EXCITATION OF THE EARTH'S CHANDLER WOBBLE BY THE NORTH ATLANTIC DOUBLE-GYRE

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ABSTRACT. We investigate the effect of North Atlantic double-gyre on Chandler wobble excitation. To this end, we calculate the motion term of the Chandler wobble excitation for the North Atlantic region using two different ocean models: i) a quasi-geostrophic double-gyre model in an idealized quadrangle domain with steady wind forcing and ii) HYCOM (HYbrid Coordinate Ocean Model) simulations with realistic continent boundaries and time dependent wind forcing. We analyze the discrepancies between the resulting excitation of the two models and discuss how the differences in the models' assumptions can result in different predictions of Chandler wobble excitation.

1. BACKGROUND

Chandler wobble, the main component of polar motion, is a 14-month free motion, the period of which is determined by elliptic geometry and the rigidity of the Earth (Dickman 1985, Munk and MacDonald 1975). Being damped by imperfections in the Earth's elasticity and non-equilibrium ocean response, the Chandler wobble requires an unceasing injection of energy to persist in time. Several geophysical phenomena such as earthquakes (Dahlen, 1971; Xu et al., 2014), atmospheric processes and oceanic flows (Gross et al., 2003; Adhikari & Ivins, 2016) have been investigated as possible sources of the excitation of the Chandler wobble while the exact role of each phenomenon is still a matter of debate. Recent GRACE (Gravity Recovery and Climate Experiment) and SLR (Satellite Laser Ranging) observations have revealed that the mass redistribution of geophysical fluids is the dominant source of excitation for the Chandler wobble (Brzezinski et al., 2012). The motion terms of Chandler wobble excitation, defined by motion of the fluid particles relative to the terrestrial reference system, are currently calculated based on general circulation models for oceans and atmosphere. Due to variety the assumptions, different geophysical models for ocean dynamics report different contributions of oceanic currents in Earth rotation excitation (Yu et al., 2018). Hence, high-resolution ocean modeling, which is the main focus of this paper, can provide a better understanding of the exact role of oceanic currents in Chandler wobble excitation.

Ocean gyres are large wind driven systems of circulating currents developed by Coriolis effect and horizontal and vertical frictions. The North Atlantic subtropical gyre together with its smaller subpolar counterpart constitute a double-gyre which is mainly characterised by its eastward jet, Gulf Stream. The isolated double-gyre dynamics has been attracting scientists' attention since 1950s (Munk 1950, Holland 1978; Shen et al., 1999) and has further been investigated using a range of methods from high-resolution techniques (Berloff, 2005; Karabasov et al., 2009; Maddison et al., 2015) to semi-analytical solutions (Jamal 2018; Naghibi et al., 2019). The double-gyre problem has also been studied as a part of general circulation ocean models such as MITgcm (Adcroft et al., 2008) and HYCOM (Wallcraft et al., 2009).

The North Atlantic double-gyre has been reported to have a small contribution in Chandler wobble excitation (Ma et al.2009; Nastula et al., 2012; Naghibi et al., 2017). We calculate the

Chandler wobble excitation for the North Atlantic region using two different ocean models: a qausi-geostrophic double-gyre model and the general circulation model, HYCOM. The goal of this study is to analyze the discrepancies between the predicted Chandler wobble excitation resulting from the two double-gyre models.

2. METHODS

2.1 Chandler wobble equation

Chandler wobble dynamics is described as

$$\frac{i}{(\sigma_0 + i/2Q)} \frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t} + \mathbf{m} = \boldsymbol{\Psi} = \left[1 - \frac{i}{\Omega} \frac{\mathrm{d}}{\mathrm{d}t} \right] \{ \alpha \mathbf{c} + \beta \mathbf{h} \}, \tag{1}$$

where $\mathbf{m} = m_1 + i m_2$ are Chandler wobble components, $\boldsymbol{\Psi} = \psi_1 + i\psi_2$ are excitation function components, $\mathbf{h} = h_1 + i h_2$ is the relative angular momentum vector and $\mathbf{c} = c_{13} + i c_{23}$ is perturbation of inertia tensor. σ_0 is the Chandler wobble frequency with the period $T_0 = 2\pi/\sigma_0 \approx 433$ days, and Q is the quality factor. The constants α and β are considered for the case of complete decoupling between the Earth's core and mantle. Equation **??** is related to the velocity and acceleration fields of the oceans through **h** vector.

