Impoved estimates of Geostropic Currents in the Southern Ocean: ACC and Drake Passage Volume Transport

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Abstract. The 3D geostrophic currents and the associated volume transport (VT) can be estimated from the GOCE and Altimetry satellite data and in-situ temperature and salinity profiles measured by the Argo floats. We updated an earlier approach by Vigo et al. (2018) [1] for the Southern Ocean between 20º S and 65º S, with their time variability over the 12-year period of 2004-2015. In this new approach, we used the DTUUH19MDT, and integrate down to full-depth. The results show the Southern Ocean circulation where a zonal Antarctic Circumpolar Current (ACC) interacts with a meridional thermohaline circulation, and prove that the current MDT products are consistent with ocean observations.
The VT reproduces the polar front and the subantarctic front of the ACC, as well as the large scale and mesoscale currents in the Southern Ocean. For the ACC, the improvement on the estimated VT is remarkable, e.g. VT at the Drake Passage is now estimated to be 137 Sv, which is in very good agreement to observations (ranging from 134 to 141 Sv). The spatially averaged ACC VT shows per 1ºwidth in the main stream a mean value of 17 Sv being mainly zonal. Water transports of barotropic and baroclinic origin have been isolated in the VT series showing that 24% of transport is barotropic and the remaining 76% baroclinic, while the variability and annual signal in the ACC is fully barotropic.

1. Methodology

Following same methodology as Vigo et al. (2018) [1], we define the Absolute Dynamic Topography (ADT) and the Relative Dynamic Topography (RDT) as:

$$ADT(x,y,t) = SSH(x,y,t) - N(x,y),$$
$$RDT(x,y,z,t) = \frac{1}{g(y)} \int_{P(z)}^{0} \frac{dP}{\rho(x,y,z,t)},$$

where *N* represents a time-averaged geoid, *x* denotes the longitude, *y* the latitude, *z* depth, *t* time, *g* the latitude-dependent gravitational acceleration, *P*(*z*) the pressure at depth *z* (in Pascal units), and ρ the density (we obtain the density from the ocean T, S, and pressure via the state Equation of Seawater from the Gibbs Seawater Oceanography Toolbox [2]) .

For the surface geostrophic currents, zonal speed (positive eastward) u_s and the meridional speed (positive northward) v_s follow from the balance between the pressure gradient force and the Coriolis force at the surface:

$$u_s(x,y,t) = -\frac{g(y)}{f}\frac{\partial ADT}{\partial y}(x,y,t),$$
$$v_s(x,y,t) = \frac{g(y)}{f}\frac{\partial ADT}{\partial x}(x,y,t),$$

where $f = 2\omega \sin y$ is the Coriolis parameter depending on ω, the angular rate of Earth's rotation. The surface geostrophic current provides the boundary value for the geostrophic current at any depth $z = z_i$ according to:

$$u_s(x,y,t) = -\frac{g(y)}{f}\frac{\partial RDT}{\partial y}(x,y,z_i,t) + u(x,y,z_i,t),$$
$$v_s(x,y,t) = \frac{g(y)}{f}\frac{\partial RDT}{\partial x}(x,y,z_i,t) + v(x,y,z_i,t).$$

Substitution and expansion of the last two set of equations allow one to calculate the geostrophic current at depth z_i from the geostrophic surface current and the spatial gradients of ADT and RDT (at depth z_i):

$$u(x,y,z_i,t) = -\frac{g(y)}{f}\left(\frac{\partial ADT}{\partial y}(x,y,t) - \frac{\partial RDT}{\partial y}(x,y,z_i,t)\right),$$
$$v(x,y,z_i,t) = \frac{g(y)}{f}\left(\frac{\partial ADT}{\partial x}(x,y,t) - \frac{\partial RDT}{\partial x}(x,y,z_i,t)\right).$$

