



HAL
open science

New production stimulated by high-frequency winds in a turbulent mesoscale eddy field.

Marina Lévy, Patrice Klein, Mahdi Ben Jelloul

► To cite this version:

Marina Lévy, Patrice Klein, Mahdi Ben Jelloul. New production stimulated by high-frequency winds in a turbulent mesoscale eddy field.. *Geophysical Research Letters*, 2009, 36, pp.L16603. 10.1029/2009GL039490 . hal-00413521

HAL Id: hal-00413521

<https://hal.science/hal-00413521>

Submitted on 16 Jun 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Copyright

New production stimulated by high-frequency winds in a turbulent mesoscale eddy field

M. Lévy,¹ P. Klein,² and M. Ben Jelloul²

Received 5 June 2009; accepted 20 July 2009; published 29 August 2009.

[1] Using an idealized model of an oligotrophic open-ocean region characterized by intense sub-mesoscale turbulence, we show that the presence of energetic near-inertial motions, forced by high-frequency winds, triggers transient nutrient inputs in the surface mixed-layer, stimulating new production. We also show that this production increase is larger than the increase due to the Ekman transport resulting from a slow-evolving wind forcing. The nutrient supplies are due to the interaction between near-inertial motions and the sub-mesoscale frontogenetic dynamics that reinforces both the vertical advection and vertical diffusion, especially within sub-mesoscale features. The net result is an uplift of new production from the subsurface to the mixed-layer. A direct consequence is that the sub-mesoscale filamentary patterns of phytoplankton should become much more observable from space in the presence of high-frequency winds.
Citation: Lévy, M., P. Klein, and M. Ben Jelloul (2009), New production stimulated by high-frequency winds in a turbulent mesoscale eddy field, *Geophys. Res. Lett.*, *36*, L16603, doi:10.1029/2009GL039490.

1. Introduction

[2] In offshore oligotrophic regions the intensity of new production (NP) is strongly related to the vertical nutrient transport, and in particular to that associated with mesoscale eddies (with diameter $O(100\text{ km})$) [McGillicuddy *et al.*, 1998]. Recently the focus has shifted to submesoscales ($O(1-10\text{ km})$) that are ubiquitous in a turbulent eddy field. Indeed theoretical and high resolution numerical studies [Capet *et al.*, 2008; Klein *et al.*, 2008] indicate that vertical exchanges of tracers in the upper oceanic layers mostly occur at small-scale and preferentially within submesoscales located around or outside mesoscale eddies. The main physics is the surface frontogenesis that triggers intense vertical velocities within these submesoscales. Results of Lévy *et al.* [2001] (hereafter LKT), who examined the transient response of an oligotrophic production regime in a mesoscale eddy field, further highlight the biogeochemical impact of these submesoscales. They showed that NP is greatly enhanced by the vertical injection of nutrients occurring within submesoscale structures, in particular anticyclonic filaments. High-resolution observations of biogeochemical parameters [Niewiadomska *et al.*, 2008; Johnson *et al.*, 2008], that reveal the existence of very

thin tongues of tracer in regions of strong density fronts, support this vision of such submesoscale impacts.

[3] Presence of a non-zero wind forcing further affects the vertical nutrient injection driven by submesoscales. The wind forcing considered (such as daily-averaged winds) usually includes only its low-frequency (LF) component (with respect to the Coriolis frequency f). Resulting effects are nonlinear Ekman pumping and eventually front intensification at the submesoscale edges [Thomas and Lee, 2005; Mahadevan *et al.*, 2008]. High-frequency (HF) winds (such as those present in 3-hourly realistic wind time series), that are known to efficiently force near-inertial motions, may trigger a much larger nutrient uplift [Klein and Coste, 1984]. Furthermore, in presence of a mesoscale turbulent field, such HF winds bring into play new physics: these structures efficiently polarize near-inertial motions, trapping them in small-scale anticyclonic structures [Young and Ben Jelloul, 1997; Klein *et al.*, 2004]. Impacts of these HF winds on the resulting submesoscale vertical advection and diffusion should further affect the vertical exchanges of tracers, which still needs to be investigated in particular in terms of the consequences on the biogeochemical system.