2.2 Double-gyre equations

Quasi-geostrophic Model: The quasi-geostrophic model represents wind-driven double-gyre dynamics in a mid-latitude flat basin bounded by north-south and east-west solid walls. The governing equations are stratified three-layer, quasi-geostrophic potential vorticity equations (Holland 1978) and the source terms consist of the meridional gradient of the Coriolis parameter, the lateral viscosity, bottom friction, and the steady wind forcing

$$\partial_t q_i + J(\psi_i, q_i + \beta y) = \delta_{1i} F_w - \delta_{i3} \frac{a_v}{H_3^2} \Delta \psi_i + a_h \Delta^2 \psi_i, i = 1, 2, 3, \tag{2}$$

where F_w, a_v and a_h are the wind curl forcing, bottom friction and lateral viscosity coefficients respectively, $J(f, g) = f_x g_y - f_y g_x$, δ_{ij} is the Kronecker symbol and β is the planetary vorticity gradient equal to $2 \times 10^{-11} \mathrm{m}^{-1} \mathrm{s}^{-1}$. q_i is the layer-wise potential vorticity defined as

$$q_i = \Delta \psi_i - (1 - \delta_{i1}) S_{i1} (\psi_i - \psi_{i-1}) - (1 - \delta_{i3}) S_{i2} (\psi_i - \psi_{i+1}). \tag{3}$$

Here S_{i1} and S_{i2} are stratification parameters linked to the first and second Rossby deformation radii $Rd_1 = 40$ km and $Rd_2 = 23$ km, respectively. The three ocean layers have the depths of $H_1 = 250$, $H_2 = 750$ and $H_3 = 3000$ meters. The governing quasi-geostropic equations (**??**) are solved using the high-resolution CABARET method (Karabasov and Goloviznin 2009).

HYCOM (HYbrid Coordinate Ocean Model): HYCOM governing equations are composed of the conservation laws for momentum, temperature, salinity and mass, as well as the equation of state:

$$\begin{aligned}
\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}.\nabla)\mathbf{v} + 2\mathbf{!} \times \mathbf{v} &= -\frac{\nabla M}{\rho} + \frac{\nabla.\boldsymbol{\o}}{\rho}, \\
\frac{\partial(\Delta h T)}{\partial t} + \nabla.(\Delta h T \mathbf{v}) &= \nabla.(\kappa \Delta h \nabla T) + F^T, \\
\frac{\partial(\Delta h S)}{\partial t} + \nabla.(\Delta h S \mathbf{v}) &= \nabla.(\kappa \Delta h \nabla S) + F^S, \\
\frac{\partial}{\partial t}(\Delta h) + \nabla.(\mathbf{v} \Delta h) &= 0, \\
\rho &= \rho(T, S, P),
\end{aligned} \tag{4}$$

where **v** is the velocity vector, **!** is the Earth's angular velocity, M is the Montgomery potential, Δh is the depth of the ocean layer and **ø** is a stress tensor (which includes viscosity). T and S are temperature and salinity with F^T and F^S being the corresponding source terms in their conservation equations, κ is diffusivity tensor and ρ is the density. HYCOM runs over 1/12 degree horizontal resolution in the longitude and latitude and 41 isopycnal layers. The hybrid coordinate is isopycnal in the open, stratified ocean. However, it smoothly returns to a terrain-following coordinates in shallow coastal egions and to z-level coordinates in the mixed layer and unstratified seas. The atmospheric wind forcing in HYCOM is time-dependent and is generated by general atmospheric circulation models (Wallcraft et al., 2009).