Estimating the geostrophic currents at several depths yields the three dimensional geostrophic flow, hereafter referred to as 3D geostrophy.
The volume of water transport (VT) at a cell of a regular grid from the surface to a depth *D* by the geostrophic flow can be estimated integrating vertically the 3D geostrophy from $z = -D$ to $z = 0$, and multiplying the result by the width of the cell perpendicular to the transport as follows:

$$VT_u(x,y,t) = w_{NS} \cdot \int_{-D}^{0} u(x,y,z,t)dz,$$
$$VT_v(x,y,t) = w_{EW}(y) \cdot \int_{-D}^{0} v(x,y,z,t)dz.$$

Where $w_{NS}(w_{EW})$ is the North-South (East-West) width of the grid cell. Note that in a regular grid w_{EW} depends on latitude *y*, unlike w_{NS}. Besides, both components of the VT depend on the depth of integration *D*. Units of volume transport are Sverdrups.

We use *barotropic transport* to refer to the portion of VT due to a water column moving uniformly as fast as the bottom current, and *baroclinic transport* to refer to the part of VT with respect to the barotropic transport, so that the geostrophic VT is the sum of the two.

2. Data

2.1 Sea Surface Height
Sea level maps are provided by the CCI-Sea Level Project (http://www.esa-sealevel-cci.org) as a monthly merged solution from several altimetry satellites (Jason 1&2, Topex/Poseidon, Envisat, ERS1&2, GFO) for the time span 1993/01/01 to 2015/12/31, with a spatial resolution of 0.25 degrees. (Version 1.1)

2.2 Mean Sea Surface, geoid, and Mean Dynamic Topography
The following products have been used:
- DTU18MSS: The high-resolution mean sea surface model DTU18MSS computed by the Danish National Space Center, based on 25 years of multi-mission satellite altimeters from several different satellites, including 3 years of Sentinel-3A and an improved 7 years Cryosat-2 LRM record. See [3] for details.
- DTUUH19MDT: The new geodetic MDT model DTUUH19MDT computed by the Danish National Space Center using the OGMOC geoid model (augmented using the EIGEN-6C4 coefficients to d/o 2160) and the new DTU18MSS mean sea surface, intergrating the drifter velocities to enhance the resolution of the MDT. See [4] for details.

2.3. Temperature and Salinity profiles
For temperature and salinity profiles we used the EN4.1.1: quality controlled subsurface ocean temperature and salinity profiles and objective analyses from Met Office Hadley Center, it assimilates ARGO data and allows us to integrate the de VT to full-depht. For details see [5].