[4] Thus the question addressed in the present study is: does the interaction of HF winds with a turbulent eddy field affects the oligotrophic NP through its impacts on the vertical mixing and the vertical velocity field? For that purpose, the numerical experiments of LKT are repeated but including HF winds (with frequencies spanning around f). More precisely our approach is to isolate the impact of near-inertial waves from the impact of Ekman fluxes. This is done by comparing simulations forced with winds with frequencies close to f , where both effects are present, with simulations forced with constant winds, where the near-inertial oscillations are much reduced and thus where the impact of Ekman fluxes prevails.

2. Numerical Experiments

[5] Following LKT, a high-resolution primitive equation model coupled with an ecosystem model (NO₃-NH₄-P-Z-D-DOM) is used to simulate primary productivity in an oligotrophic region characterized by intense mesoscale activity, during the stratified season. Vertical diffusion is calculated with a 1.5 turbulent closure model [Blanke and Delecluse, 1993]. Other details of the model are given in LKT. The initial conditions are constructed as follows. Interactive mesoscale vortices with submesoscale vorticity filaments between and around them (Figures 1a, 1b, and 1e) are generated from the spin-down of a large-scale unstable zonal jet, in a periodic β -plane channel centered at 30°N ($f = 8 \times 10^{-5}\text{ s}^{-1}$). The initial conditions for the ecosystem are homogeneously set from the steady state solution away from

¹LOCEAN, IPSL, Université Pierre et Marie Curie, CNRS, Paris, France.

²LPO, IFREMER, UBO, CNRS, Brest, France.

