The Dynamics of Sverdrup Balance in the Ocean

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Abstract

Since its conception in the 1940's Sverdrup Balance has become a cornerstone of oceanography, forming the basis of much oceanic theory. If the Sverdrup Balance were to hold it would also provide a significant tool for remotely determining the subtropical gyre by linking the surface wind stress alone to the meridional mass flux. Until recently it has not been possible to verify the accuracy of Sverdrup Balance due to practical difficulties in obtaining observational data with sufficient spatial and temporal resolution. In this study we use the ECCO-GODAE model state estimate to quantify the extent to which Sverdrup Balance holds, and to determine the dynamical mechanisms responsible for any discrepancies. Averaging between 1992 and 2007, we found that, away from western boundaries between 35°S and 35°N, deviations from the zonally averaged Sverdrup Balance are between 5% and 40% with an average of ~10%. A pointwise balance, although in many areas exceeding 100%, averages out to ~15%. We argue that these discrepancies in the steady-state solution are largely due to the linear vorticity assumption rather than the assumption of a level of no motion. Steady state is only reached following an adjustment time scale which we show is set up by the propagation of Rossby Waves across the ocean.

1. Introduction

Sverdrup balance (2) is a relationship that directly links the ocean transport (*V*) to the surface wind stress (τ). It is formed from the depth integrated linear vorticity equation (1) and the assumption that there is a depth at which velocity is negligible (a level of no motion, or LONM).

$$\int_{LONM}^{surface} \beta v \; dz = \int_{LONM}^{surface} f \frac{\partial w}{\partial z} \; dz \qquad (1)$$

$$V = f\left[w(surface) - w(LONM)\right] = \frac{\nabla \times \tau}{\beta} \qquad (2)$$

w here is the vertical velocity and β denotes the north-south gradient of the coriolis paramter.

We investigate how well this balance holds and the validity of the two assumptions:

1) vorticity is linear
2) There is a level of no motion (LONM)

3. Adjustment

The primary mechanism of ocean adjustment in response to forcing is through the propagation of Rossby Waves (RW). We would therefore expect to have to time average before we get Sverdrup Balance. Figure 3 represents the amount of averaging time that is required at each latitude in the Atlantic before the system comes into (relative) sverdrup balance.

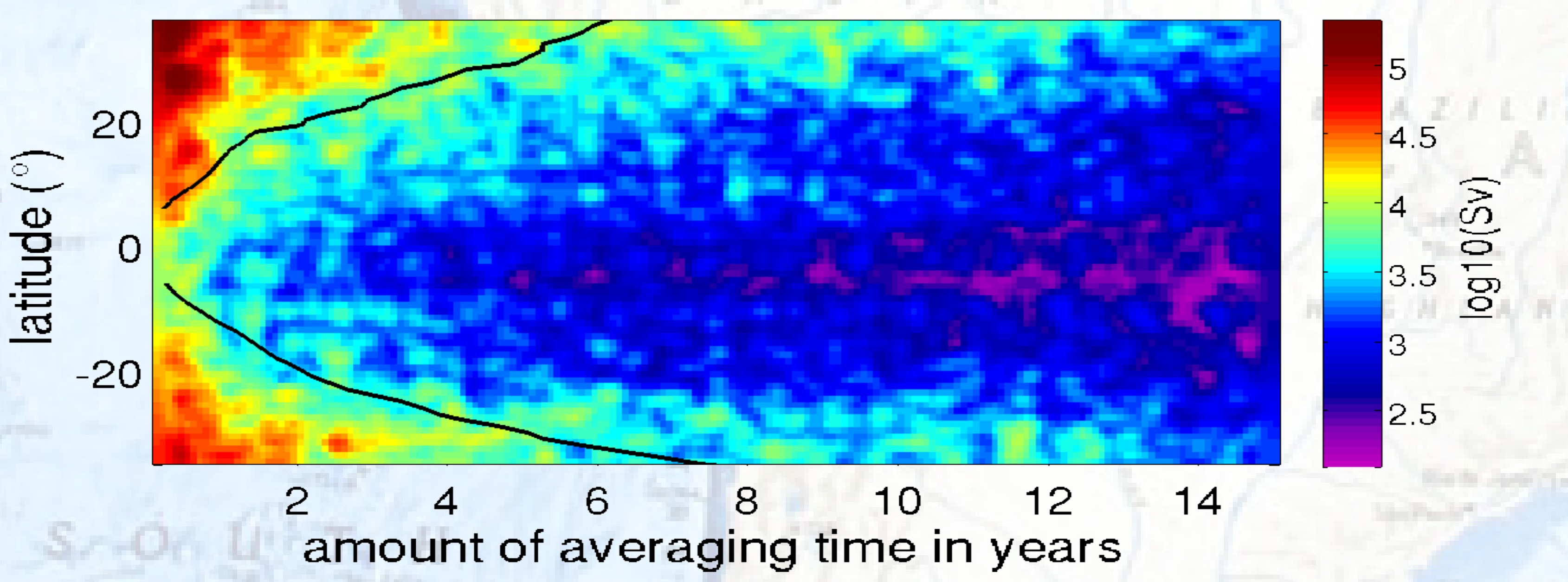

Figure 3. Running standard deviation of Sverdrup Balance error vs amount of averaging time, in the Atlantic. When the Error stops fluctuating (i.e. small standard deviation), the system has reached steady state. The black line is the amount of time it takes for a 500km wavelength Rossby Wave to cross the Atlantic Ocean.