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3. Results

VT from 3D Geostrophic Currents in the Southern Ocean

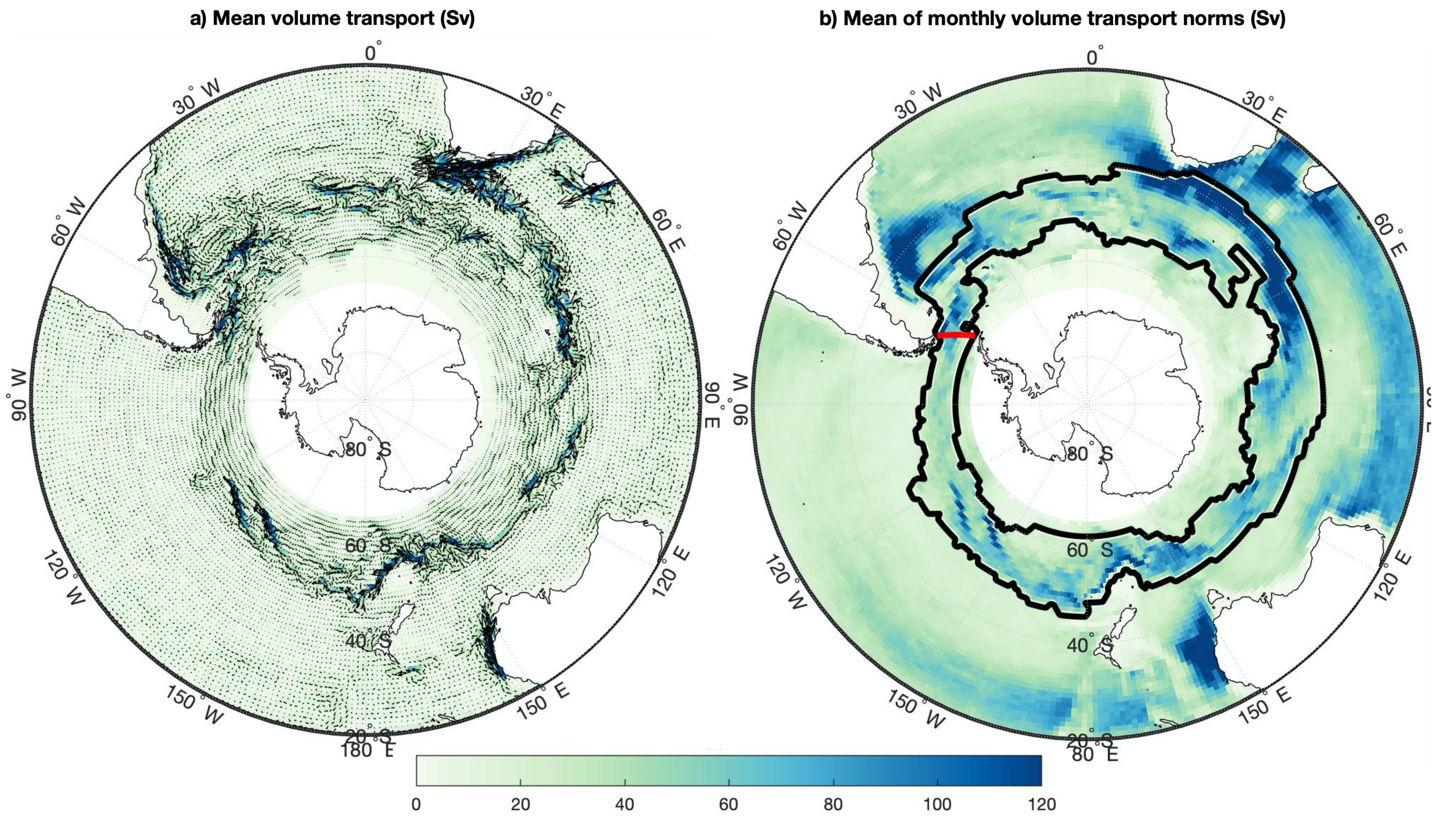

Figure 1. 2004–2015 mean geostrophic volume transport: (a) Arrows are the mean vectors, and the color represents their norms; (b) Mean of the monthly vector norms. The ACC region is outlined in black, the Drake Passage in red. The color scale is saturated at 120 Sv, thought maximum values can reach over 300 Sv. Units are Sv.