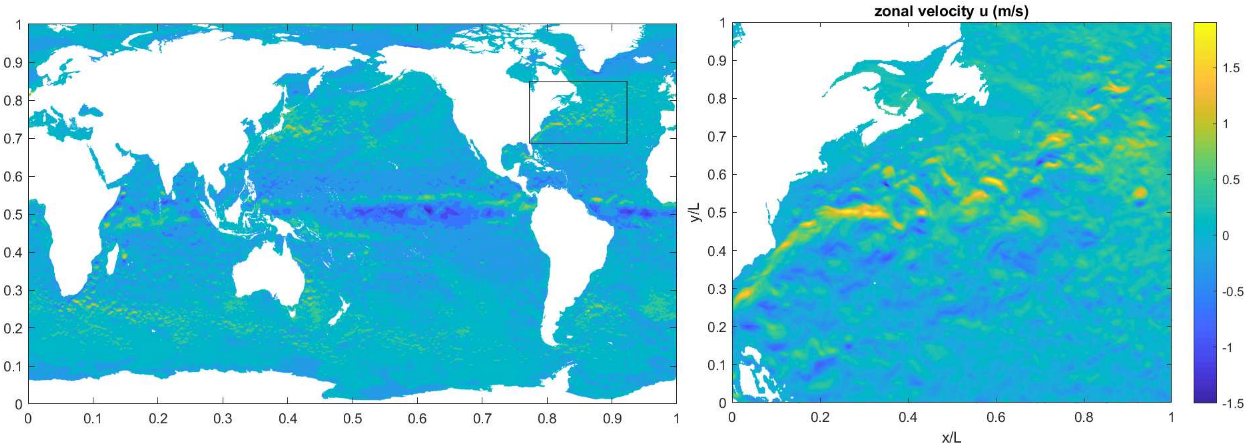

Figure 1: Top layer zonal velocity distribution in HYCOM outputs. Left panel shows global oceans and right panel shows the North Atlantic region

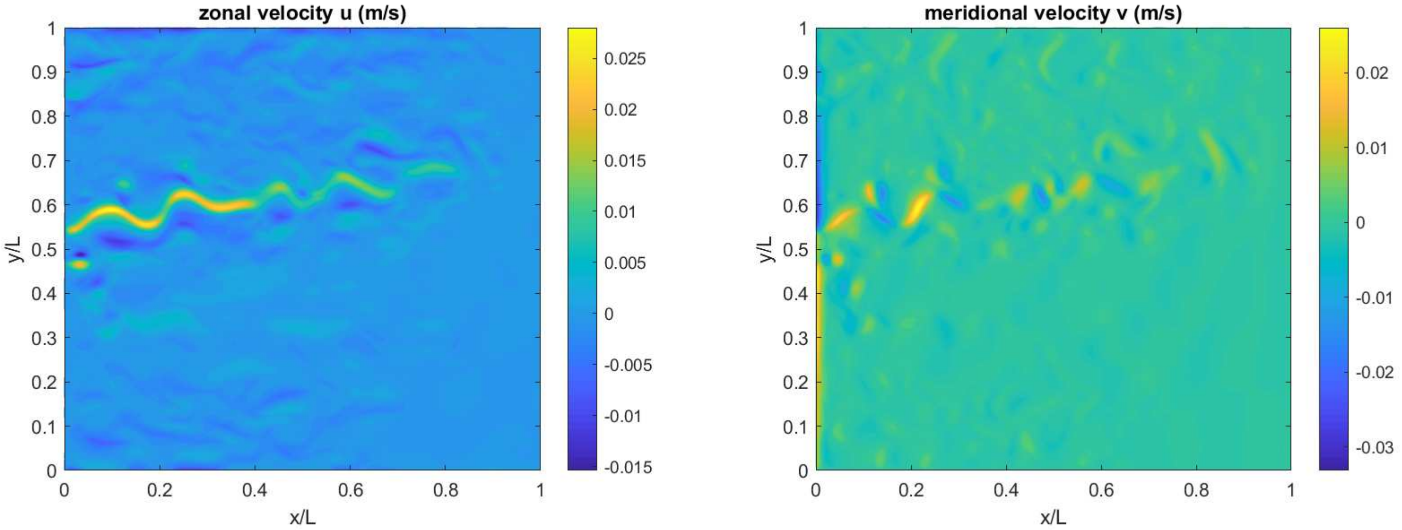

Figure 2: Top layer zonal (left) and meridional (right) velocity distributions in the quasi-geostrophic model

