sv, 2.6 ± 0.8 Sv, and 3.2 ± 1.8 Sv [Hautala et al., 2001]. Therefore, we expect that this model can provide useful insight into the circulation in the Indonesian and South China Seas.

[9] The average vertical profiles of the meridional velocity at 3°S in Makassar Strait are shown in Figure 3a. In CTRL, the model is successful in reproducing the subsurface maximum; the southward velocity increases from 0.05 m s\(^{-1}\) near the surface to 0.13 m s\(^{-1}\) at 110 m depth and then decreases again to less than 0.03 m s\(^{-1}\) at a depth of about 270 m. The shallower maximum in velocity compared with the observation may be related to the vertical resolution of the OGCM. In contrast, when the SCST is blocked, the meridional velocity shows its maximum at the surface with 0.27 m s\(^{-1}\) and decreases to a negligible value below a depth of about 270 m. This demonstrates that the SCST significantly reduces the southward flow near the surface and thus plays an important role in generating the subsurface maximum in the Makassar Strait throughflow.

[10] As a result of this change in the velocity profile, the transport-weighted temperature changes drastically from 19.3°C in CTRL to 21.4°C in NOSCST. Also, the volume transport of the Makassar Strait throughflow increases by 1.5 Sv from 4.6 Sv in CTRL to 6.1 Sv in NOSCST (Figure 2). This has a significant impact to the heat transport; it increases from 0.38 PW in CTRL to 0.56 PW in NOSCST when a reference temperature of 0°C is used. The above results support the earlier hypothesis that the SCST has a large impact on the heat transport by the Indonesian Throughflow [Qu et al., 2005] and likely to play a more active role than previously thought in regulating...
the temperature pattern and thus climate variability in the Indo-Pacific Ocean [Qu et al., 2006].

[11] Furthermore, the SCST exerts even greater influence during boreal winter (Figures 3b and 3c). The flow through the Makassar Strait is surface intensified and southward for the whole column in NOSCST, whereas it is northward near the surface and southward in the subsurface in CTRL during boreal winter. The velocity profile does not change much in both NOSCST and CTRL in boreal summer. This is because the SCST is dominant only during boreal winter.

[12] As a result, the volume transport varies from southward 7.8 Sv in August to northward 0.4 Sv in December and the heat transport varies from southward 0.70 PW in August to northward 0.01 PW in January for CTRL (Figure 4). On the other hand, the volume and heat transport in NOSCST are dominated by semiannual harmonics and the amplitudes are significantly smaller. Thus, the SCST plays a determining role in the seasonal variation of the volume and heat transport through the Makassar Strait.

4. Conclusions and Discussion

[13] Comparing OGCM outputs with and without the South China Sea throughflow (SCST), we have demonstrated that the SCST, which is associated with fresher water [Gordon et al., 2003; Qu et al., 2005], does play an important role in forming the observed subsurface maximum in the meridional velocity of the Makassar Strait throughflow by inhibiting the upper part of the southward flow. This results in 0.18 PW difference in the southward heat transport by the Makassar Strait throughflow, suggesting that the SCST may play an important role in climate variability of the Indo-Pacific region. Furthermore, in addition to the large-scale wind [Wajsowicz, 1999] and the non-equilibrated pressure field originating from the equatorial Indian Ocean discussed by Yamagata et al. [1996], the present study suggests for the first time that the SCST significantly influences the seasonal variation of the Indonesian Throughflow.

[14] Although we have concentrated on its impact on the Makassar Strait throughflow in this study, our experiments also show significant differences in the thermal structure, especially in the South China Sea (figure not shown). The South China Sea becomes warmer by as much as 2.5°C in the upper 50 m when the SCST is blocked. This is because the water that enters through the Luzon Strait is colder compared with the water that exits through the Karimata and Mindoro Straits at shallower depths [Qu et al., 2004]. This temperature increase is equivalent to a surface heat gain of about 0.2 PW over the entire South China Sea, which is primarily balanced by the heat export of SCST conveyor belt [Qu et al., 2006]. We note that the effect of SCST may be underestimated in this study because of the restoring of SST to the climatology.

[15] Since this particular region in the world ocean has high SST, even a small change in the SST may lead to a significant change in terms of coupled dynamics [cf. Graham and Barnett, 1987]. For instance, the SST difference between the South China Sea and the western tropical Pacific generates an atmospheric pressure difference and is considered to play a role in triggering the zonal wind stress anomaly in the western equatorial Pacific and thus ENSO events [Yamagata and Masumoto, 1992]. Therefore, future studies investigating the role of the SCST in a coupled GCM are expected to improve our understanding of climate variability.

[16] It will be also interesting to apply our hypothesis to paleo-climate. During the Last Glacial Maximum, when thick ice sheets covered large areas in northern latitudes, the sea level was actually lower by about 130 m [Tokayama et al., 2000]. This is large enough to block the shallow straits of the South China Sea and suggests a complete shutdown of the SCST in the past. In fact, measurements from surface- and thermocline-dwelling planktonic foraminifers suggest that the vertical profile of the Indonesian Throughflow changed from surface intensified flow to thermocline dominated flow toward the end of Termination II as the sea level became higher [Xu et al., 2006]. Our theory successfully explains this interesting change in the vertical profile of the Indonesian Throughflow [Kuhnt et al., 2004]. This change modifies the heat export by the Indonesian Throughflow from the western Pacific warm pool. Thus, the SCST can even be an important factor to global climate change on orbital time-scales.

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