VT in the ACC Region

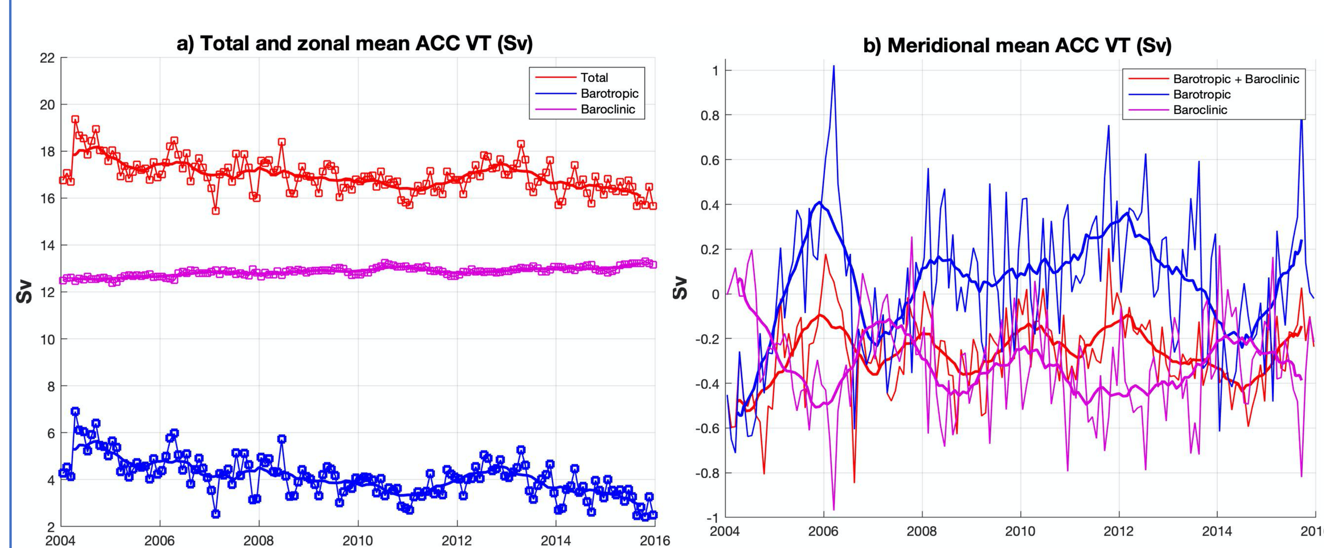

Figure 2. Volume transport in the ACC región per 1◦ gridcell: (**a**) zonal (thincurves) and total (squares) VT; (**b**) mean meridional (thin curves) VT. Barotropic transport in blue, baroclinic transport in magenta, and their sum (barotropic+baroclinic) in red. Thick curves are 12-months running means. Note that these values refer to the VT per unit cross-section area. Units are Sv.