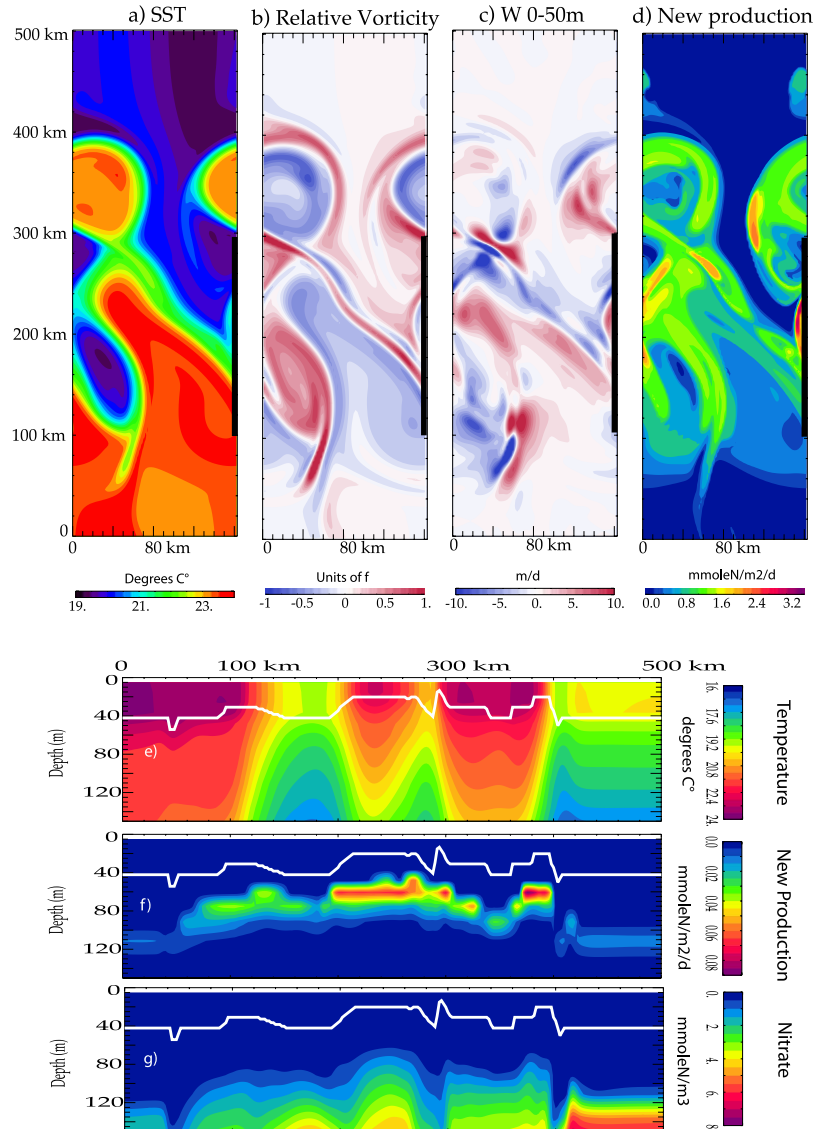


Figure 1. Model fields before the wind forcing is applied. Horizontal views of (a) sea surface temperature (SST), (b) relative vorticity at the surface, (c) vertical velocity averaged from 0–50 meters and (d) new production integrated between 0–150 meters. Vertical section along $x = 30$ km of (e) temperature, (f) new production and (g) nitrate. The thick vertical black line on Figures 1a–1d marks the position of the latitudinal section shown in Figure 3. The white line on Figures 1e–1g is the mixed-layer depth.

the interacting vortices. They are representative of a highly oligotrophic system, typical of summer conditions at mid latitudes; the nitracline and NP subsurface maxima are located at 120 m depth and the mixed-layer is shallow (≈ 40 m) (Figures 1f and 1g). The absence of a large scale horizontal nutrient gradient enables us to highlight the vertical processes: any additional vertical transport of nutrient into the euphotic layer destabilizes the biological steady state by stimulating new production (LKT). Sub-mesoscale fronts associated with the filaments trigger intense vertical velocities, which leads to significant nutrient injection and NP. NP is confined within the vorticity filaments, where both vertical velocities and horizontal stretching are strong (Figure 1d). The nutricline and the subsurface NP maximum are closer to the surface (≈ 60 m) in regions of strong upwelling (Figures 1f and 1g).

[6] We present the results of four experiments varying in wind forcings (Table 1). The experiments are performed

during 10 days, starting from the situation shown in Figure 1. During these 10 days, the mesoscale eddy field slowly evolves, with, in particular, the deformation and westward propagation of the main vortices over 20–40 km (not shown). The wind forcing is homogeneous and eastward, thus with no preferred angle with respect to the submesoscale fronts which are oriented in all directions. The wind is constant (0.1 Nm^{-2}) in the CW experiment. The wind is time-varying with inertial (f) and subinertial ($0.75 f$) frequencies in IW and SW (square oscillatory functions varying between 0 and 0.2 Nm^{-2} , thus with 0.1 Nm^{-2} mean). In NW, the integration is simply continued with no wind.

3. Results

[7] We examine the differences in NP that result from the different wind scenarios. NP is computed as the consump-

Table 1. Wind Forcing and Mean Nutrient Budgets for the Four Model Experiments^a

	NW	CW	SW	IW
mean wind stress ($N m^{-2}$)	0	0.1	0.1	0.1
wind stress frequency	–	–	0.75 f	f
wind stress period (h)	–	–	25.1	18.8
0–150 m NP	0.82	0.84 (+2%)	0.90 (+10%)	0.98 (+20%)
0–150 m AD	1.03	1.00	1.08	1.22
0–150 m DF	0.04	0.04	0.04	0.04
0–50 m NP	0.09	0.14 (+55%)	0.23 (+155%)	0.30 (+233%)
0–50 m AD	0.11	0.14	0.20	0.23
0–50 m DF	0.005	0.03	0.08	0.11

