Net Primary Production in the Gulf Stream Sustained by Quasi-Geostrophic Vertical Exchanges

Ananda Pascual[1], B. B. Nardelli[2], S. Ruiz[1], D. Iudicone[3], S. Guinehut[4], D. Galbrun[5], P. Gaube[6], M. Capllonch[1]

(1) IMEDEA(CSIC-UIB), Mallorca, Spain; (2) CNR, Napoli, Italy; (3) Stazione Zoologica, Napoli, Italy; (4) CLS, Toulouse, France; (5) ENSTA ParisTech, France; (6) University of Washington, Seattle, US

Corresponding author: ananda@imedea.uib-csic.es

Abstract

We analyze 12 years of mesoscale vertical motion derived from an observation-based product in the top 1000 m of the North West Atlantic Ocean. Vertical velocities [O(10 m day-1)] associated with Gulf Stream instabilities consist of alternating cells of upwelling and downwelling. Here we show that the magnitude of the vertical motions decays exponentially southwards with an e-folding length scale is informative on the dynamics of the system. We further investigate the impact of the vertical supply of nutrients on phytoplankton growth with a conceptual model incorporating the mean effect of nutrient distribution, quasi-geostrophic dynamics and Ekman suction/pumping. Results confirm that the mean effect of mesoscale vertical velocity variability alone can sustain observed levels of net primary production in the immediate vicinity of the Gulf Stream, while other mechanisms, including horizontal advection and submesoscale dynamics, need to be considered when moving towards the subtropical gyre.

Vertical motion – Quasi-Geostrophic (QG) framework

Vertical motion associated with mesoscale and sub-mesoscale oceanic features is of fundamental importance for the exchanges of heat, fresh water and biogeochemical tracers between the surface and the ocean interior (Ruiz et al., 2009; Gaube et al., 2013). Unfortunately, direct measurements of the vertical velocity are difficult to obtain for usual values (order 10's m/day). Various indirect methodologies have thus been proposed to estimate vertical velocity from observed density and geostrophic velocity fields. The most used technique is based on the solution of the quasi-geostrophic (QG) Omega equation (see Eq. 1 and 2).

$$\nabla_h^2\left(N^2 w\right)+f^2\frac{\partial^2 w}{\partial z^2}=2\nabla_h\cdot\vec{Q} \quad \text{(Eq. 1)}$$

$$\vec{Q}=\left[f\left(\frac{\partial V}{\partial x}\frac{\partial U}{\partial z}+\frac{\partial V}{\partial y}\frac{\partial V}{\partial z}\right),-f\left(\frac{\partial U}{\partial x}\frac{\partial U}{\partial z}+\frac{\partial U}{\partial y}\frac{\partial V}{\partial z}\right)\right] \quad \text{(Eq. 2)}$$

(U,V): geostrophic velocity components
w: quasi-geostrophic vertical velocity (QG-w)
Q: Q vector
N: Brunt-Vaisala frequency
f: Coriolis parameter

QG approximation valid for Ro = U/(f L) << 1

Ro: Rossby number
L: characteristic scale

Hoskins et al. (1978)
Tintoré et al. (1991)

QG-w derived from synthetic fields

Input Data → **Method** → **Output Data**

ARMOR3D reanalysis → Omega equation → QG-w re-analysis

3D fields of temperature, salinity and steric height derived from an observational-based product that combines satellite (SST and altimetry) and in-situ (Argo profiling floats, XBT, CTD and moorings) data. (Guinehut et al. 2012).

