Do tropical cells ventilate the Indo-Pacific equatorial thermocline?

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Abstract. Source waters of the Indo-Pacific equatorial thermocline are studied with a high-resolution ocean model. In the annual mean fields, tropical and subtropical overturning cells are found that upwell at the equator and downwell at 5 degrees and 20 degrees poleward of the equator respectively. Tropical cells are common in ocean models, but their role in ventilating the equatorial thermocline is obscure because the downwelled water is too warm to match the subsurface equatorial waters. The tropical cells are much weaker when the overturning is considered in density coordinates. When high-frequency mass fluxes are included tropical cells are compensated by an eddy-induced overturning. Seasonal variations and tropical instability waves are responsible for the compensation. It follows that only subtropical cells transfer surface water to the equatorial thermocline. Strong tropical cells are shown to be an artefact.

1. Introduction

In the upper tropical and subtropical oceans, overturning cells transfer heat and salt in the meridional direction. These cells play an important role in ventilating the equatorial thermocline and have an impact on phenomena such as El Niño that depend critically on the mean state of the equatorial thermocline.

The eastward flowing Equatorial UnderCurrents (EUCs) in the Atlantic and the Pacific have relatively high densities. Since vertical mixing in the equatorial region is not excessive [*Johnson and Luther*, 1994] this implies that the source waters of the EUC are situated in the extratropics [*Wyrtki and Kilonsky*, 1984]. The ventilated thermocline theory provides a framework that explains the oceanic connection between the extratropics and the equator [*Pedlosky*, 1987]. *McCreary and Lu* [1994] applied the theory to an idealized model and showed the existence of the subtropical overturning cell (STC) with a downwelling branch around 20°N and upwelling at the equator. At the surface Ekman divergence transports the water poleward again. Evidence for subsurface pathways of water from the extratropics to the equator came from tracer and salinity measurements [*Fine et al.*, 1987; *Johnson and McPhaden*, 1999].

In elaborate numerical ocean models also strong tropical cells (TC) transfers water subsurface towards the equatorial thermocline [*Philander et al.*, 1987; *Kessler et al.*, 1998]. This cell has its downwelling branch around 5°N. *Wyrtki and Kilonsky* [1984] point out that Ekman convergence might drive this cell. However, there is not much observational evidence for the TC. Also, the downwelled tropical water must cool to match with the relative cold water of the EUC. A mechanism for this cooling is not known, especially since the vertical mixing is observed to be too small to accommodate such cooling.

Here we investigate the STC and TC in a high-resolution ocean model. Oceanic high-frequency variability may be important for the overturning cells. For instance, in the tropical Atlantic large eddies occur in the northward flowing Brazil Current. Moreover, instability waves on a submonthly time scale occur in all tropical oceans [*Legeckis*, 1977; *Halpern et al.*, 1988].

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2. Methodology

2.1. Ocean model

We analyzed data obtained form calculations with the high high-resolution global ocean model OCCAM [*Webb et al*, 1997]. This model has realistic topography, a horizontal resolution of 0.25°, and 36 vertical levels with variable thickness. A Laplacian horizontal diffusion and friction is used. The diffusion coefficient is 100 m^2s^{-1} and the viscosity coefficient is 200 m^2s^{-1}. For the vertical mixing of tracers the Pacanowski and Philander scheme is used. A Laplacian mixing with a coefficient of 1 cm^2s^{-1} is applied to the velocity fields. The sea surface temperature (SST) of the model is relaxed to observed monthly mean SST [*Levitus et al.*, 1994]. The fresh water flux is derived from the difference between the simulated surface salinity and that of the Levitus dataset. The model has been spun up for 12 years with monthly mean winds and wind stresses from ECMWF [*Gibson et al.*, 1997]. In the following 3 years six-hourly winds and wind stresses were used. We employed five-day running mean data from the last three years of the model run. The simulated mean circulation in the Pacific has been discussed and compared with observations by *Saunders et al.*, [1999].