^aFour model experiments: no wind (NW), constant wind (CW), subinertial wind (SW) and inertial wind (IW). The new production (NP), advection (AD) and vertical diffusion (DF) budgets are expressed in $mmoleN/m^2/d$. They are averaged over the 10 days of the experiments and over the entire model domain. Fluxes are integrated over different vertical layers: 0–150 m and 0–50 m. Percentages indicated in brackets refer to the percent increase with respect to the NW experiment.

tion of nitrate by phytoplankton for photosynthesis and is vertically integrated, either over the euphotic layer (0–150 m, NP_{tot}) or closer to the surface (0–50 m, NP_{surf}). Results are summarized in Table 1. A non-zero wind forcing systematically increases NP. The NP increase is much

stronger when the wind is variable in time and, this increase is particularly strong in the surface mixed-layer. More precisely in the constant wind experiment, NP_{tot} is almost unchanged with respect to the no wind experiment (+2%). In the case of variable winds, a moderate increase is obtained for sub-inertial winds (+10%) and a larger one for inertial winds (+20%). NP_{surf} increases by +55% with a constant wind and +233% with an inertial wind (Table 1).

[8] We now examine the processes responsible for the mean increase of NP_{tot} . Table 1 shows the mean vertical fluxes (advective and diffusive) of nitrate across 150 m for all experiments. Diffusive fluxes are two orders of magnitude smaller than the advective fluxes, clearly suggesting that the NP_{tot} increase results from an increase of the advective supply of nitrate at the base of the euphotic layer. The advective supply of nitrate is maximum in the inertial wind experiment, intermediate in the subinertial wind experiment, and minimum in the no wind and constant wind experiments.

[9] The 0–50 m nutrient budget is also dominated by the advective supply of nitrate (Table 1). However, vertical diffusion becomes non-negligible since, with inertial and subinertial winds, it represents, at 50 m, about one third of the total nitrate supplies. This is due to the deepening of the mixed-layer below 50 m with HF winds (Figure 2b). Furthermore, vertical diffusion takes over vertical advection. Indeed,