4. RESULTS

We first present the instantaneous velocity outputs of the two double-gyre models. Figure **??** depicts top layer zonal velocity distribution in HYCOM outputs for global oceans as well as the

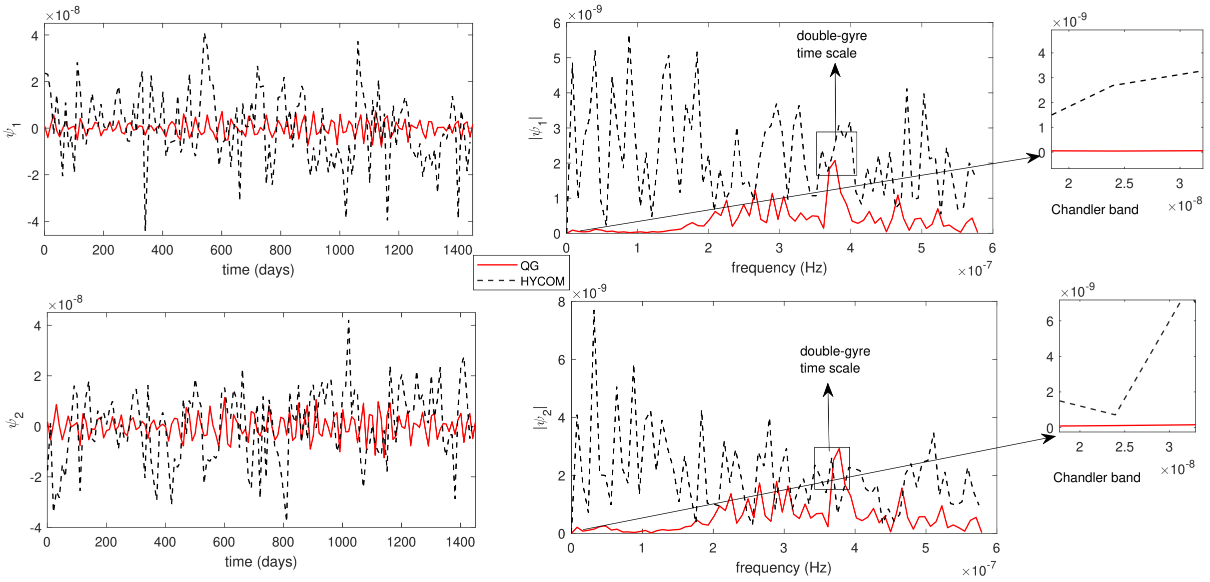

Figure 3: Comparison of Chandler wobble excitation functions using HYCOM and quasi-geostrophic (QG) model velocity fields for the North Atlantic region. Left panels are in time domain and right panels are in frequency domain.

North Atlantic region, which is a basin of the size 3840 km × 3840 km in both models. Figure **??** illustrates top layer meridional and zonal velocity distributions in the quasi-geostrophic model.

Figure **??** compares Chandler wobble excitation functions using HYCOM and quasi-geostrophic model velocity fields for the North Atlantic region both in time and frequency space. The outputs of both models are analysed in a four-year period and sampled every 10 days. The mean values of the Chandler wobble excitation functions are filtered in all graphs. As observed in Figure **??**, the two models behave differently specially in the frequency spectra. The only frequency line both models agree in corresponds to the time scale of one month which is approximately equal to the time required for the jet to travel the diagonal of the quadrangle region. This implies that, as an idealized model, the quasi-geostrophic model is only calibrated to mimic the jet dynamics in high fidelity models such as HYCOM. Figure **??** compares the meanflow and RMS profiles for zonal velocity in HYCOM and quasi-geostrophic model. As it can be seen in this Figure, the meanflow and RMS profiles reasonably agree in both models which again confirms that the parameters in the quasi-geostrophic model are calibrated to capture the mean jet correctly.

Finally, Figure **??** compares the Chandler wobble excitation functions for global oceans vs. the North Atlantic region in HYCOM. In agreement with similar works [21, 20] on regional excitation of the Chandler wobble, North Atlantic is not the dominant contributor in the excitations.