Period: 1993-2009
Monthly fields
Domain: NW Atlantic

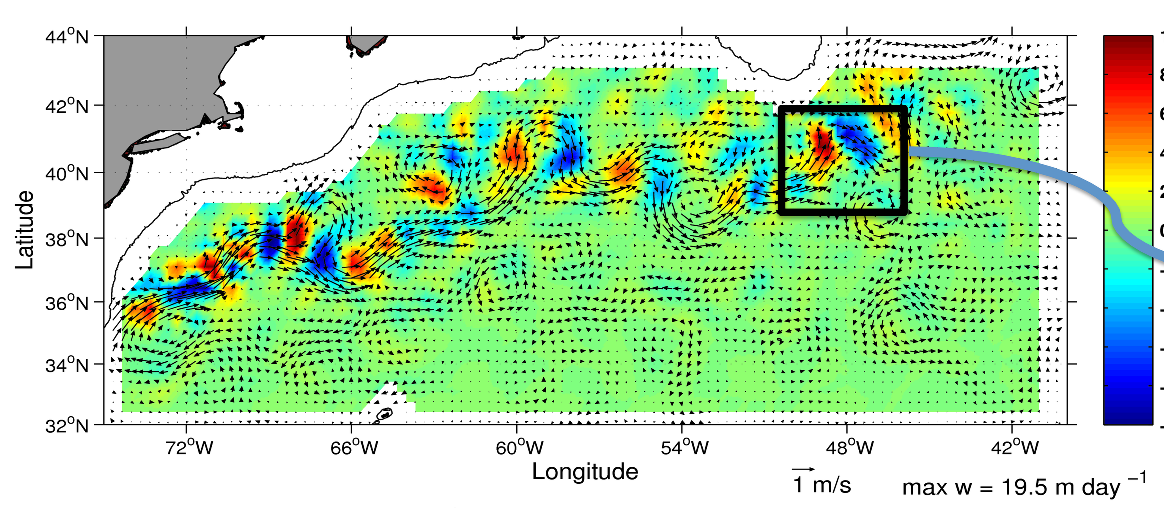
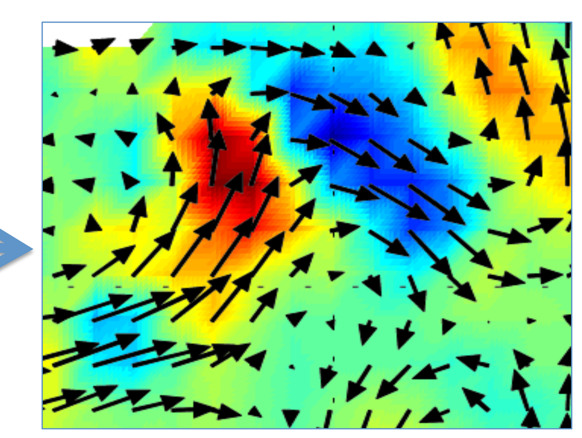
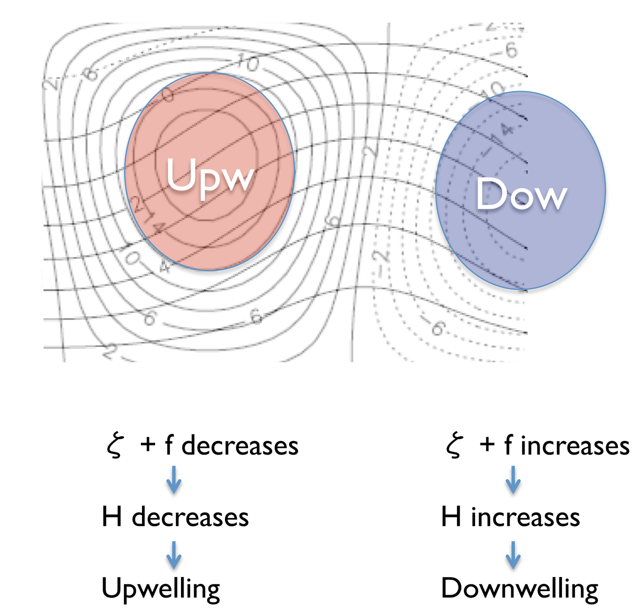


Fig. 1: Vertical velocity (m day^{-1}) at 100 m, obtained by integrating the QG omega equation from the 3D field of ARMOR3D corresponding to September 2005. Horizontal geostrophic currents are overimposed.