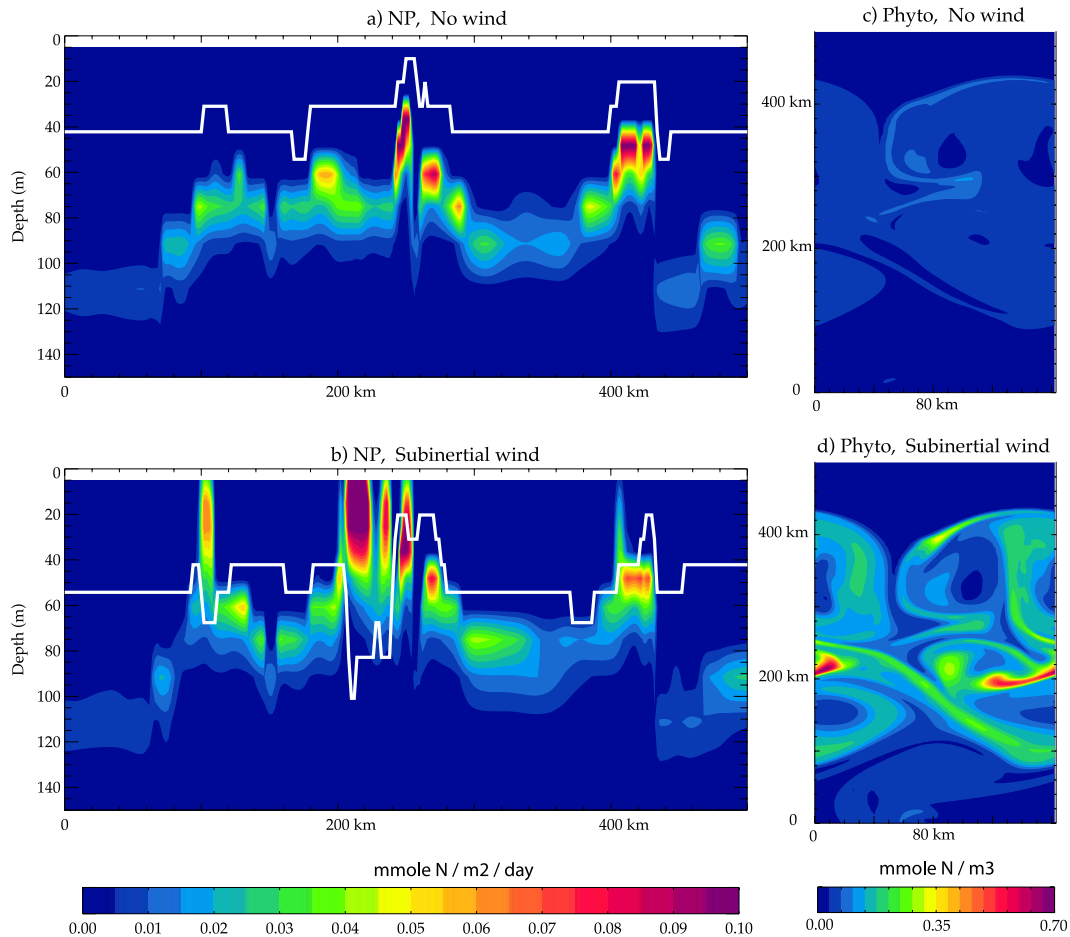


Figure 2. Vertical section of new production after 10 days along $x = 0$ km in the experiments (a) with no wind and (b) with sub-inertial wind; the white line shows the mixed-layer depth. (c and d) Corresponding imprint on sea-surface phytoplankton.