3. CONCLUSION

This paper compares the Chandler wobble excitation for the North Atlantic region using two different ocean models: an idealized quasi-geostorphic double-gyre model and the general circulation model, HYCOM. The resulting excitation functions are significantly different in the two models. Our analysis of the frequency domains show that the quasi-geostrophic model is only calibrated to capture mesoscale dynamics of the double-gyre and its eastward jet and does not produce the same excitation for the Chandler wobble as HYCOM. Different predictions of the two models can

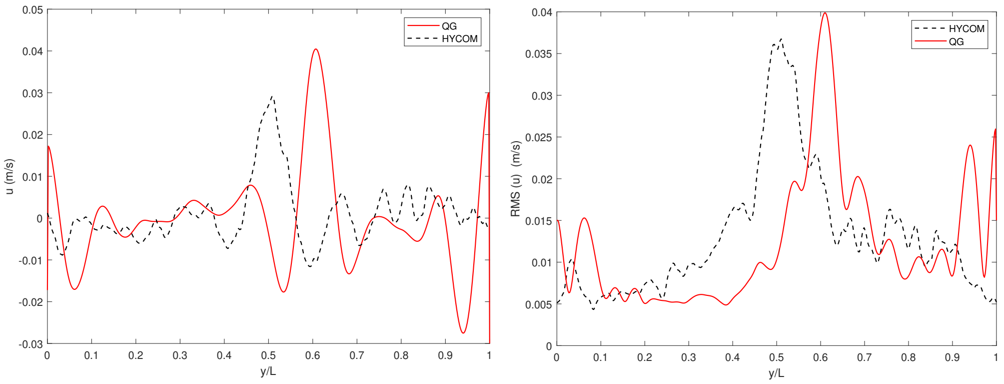

Figure 4: Comparison of the meanflow (left) and RMS (right) profiles for zonal velocity in HYCOM and quasi-geostrophic (QG) model

also be related to differences in the time variations of the wind forcing.

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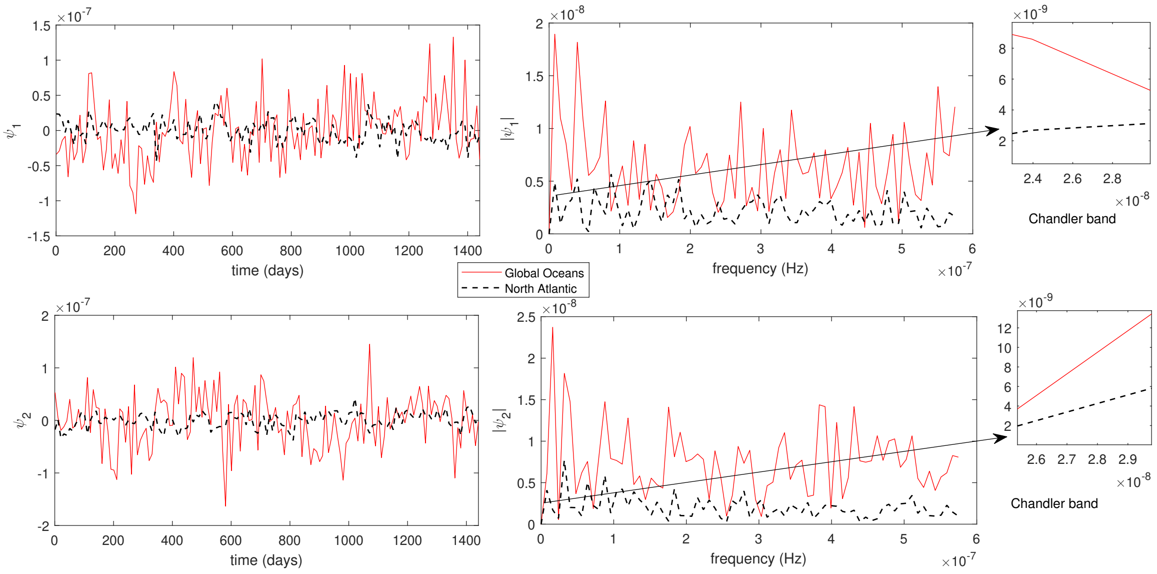

Figure 5: Chandler wobble excitation functions: Global oceans vs. the North Atlantic (motion term). Left panels are in time domain and right panels are in frequency domain

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