VT at Drake Passage

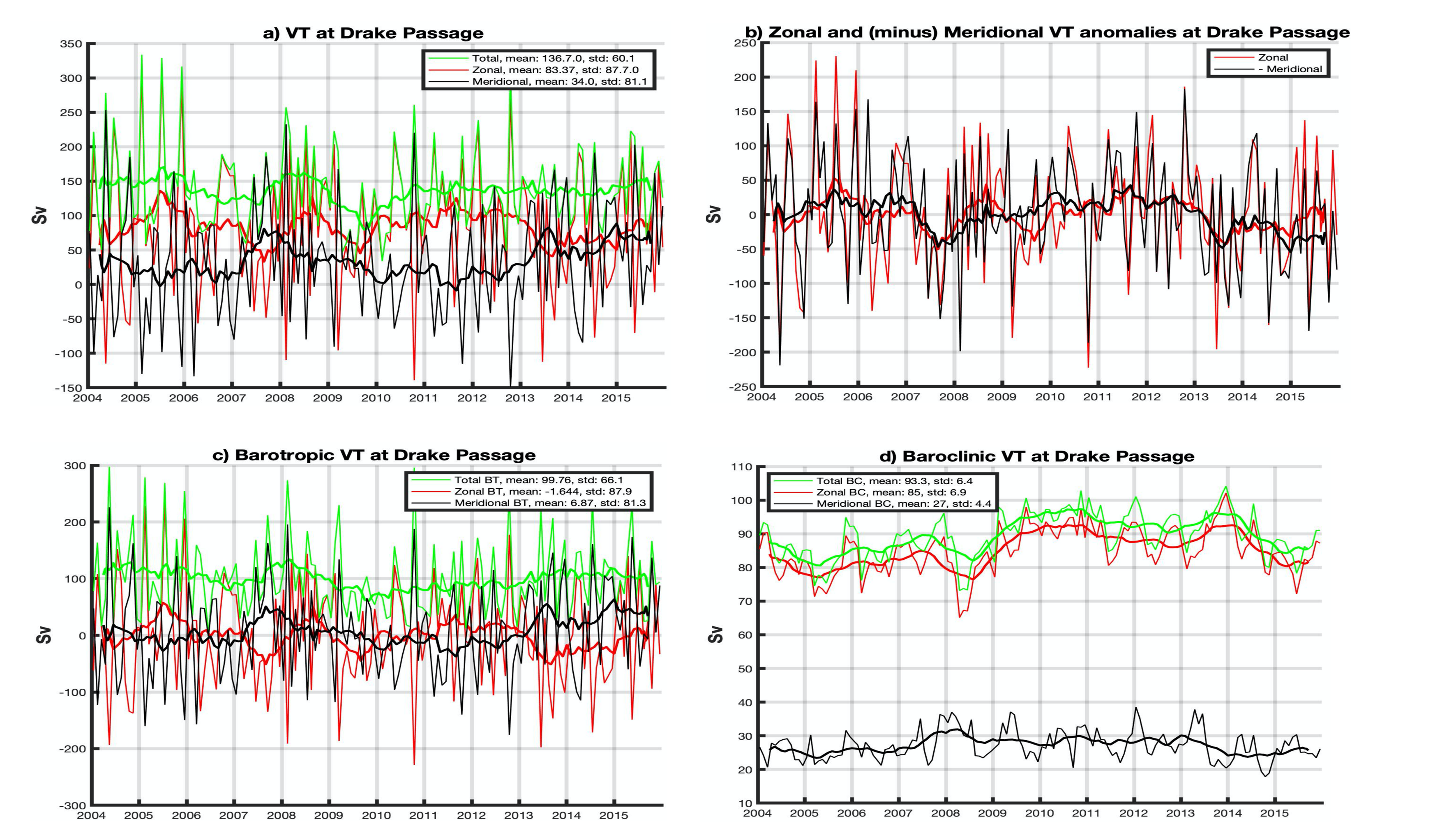

Figure 3. VT at Drake Passage. (**a**) Mean zonal (red), meridional (black), and total VT (green). (**b**) Anomalies with respect to the mean of zonal and negative meridional signals in (**a**). (**c**) Same as (**a**) but for the barotropic transport. (**d**) Same as (**a**) but for the baroclinic transport. Thick curves are 12-months running means. The sign of the meridional component is reversed to better show its correlation with the zonal component. Units are Sv.

4. Discussion and conclusions

In this study we calculate the 3D geostrophic currents and the associated VT using the SSH from a monthly merged solution from several altimetric missions, the MDT product DTUUH19MDT computed by DTU using a geoid model from the GOCE mission and that integrates drifter velocities to enhance the resolution, and the monthly T/S profiles EN4.1.1 that assimilates ARGO data. We do so for the Southern Ocean between 20°S and 65°S at full depth for the 12-year period of 2004–2015.
The VT patterns shown in Figure 1 are similar to those from the geostrophic currents. In particular ACC can be clearly identified as the dominant current. The eastward component is driving the transport, with some alternating north-south departures produced by eddies. In some areas, as in south of Africa, the subantarctic and polar fronts can be discerned. The mean of the monthly VT vectors and VT vector norms in 1° grid cell width reaches values up to 178 Sv and 231 Sv, with mean values of 26 Sv and 56 Sv, respectively.
Figure 2 shows the time evolution in the ACC region of the zonal, meridional, and total VT, for both the barotropic and the baroclinic components. Note that these values refer to the VT per 1◦ gridcell. So, for any section along a meridian, the mean zonal VT at a given time can be estimated multiplying the zonal value at Figure 2 at such time by the number of grid points at the given section. The global satellite coverage, allows us to study of the ACC globally and provides very reliable estimates. In particular, at the Drake Passage (in red in Figure 1.b) the estimated mean total VT is 136.7 Sv (std 60.1 Sv), which is in very good agreement with in-situ observations that provide a mean flow that range between 134 to 140 Sv [6,7,8]. This result improve previous estimates based on satellite data [1], that overestimate the VT for the Drake Passage (202 Sv for mean total VT, up to 2000m. depth). Thus, we can conclude that the current satellite data makes feasible MDT products that are consistent with in-situ ocean observations enabling the possibility of new studies in oceanography at global scales.

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