2.2. Data processing and analysis

A convenient diagnostic to study meridional transports is the meridional stream function. It is mostly determined using long-term mean transports in Cartesian coordinates. There are two caveats when this procedure is followed. Firstly, the subsurface motion in the tropical Pacific is essentially three-dimensional and mainly follows isopycnal surfaces [*Bryden and Brady*, 1985]. In the EUC the isopycnals are slanted. So spurious upwelling and downwelling may occur when the transports are integrated meridionally at constant z levels. We therefore compute and compare stream functions in level and in density coordinates. Secondly, high-frequency eddy motions induce a mass transport in addition to the transport by the Eulerian mean flow due to correlations between velocity and isopycnal thickness variations.

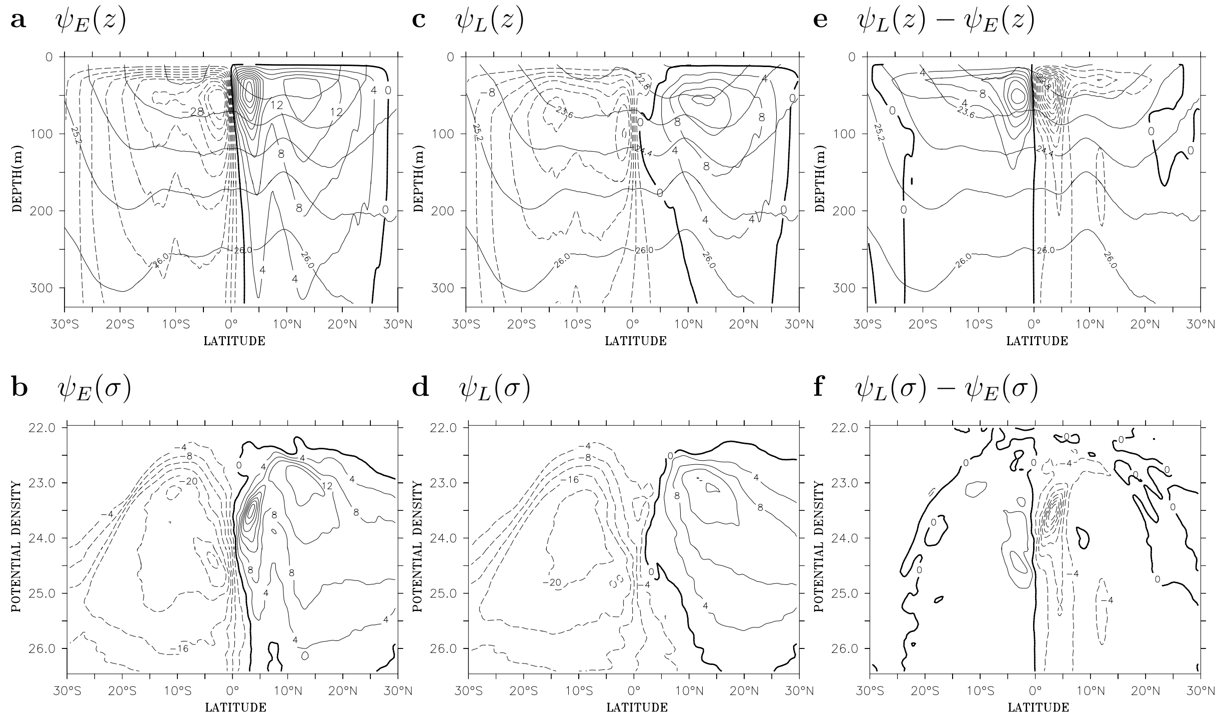

Figure 1. Eulerian and Lagrangian meridional stream function in the Indo-Pacific Ocean (in Sv=10^6 m^{3}s^{-1}). (a) $\psi_E(z)$, (b) $\psi_E(\sigma)$ (c) $\psi_L(z)$ (d) $\psi_L(\sigma)$ (e) $\psi_L(z)$-$\psi_E(z)$ (f) $\psi_L(\sigma)$-$\psi_E(\sigma)$. Zonally averaged potential density (kg m^{-3}) contours are overlayed in (a,c,e).