U = 1 m s-1, f = 10-4 s-1, and L (half diameter) = 100 km -> Ro ~0.1



Upwelling upstream of a meander crest
Downwelling downstream of a meander crest



QG-w patterns are consistent with those predicted by QG theory (Pascual et al. 2004; Gomis et al. 2005)

An analytical model to explain the NPP response to QG-w

Observed Net Primary Production (NPP)

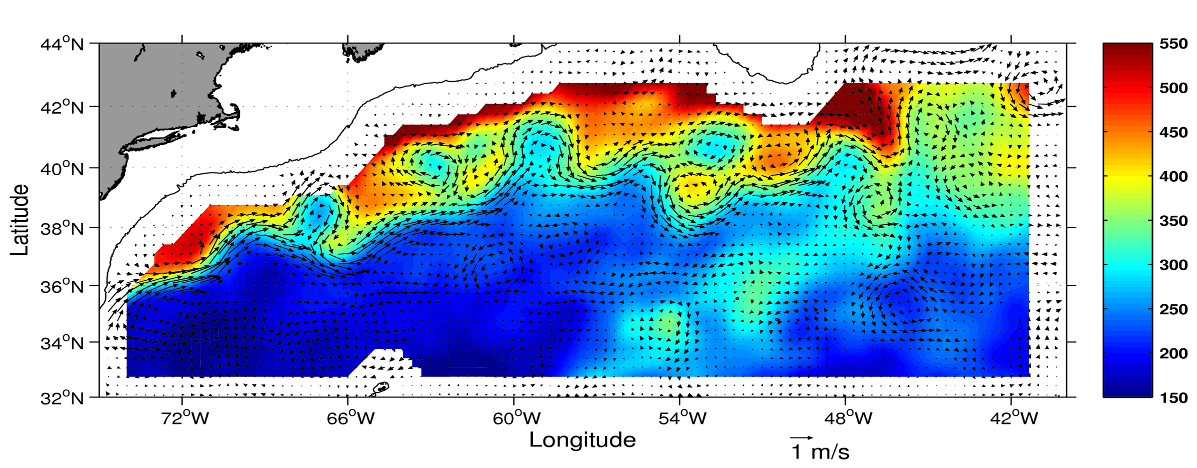


Fig. 2: Horizontal geostrophic currents at 100 m derived from ARMOR3D data for September 2005. The colormap corresponds to the monthly mean of net primary production (mg C m-2 day-1) for the same month from Oregon State University.

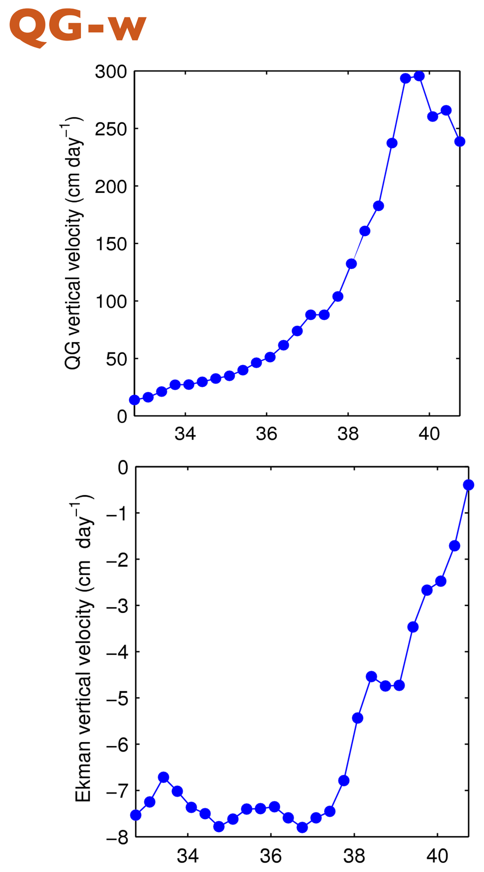


Fig. 3: Vertical velocity inputs for the application of the L11 model, as a function of latitude, averaged from 65ºW to 40ºW and over 1998-2009 period: (Top) Rms of QG-w at 100 m (cm day^{-1}); (Bottom) Climatological Ekman vertical velocity (cm day^{-1}).