The phase speed of RW's varies with latitude according to the "beta-effect" which ensures that phase speed decreases with latitude. The black line in Figure 3 is the amount of time required for a 500km wavelength RW to cross the Atlantic. There is a clear correlation between RW phase speed and adjustment time.

2. Percentage Sverdrup Balance

The model was depth-integrated to 1000m and compared to the Sverdrup Tranport (rhs eq (2); Figure 1). The two display similar spatial structure in the interior subtropical gyre, but not at high latitudes or western boundaries. Sverdrup Transport also displays more small scale variability. Stippled regions in a) and b) are masked in the zonal integrals of c) and d). Considering the unmasked region between 35°S and 35°N, Sverdrup Balance holds to ~85% pointwise, and ~90% if zonally integrated.

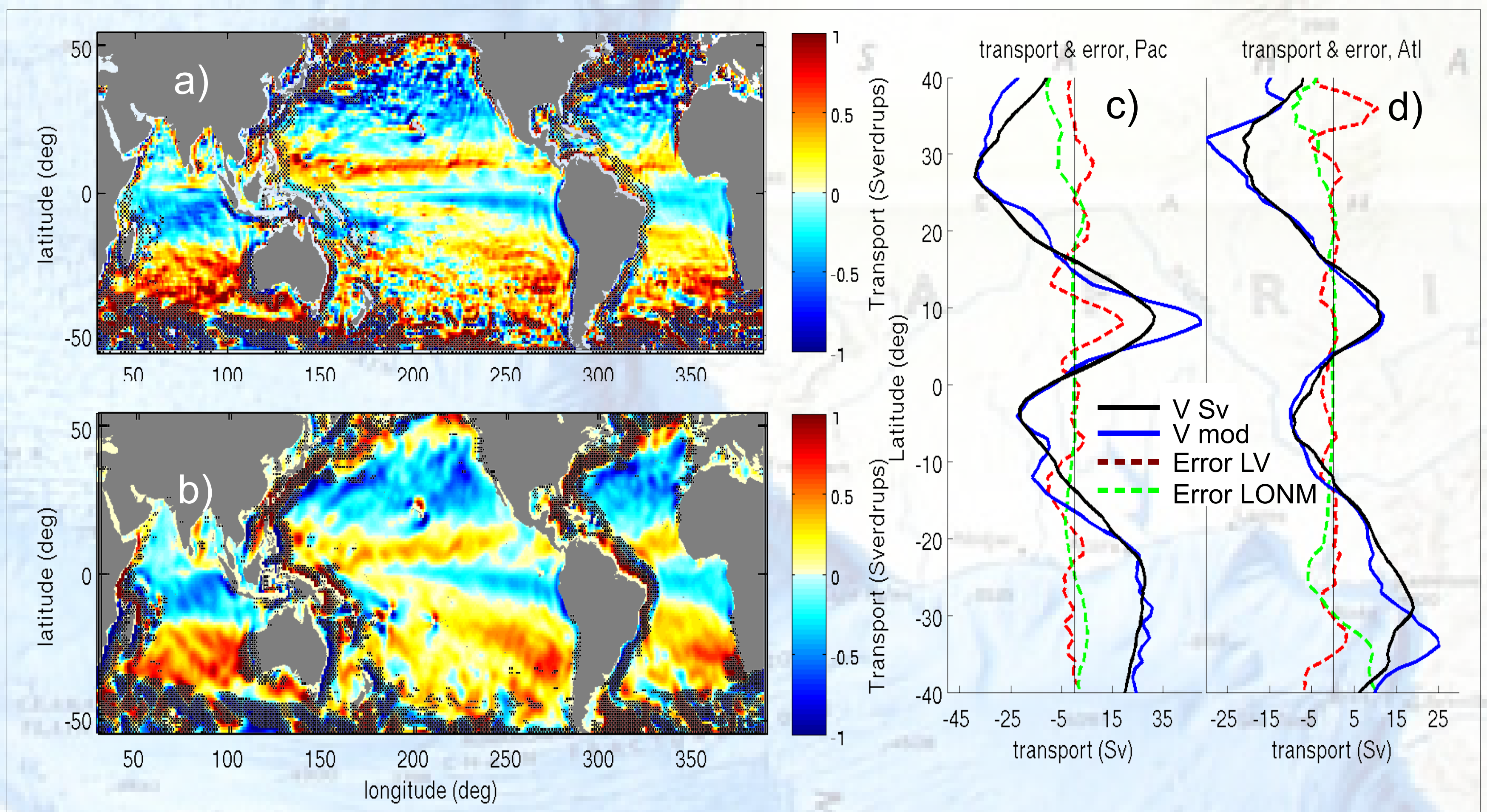

Figure 1. (a) Sverdrup Transport and (b) Model transport integrated to 1000m. Zonal (east-west) integrals of transport in the Pacific (c) and Atlantic (d) with error components associated with the assumptions of linear vorticity (red) and a LONM (green). Zonal integrals mask out the stippled areas in a) and b).