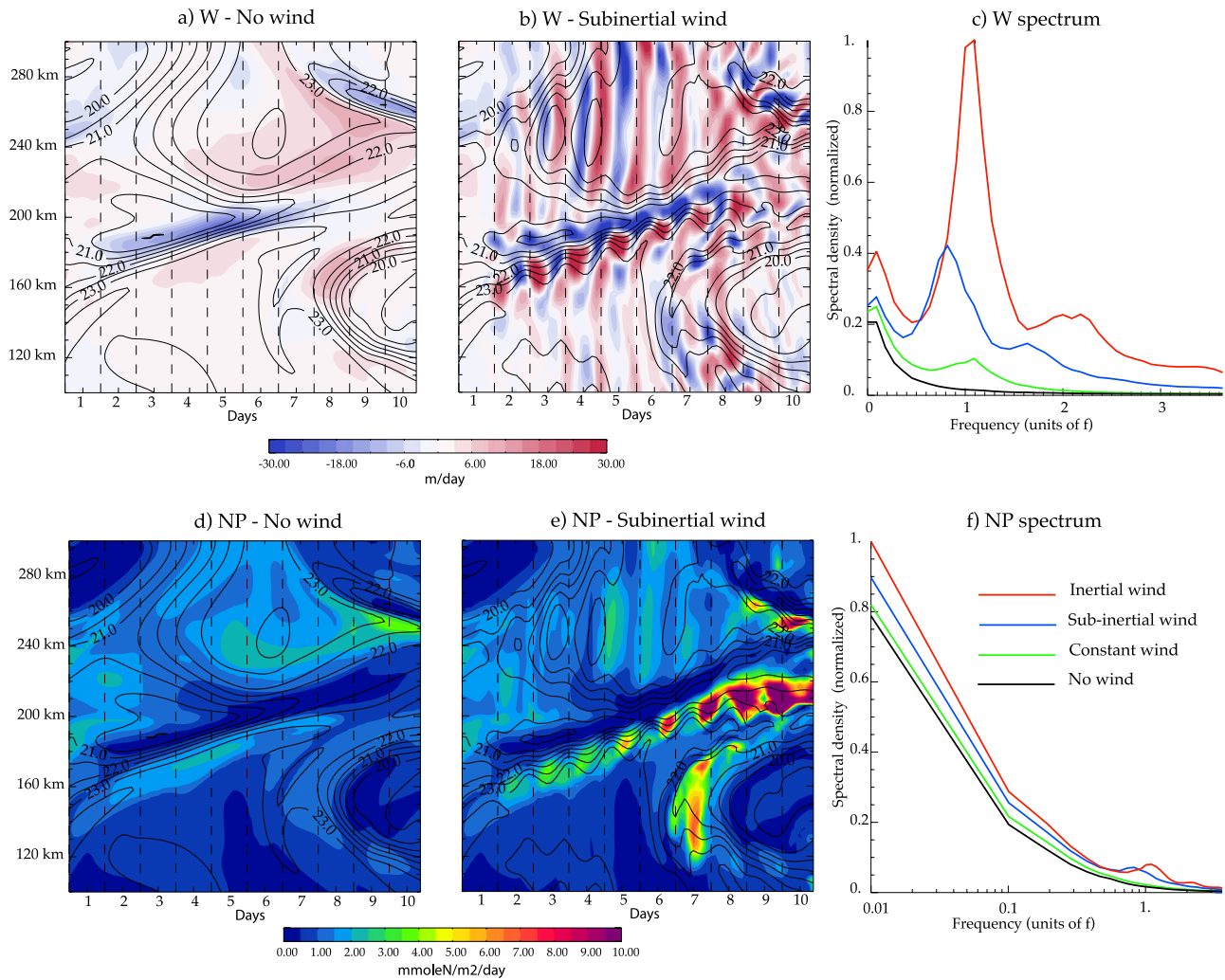


Figure 3. Hovmoller of the 0–50 m vertical velocity along $x = 180$ km in the experiment (a) with no wind and (b) with subinertial wind; contours show the sea surface temperature. The position of the section is shown by the thick vertical black line on the right side of the top panels in Figure 1. (c) Frequency spectrum of 0–50 m vertical velocity in the four experiments. (d–f) Same as Figures 3a–3c but for the 0–150 m new production. Note that a log scale is used along the x-axis in Figure 3f and a linear scale in Figure 3c.

with HF winds, the intensified vertical advection is able to move subsurface maxima of NP and phytoplankton, and also the deeper nutricline, closer to the surface. This is the case within the submesoscale structures affected by frontogenesis (Figure 2). Then vertical diffusion brings the biogeochemical material to the surface mixed-layer (Figure 2).

[10] The uplift of nutrient from subsurface to the surface strongly reduces the time scale of the biological response to nutrient supplies which further increases NP. This is because at sub-surface the lack of light is a strong limiting factor of productivity. To quantify this effect, we estimate the phytoplankton effective growth rate $\mu = NP/PHY$ (in d^{-1}), where NP is new production (in $mmoleN\ m^{-3}d^{-1}$) and PHY is the concentration of phytoplankton (in $mmoleN\ m^{-3}$). In all experiments, the time scale associated with phytoplankton growth, $1/\mu$, is close to 10 days when NP occurs at 100 m, and can be as fast as 1 day when NP occurs at 10 m. Thus, close to the surface, the biological response time scale becomes close to the inertial frequency, which enables the partial utilization of the nutrients that are advected by the near-inertial waves.

This is supported by the nutrient budgets: the 0–150 m nutrient supplies are not immediately uptaken by NP (0–150 m $(AD + DF) > NP_{tot}$ in Table 1), while the 0–50 m supplies equal NP (0–50 m $(AD + DF) \approx NP_{surf}$ in Table 1). These dynamical and biological arguments explain the much stronger change in the surface mixed-layer (NP_{surf}) compared to the change in total NP (NP_{tot}).