Conceptual model by LATHUILIERE et al. JMR 2011 (L11)

$$NPP=\mu NP-mP=\frac{N}{H}\frac{\alpha^2+\alpha w_{Ek}}{\alpha+w_c-w_{Ek}} \quad \text{(Eq. 3)}$$

- Nutrients at the subsurface layer World Ocean Atlas (WOA) climatology (Boyer et al., 2009)
- Climatological Ekman pumping - Scatterometer Climatology of Ocean Winds (SCOW) (Risien and Chelton, 2008) and wEk estimated in this study.
- Phytoplankton production
- Phytoplankton loss
- Depth of the euphotic layer (~100 m - Oschlies and Garçon, 1998).
- Intensity of mesoscale activity in the ocean (QG-w, this study)
- Critical upwelling velocity. Mortality and remineralization out of the euphotic layer. 1-3 m/day L11

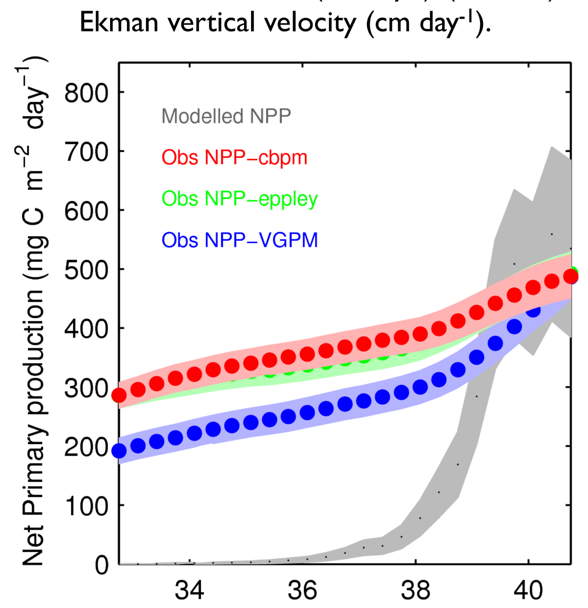


Fig. 4: Observed mean NPP (in blue the NPP-VGPM, green Eppley and red cbpm) versus modelled mean NPP (grey) as a function of latitude.

How realistic are QG-w estimates compared to total w?