This eddy-induced circulation has to be taken into account when determining total transport by meridional cells [*Döös and Webb*, 1994; *McIntosh and McDougall*, 1996]. This can be done by time averaging the mass transports on isopycnals instead of constant z levels. Isopycnal mass transports vh_σ at every point are calculated using an interpolation scheme to determine the physical height of potential density (σ) surfaces to get the layer thickness $h_\sigma = h(x, y, \sigma, t)$. We employed a discretization of $\Delta\sigma = 0.01$ kg m^{-3}. At every gridpoint the averaged isopycnal transport is transformed back to a z level transport using the averaged layer thickness.

3. Results

3.1. Meridional Overturning Cells

Fig. 1a shows the meridional stream function in the Indo-Pacific in z coordinates: the Eulerian mean circulation $\psi_E(z)$. Fig. 1 In both hemispheres a STC is found. The downwelling branches are around 25°N and 30°S. Upwelling occurs at the equator driven by divergent Ekman flow. These results are comparable to those found in other ocean models. Also TCs are present. Downwelling takes place five degrees poleward of the equator and upwelling at the equator. The cells are strong. For instance, in the Northern Hemisphere the TC transports up to 24 Sv (1 Sv = 10^6 m^3/s) in addition to the 12 Sv provided by the STC.

Mass transports should be integrated along isopycnal surfaces to determine the diapycnal motions associated with overturning cells. An Eulerian mean circulation in σ-coordinates [$\psi_E(\sigma)$] is then obtained in which STCs are still present (Fig. 1b). However, the strength of the TCs decreases. In both the Northern and Southern Hemispheres the TC weakens by 4 Sv. Note that also the STCs weaken.

The Lagrangian mean circulation $\psi_L(z)$, obtained using isopycnal transports vh_σ, exhibits a strikingly different picture (Fig. 1c). Especially for the Northern Hemisphere the impact of the eddies is huge. The eddies appear to compensate the TC entirely. Also in the Southern Hemisphere the TC has been reduced, but a cell is still present. Note that, exept for near the surface, Lagrangian mean depths and Eulerian mean depths hardly differ.

To eliminate the effect of sloping isopycnals we show the Lagrangian mean circulation in σ-coordinates [$\psi_L(\sigma)$]. Now the Southern Hemisphere TC vanishes as well (Figure 1d). So, in the present model TCs are not related to diapycnal transports and do not feed the equatorial thermocline. Eddies (defined as the departure from the annual Eulerian mean) induce an equatorward flow at the surface in tropics and a poleward flow at depth (Figure 1e,f). In the Northern Hemisphere eddies act almost entirely on intraseasonal time scales. In level coordinates 8 Sv of the Northern Hemisphere TC is compensated due to seasonal variations. The remaining 16 Sv is due to higher frequency variations. In density coordinates these numbers are 9 Sv and 11 Sv respectively. On the Southern Hemisphere seasonal variations are more important in compensating the TC. The reduction of 4 Sv is entirely due to seasonal variations. In density coordinates 7 Sv is due to seasonal variability and 1 Sv due to higher frequency variations.

From $\psi_L(\sigma)$ we note that the EUC is much better ventilated from the Southern Hemisphere than from the Northern Hemisphere. This is in accordance with transport estimates from in situ data [*Johnson and McPhaden*, 1999].

3.2. High-frequency variability in the tropics

The seasonal variations that compensate the TC mainly consist of a meridional displacement of the STC. In general