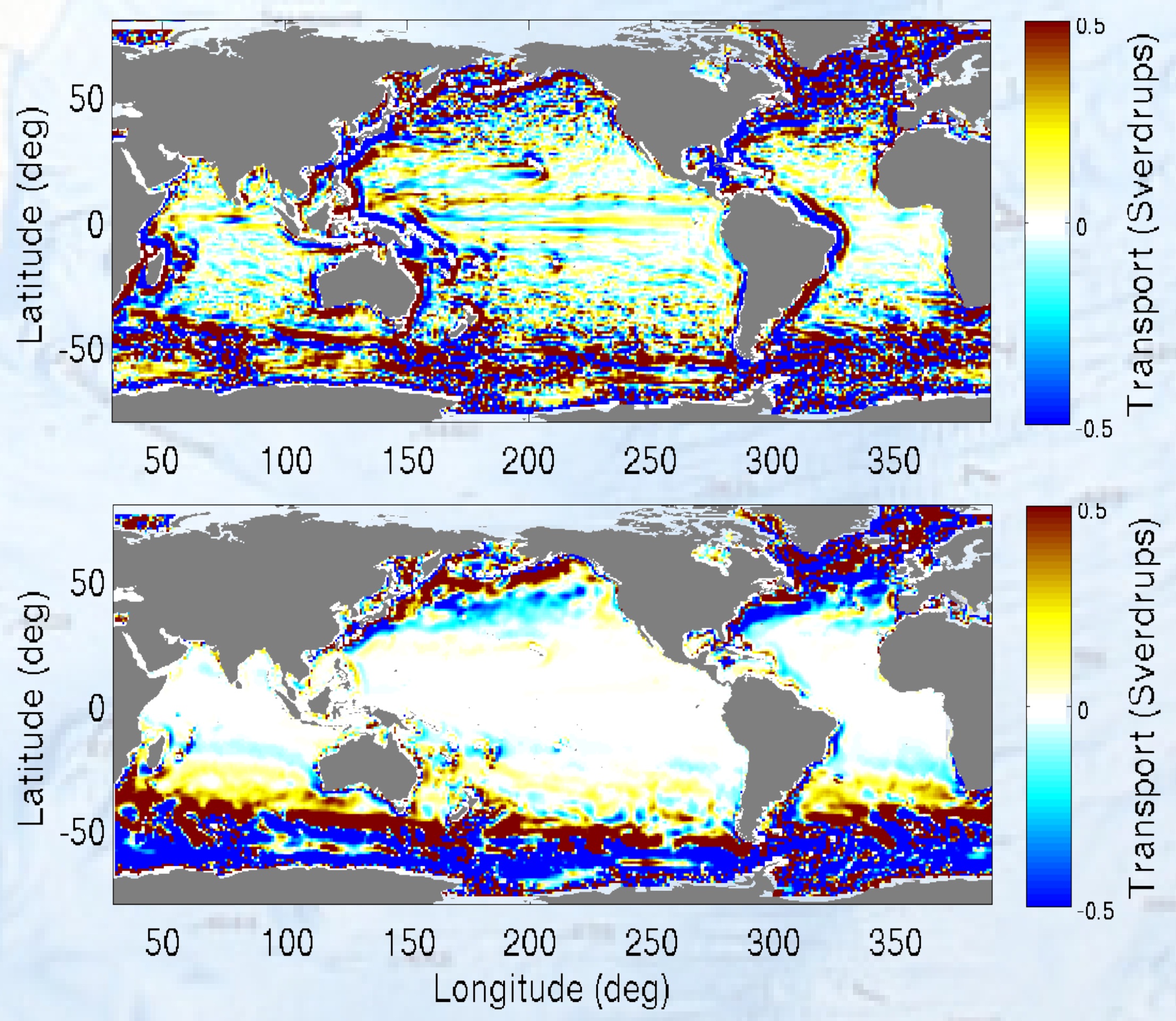

Figure 2. Error Components of Sverdrup Balance integrated to 1000m. a) linear vorticity error; b) LONM error.

The Sverdrup Balance error (Figure 1a minus b) is decomposed into its two component parts (Figure 2 and Figure 1 c and d): Linear Vorticity error (LV; red) and LONM error (green). We find that LV error composes all of the low latitude error, while at high latitudes both components contribute significantly to the error.

Conclusions

- Sverdrup Balance in the interior subtropical gyre away from western boundaries holds to ~15%
- Zonally integrated Sverdrup Balance error is ~10%, showing that pointwise errors cancel over a longitudinal section.
- This error may be decomposed into its two component parts; assumptions of linear vorticity and a LONM. The linear vorticity error dominates the subtropics, while at high lats both are significant.
- The adjustment time for the system to come into balance varies with latitude, corresponding with the 1st baroclinic Rossby Wave phase speed.

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