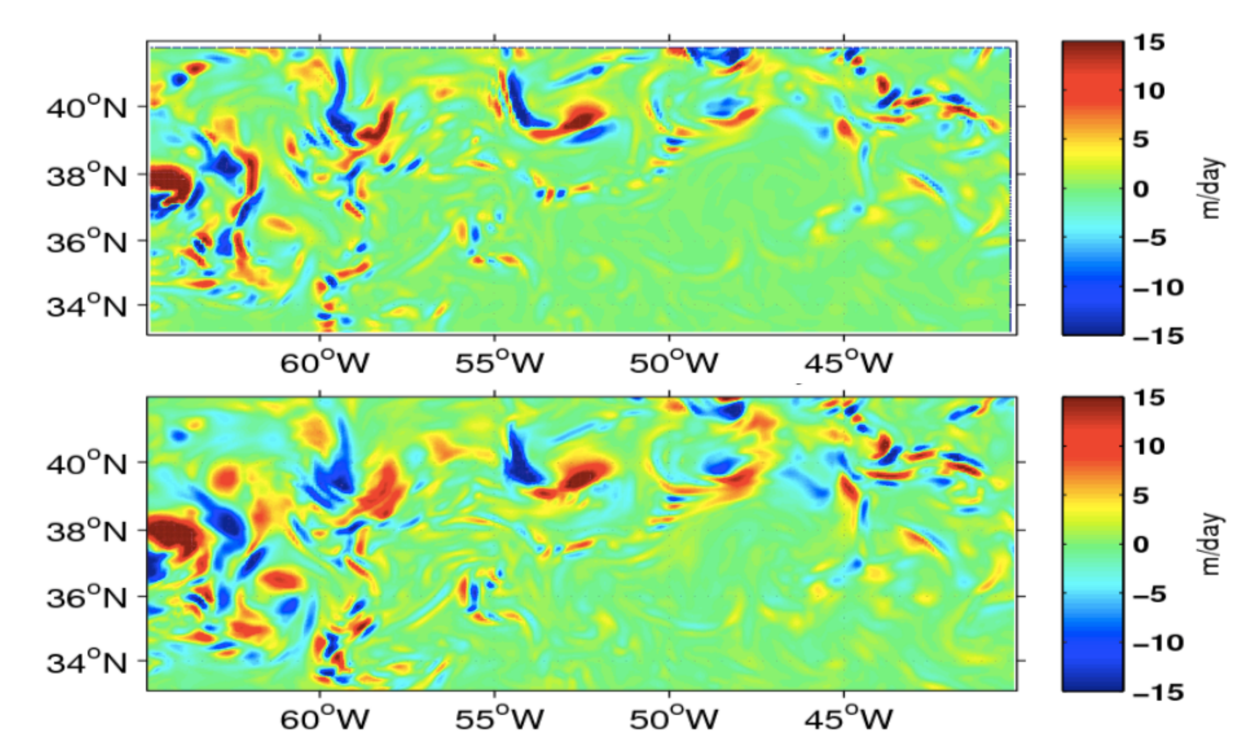


Fig. 5: Snapshot of QG-w (top) at 104 m estimated from temperature and salinity POP model fields (Anderson et al. 2011) and given POP vertical velocity (bottom). Correlation: 0.74.

QG-w explains more than 70% of the model-w variance.

Key Points

- New estimation of vertical velocity derived from an observational-based approach that combines in situ and satellite (altimetry and SST) data.
- QG-vertical velocities can sustain net primary production in the Gulf Stream.
- The same methodology can be applied to other regions of the Global Ocean.
- Vertical motion is a crucial variable for better understanding the biogeochemical response at a wide range of scales.
- More details in: Pascual et al. GRL (2015)

Acknowledgements

This work has been carried out as part of MESCLA (PB-LC 10-013) and E-MOTION (CTM2012-31014) projects, funded within the Open Call for R&D activities in the framework the MyOcean project (EU N° FP7-SPACE-2007-1-Grant Agreement 218812) and the Spanish National Research Program, respectively.

REFERENCES

Anderson, L., D. McGillicuddy, M. Maltrud, I. Lima, and S. Doney (2011), Impact of eddy-wind interaction on eddy demographics and phytoplank- ton community structure in a model of the North Atlantic Ocean, Dyn. Atmos. Oceans, 52, 80–94.
Gaube, P., D. B. Chelton, P. G. Strutton, and M. J. Behrenfeld (2013), Satellite observations of chlorophyll, phytoplankton biomass, and Ekman pumping in nonlinear mesoscale eddies, J. Geophys. Res. Oceans, 118, doi:10.1002/2013JC009027.
Gomis, D., Pascual, A., and Pedder, M. A.: Errors in dynamical fields inferred from oceanographic cruise data: Part II. The impact of the lack of synopticity, Journal of Marine Systems, 56, 334-351, 2005.
Guinehut, S., Dhomps, A. L., Larnicol, G., and Le Traon, P. Y.: High resolution 3-D temperature and salinity fields derived from in situ and satellite observations, Ocean Science, 8, 845-857, 2012.
Lathuiliere, C., M. Levy, and V. Echevin, 2011: Impact of eddy-driven vertical fluxes on phytoplankton abundance in the euphotic layer. J. Plankton Res., 33, 827–831, doi:10.1093/plankt/fbq131.
Hoskins, B. J., I. Draghici, and H. C. Davies (1978), A new look at the omega-equation, Q. J. R. Meteorol. Soc., 104, 31–38.
Pascual, A., D. Gomis, R. L. Haney, and S. Ruiz (2004), A quasigeostrophic analysis of a meander in the Palamos Canyon: Vertical velocity, geopotential tendency, and a relocation technique, Journal of Physical Oceanography, 34(10), 2274-2287.
Pascual, A., S. Ruiz, B. Buongiorno Nardelli, S. Guinehut, D. Iudicone, and J. Tintoré (2015), Net primary production in the Gulf Stream sustained by quasi-geostrophic vertical exchanges, Geophys. Res. Lett., 42, doi:10.1002/2014GL062569.
Ruiz, S., A. Pascual, B. Garau, I. Pujol, and J. Tintoré (2009), Vertical motion in the upper ocean from glider and altimetry data, Geophysical Research Letters, 36(14).
Tintoré, J., D. Gomis, S. Alonso, and G. Parrilla (1991), Mesoscale dynamics and vertical motion in the Alboran Sea, J. Phys. Oceanogr., 21, 811–823.