4. Discussion

[11] The additional NP uplift with HF winds thus results both from the stronger vertical advection at 50 m and from the stronger diffusion (Table 1). We discuss how HF winds may affect these physical mechanisms.

[12] Impacts of HF winds on vertical velocity (W) is illustrated on Figure 3, which shows the time evolution of W and NP across a filament oriented approximately along the NW-SE direction (see Figure 1). In the no wind experiment, W has a bipolar structure characteristic of frontogenesis [Hoskins and Bretherton, 1972], with upwell-

ing (downwelling) on the warm (cold) side of the filament (Figure 3a). It varies between $-20/+10 \text{ md}^{-1}$. With HF winds, W shows distinct near-inertial oscillations (Figure 3b), and varies between $-81/+47 \text{ md}^{-1}$. Most of all, there is a clear asymmetry in the upwelling/downwelling motions associated to the near-inertial motions leading to a dominance of upwellings (downwellings) on the warm (cold) side of the front (Figure 3b). Averaged over an inertial period, the mean W -fields (not shown) from the HF wind experiments emphasize the impact of this asymmetry, displaying the same positive and negative patterns as Figure 1c but with larger amplitude and spatial extension. Thus contribution of the near-inertial motions appears to reinforce the contribution of the vertical velocity associated with the frontogenesis. The W -frequency spectra confirm the preceding results, concerning not only the strong energy increase at the inertial frequency but also the significant increase at lower frequencies. Increase of the mean vertical velocity in presence of HF winds has been observed as well in high-resolution numerical simulations of a fully turbulent mesoscale eddy field (P. Klein et al., manuscript in preparation, 2009) and appears to be due to the nonlinear interactions between near-inertial waves as already noticed by Klein and Tréguier [1993]. Understanding these characteristics requires a more thorough dynamical study that is beyond the scope of the present study, but that would extend the results of Thomas and Lee [2005].

[13] Regarding diffusion, HF winds are known to increase the amplitude of the diffusion fluxes and to deepen the mixed-layer [Klein and Coste, 1984]. This is due to the energetic near-inertial motions that produce strong vertical shears at the mixed-layer base. But this mixed-layer deepening and diffusion fluxes are also modulated by the submesoscales. As mentioned in the introduction, energetic near-inertial motions become rapidly trapped within submesoscales and principally within anticyclonic structures. This means that diffusion fluxes and mixed-layer deepening are enhanced in those regions where furthermore the vertical velocity is statistically upward. Both mechanisms act consequently in phase to further uplift biogeochemical material in the surface layers.

[14] These stronger vertical velocity and diffusion is accompanied by an intensification of NP_{tot} as illustrated by the comparison of Figures 3d and 3e. The NP spectrum (Figure 3f), on the other side, shows that the increase of NP in response to HF winds NP mostly concerns the low-frequency part of the spectrum (although there is a signal close to the wind forcing frequency). This reflects the cumulative uptake of nutrients by phytoplankton that acts as a time-integrator of the advective fluxes.

5. Conclusion

[15] Our results suggest that HF winds re-inforce vertical velocities, as well as the mixed-layer deepening, within submesoscale structures. These effects stimulate NP, particularly close to the surface, with a smaller impact on the total NP budget. A direct consequence is that the submesoscale filamentary patterns of phytoplankton become observable from space in the presence of HF winds, which is not the case without wind (see Figures 2c and 2d). By comparing experiments with the same time-mean wind stress but with

different wind frequencies, we have shown that the increase of NP due to near-inertial oscillations is more important than the increase due to the Ekman transport resulting from a slow-evolving wind forcing.

[16] The present results are based on transient, highly idealized model simulations, and are not quantitatively representative of any specific biogeochemical provinces. In particular, the intensity of the vertical transport depends on many parameters such as the nutrient large-scale field and the strength of the mesoscale eddy field. Estimating their contribution to basin-scale budgets requires long simulations at the scale of an ocean basin, which will involve complex adjustments associated with the equilibration of the circulation and of the nutrient pool. However the present results suggest that a complete understanding of submesoscale-biological interactions needs also to take into account the interaction with rapid phenomenon such as near-inertial waves forced by HF winds.