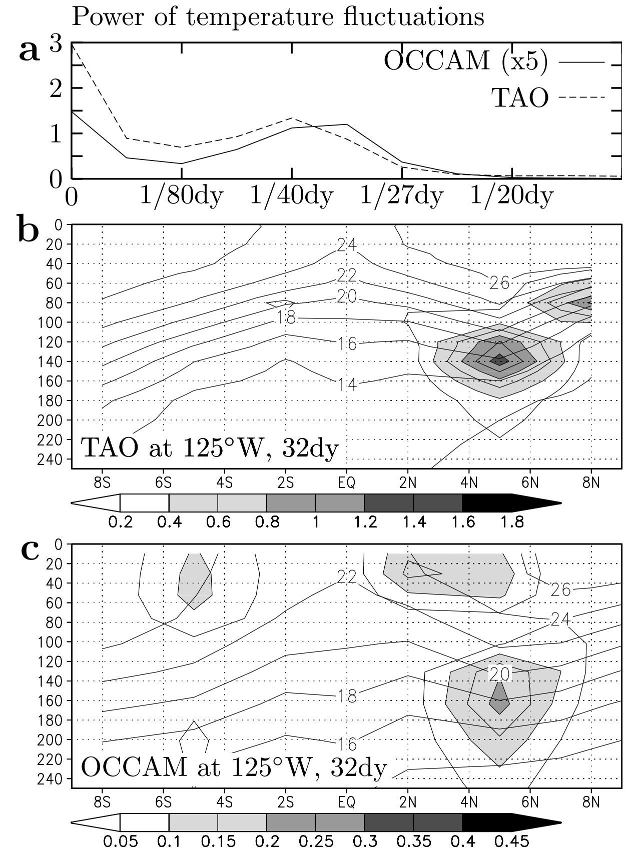

Figure 2. (a) Spectra of modeled and observed temperature in the tropical Pacific at 160 m (OCCAM, amplitude is multiplied by a factor of 5) and 140 m (TAO data) at 125^{o}W, 5^{o}N. Power of the spectra at a period of 32 days at 125^{o}W in (b) the OCCAM model and (c) the observations. Overlayed is the climatological temperature.

the STC in the winter hemisphere dominates and crosses the equator compensating partly the TC on the summer hemisphere (not shown). In the tropical South Pacific and at the equator the seasonal cycle dominates. In the tropical North Pacific, however, there is strong variability at a time scale of a month. Snapshots of SST showed that it is associated with tropical instability waves (TIWs). These westward propagating disturbances are primarily generated by the shear of the equatorial currents [*Philander et al.*, 1978].

The TIWs in the model are fairly realisticly simulated. Spectra of temperature from the TAO buoy data [*McPhaden et al.*, 1998] and the model both show a peak around 30 days (Fig. 2a). Fig. 2 On the 30-day time scale in the model and in the data the amplitude of variability is high at 5°N at thermocline depth (Fig. 2b,c). The latter is in accordance with *McPhaden* [1996]. The location and time scale of the variability shows that it is associated with TIWs. The amplitude of temperature variability is underrated in the model by a factor of 2. This can be explained by the smaller temperature gradients in the model due to the diffuse equatorial thermocline. Also, the winds do not feed back on the SST in our model. Note that the model has 30-day variability in the Southern Hemisphere that is not visible in the data. In accordance to the data TIWs are mainly generated in the Northern Hemisphere where the shear of the equatorial currents is largest. Here the TIWs play an important role in the compensating TCs by homogenizing the flow.

4. Summary and Conclusions

The modeled Eulerian mean circulation shows the presence of TCs and STCs. TCs vanish when high-frequency eddy motions and the effect of sloping isopycnals are taken into account. The compensation of TCs is partly due to the zonal averaging along isopycnals instead of fixed levels and partly due to high-frequency motions associated with TIWs. The TIWs essentially act to homogenize the flow as can be seen in Fig. 1c,d. In the South Pacific also seasonal variations in the flow are important.

We conclude that high-frequency, small scale variability associated with TIWs is important to the large-scale mean circulation in the tropics. This implies, for example, that Lagrangian trajectory calculations should be performed with high-frequency isopycnal mass transports. These findings also raise the question whether current parameterizations of subgrid-scale eddies [*Gent and McWilliams*, 1990] are adequate. Preliminary analysis indicate that parameterized eddy-induced transport does not compensate the TC. Since phenomena like El Niño depend critically on the mean state, high-frequency variability need to be properly accounted for.

Finally, the picture of the ventilation of the equatorial thermocline becomes remarkably simple. The STCs transfer mass, heat, and salt from the surface layers in the subtropics to the equatorial thermocline. This is true for both the Indo-Pacific Oceans and for the Atlantic (not shown). In the Pacific the largest transports comes from the south in accordance to observations [*Johnson and McPhaden*, 1999].

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