[17] **Acknowledgments.** The calculations reported in this study were performed on the NEC SX8 of IDRIS (France). The authors thank Xavier Capet for his useful comments and Leif Thomas for encouraging us to publish these results.

References

- Blanke, B., and P. Delecluse (1993), Variability of the tropical Atlantic Ocean simulated by a general circulation model with two different mixed-layer physics, *J. Phys. Oceanogr.*, **23**, 1363–1388.
- Capet, X., J. C. McWilliams, M. J. Molemaker, and A. F. Shchepetkin (2008), Mesoscale to submesoscale transition in the California Current System. Part 2: Dynamical processes and observational tests, *J. Phys. Oceanogr.*, **38**, 44–64.
- Hoskins, B. J., and F. P. Bretherton (1972), Atmospheric frontogenesis models: Mathematical formulation and solution, *J. Atmos. Sci.*, **29**, 11–37.
- Johnson, K. S., L. Coletti, H. Jannasch, T. Martz, D. Swift, and S. Riser (2008), Long-term observations of ocean biogeochemistry with nitrate and oxygen sensors in Apex profiling floats, *Eos Trans. AGU*, **89**(53), Fall Meet. Suppl., Abstract OS31A-1232.
- Klein, P., and B. Coste (1984), Effects of wind-stress variability on nutrient transport into the mixed layer, *Deep Sea Res., Part A*, **31**, 21–37.
- Klein, P., and A. M. Tréguier (1993), Inertial resonances induced by a geostrophic jet, *J. Phys. Oceanogr.*, **23**, 1897–1915.
- Klein, P., G. Lapeyre, and W. G. Large (2004), Wind ringing of the ocean in presence of mesoscale eddies, *Geophys. Res. Lett.*, **31**, L15306, doi:10.1029/2004GL020274.
- Klein, P., B. L. Hua, G. Lapeyre, X. Capet, S. LeGentil, and H. Sasaki (2008), Upper ocean turbulence from high 3-D resolution simulations, *J. Phys. Oceanogr.*, **38**, 1748–1763.
- Lévy, M., P. Klein, and A. M. Tréguier (2001), Impacts of sub-mesoscale physics on phytoplankton production and subduction, *J. Mar. Res.*, **59**, 535–565.
- Mahadevan, A., L. Thomas, and A. Tandon (2008), Comment on “Eddy/wind interactions stimulate extraordinary mid-ocean plankton blooms”, *Science*, **320**, 448.
- McGillicuddy, D. J., Jr., et al. (1998), Influence of mesoscale eddies on new production in the Sargasso Sea, *Nature*, **394**, 263.
- Niewiadomska, K., H. Claustre, L. Prieur, and F. d’Ortenzio (2008), Submesoscale physical-biogeochemical coupling across the Ligurian Current (northwestern Mediterranean) using a bio-optical glider, *Limnol. Oceanogr.*, **53**, 2210–2225.
- Thomas, L. N., and C. M. Lee (2005), Intensification of ocean fronts by down-front winds, *J. Phys. Oceanogr.*, **35**, 1086–1102.
- Young, W. R., and M. Ben Jelloul (1997), Propagation of near inertial oscillations through a geostrophic flow, *J. Mar. Res.*, **55**, 735–766.

P. Klein and M. Ben Jelloul, LPO, IFREMER, UBO, CNRS, BP 70, F-29280 Brest CEDEX, France.

M. Lévy, LOCEAN, IPSL, Université Pierre et Marie Curie, CNRS, BC100, 4 Place Jussieu, F-75252 Paris CEDEX 05, France. (marina@locean-ipsl.upmc.fr)