

On the wind-driven formation of mesoscale plankton patches in island wakes

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Abstract

Using a three-dimensional coupled physical-biological model, this paper explores the creation of phytoplankton blooms around tropical islands in the presence of ambient currents and short-lived (~4 days) wind events. The ambient flow creates a retention zone of weak flows in the lee of the island, which is a typical feature of island wakes. Findings reveal that wind-induced upwelling effects are essential for the initial nutrient enrichment and phytoplankton growth that occur mainly in this retention zone. Oscillating flow, typical of island wakes, occasionally releases mesoscale patches of upwelled water and its phytoplankton load into the ambient ocean. The phytoplankton continues to grow within floating structures that are of up to 20 km in diameter. This mechanism complements the plankton growth associated with the formation of mesoscale eddies.

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2 **On the wind-driven formation of mesoscale plankton patches in island wakes**
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6 **Key Points:**

- 7 • Uses a modelling approach to study phytoplankton growth around tropical islands in the
8 presence of ambient currents and short-lived wind events
- 9 • Wind-induced upwelling effects are essential for the initiation of phytoplankton growth
10 in the retention zone of the island wake
- 11 • Oscillating flow, typical of island wakes, occasionally releases mesoscale patches of
12 upwelled water and its phytoplankton load into the ambient ocean.

Abstract

Using a three-dimensional coupled physical-biological model, this paper explores the creation of phytoplankton blooms around tropical islands in the presence of ambient currents and short-lived (~4 days) wind events. The ambient flow creates a retention zone of weak flows in the lee of the island, which is a typical feature of island wakes. Findings reveal that wind-induced upwelling effects are essential for the initial nutrient enrichment and phytoplankton growth that occur mainly in this retention zone. Oscillating flow, typical of island wakes, occasionally releases mesoscale patches of upwelled water and its phytoplankton load into the ambient ocean. The phytoplankton continues to grow within floating structures that are of up to 20 km in diameter. This mechanism complements the plankton growth associated with the formation of mesoscale eddies.

Plain Language Summary

Phytoplankton forms the basis of most marine food webs. Phytoplankton growth in the surface layers of the oceans is generally limited by nutrient availability and requires nutrient supply through physical processes such as upwelling. This study reveals that short-lived wind effects are essential to initiate nutrient enrichment and phytoplankton growth near an island. In the presence of an ambient current, this wind-driven phytoplankton growth occurs in a zone of weak flow forming in the lee of the island. However, oscillating flow occasionally releases mesoscale patches of upwelled water and its phytoplankton load into the ambient ocean. The phytoplankton continues to grow within these patches, forming floating confined marine ecosystems that are up to 20 km in diameter.

1 Introduction

Plankton concentrations in the sea are spatially heterogeneous and not randomly distributed (Hutchinson, 1953; Frontier, 1973; Cassie, 1962, 1963; Levin and Segel, 1976; Owen, 1989; Davis et al., 1992; Pinel-Alloul, 1995; Benoit-Bird et al., 2013). The spatial heterogeneity is characterized as patches, aggregations, or clusters in with planktonic organisms exhibit higher concentrations than found in surrounding water. In the oceans, patches form and exist at various horizontal scales, from the microscale (0.01 to 1 m) to the mesoscale (10 to hundreds of kilometers), noting that plankton patches, or layers, also form in the vertical as “thin layers” or subsurface phytoplankton blooms. Moreover, they can exist at multiple scales simultaneously, with smaller patches comprising larger aggregations (Haury et al., 1978). Phytoplankton forms the basis of most marine food webs. Hence, the knowledge of physical processes that influence phytoplankton growth and plankton patchiness is essential for the understanding the function of marine food webs including carbon and nutrient cycling, and the improvement ecosystem models and fishery predictions. Despite the importance of plankton patchiness over a range of spatial scales, the understanding of the mechanisms underlying the generation and maintenance of plankton patches is relatively poor (Robinson et al., 2021).

The “island mass effect” summarizes various coupled physical-biogeochemical mechanisms that enhance plankton productivity near an island, or groups of islands (Doty and Oguri, 1956). Mechanisms include the interaction of oceanic flows with the island topography (Mann and Lazier, 2005), tidal mixing around islands (Kodaira and Waseda, 2019), tidally induced internal waves (Griffin et al., 1987), turbulent mixing in island wakes (Hasegawa et al., 2021), and other factors such as nutrient intake from island runoff (Bell, 1992), atoll flushing (Gove et al., 2016), groundwater discharge (Street et al., 2008) and human activities that increase nearshore nutrient concentrations above natural levels (Vitousek et al., 1997).

Island wakes are flow patterns in fluids that arise from horizontal flow around an obstacle. Ample studies have focused on physical processes in the wakes of islands and headlands (e.g., Batchelor, 1967; Barkley, 1972; Pattiaratchi et al., 1987; Wolanski and Hamner, 1988; Tomczak, 1988; Aristegui et al., 1994; Heywood et al., 1996; Dietrich et al., 1996; Barton et al., 2000; Aiken et al., 2002; Coutis and Middleton, 2002; Harlan et al., 2002; Neill and Elliott, 2004; Caldeira et al., 2005). Typical features of island wake are (i) the formation of a stagnant zone in the lee of the island, henceforth referred to as retention zone, often exhibiting a return flow that operates as a trap for floating particles, and (ii) the formation of an island wake that follows from an oscillating flow in the retention zone (Kämpf and Chapman, 2016). The generation of cyclonic eddies via barotropic or baroclinic instabilities (Dong et al., 2007; Teinturier et al., 2010), and flow divergence (Hasegawa et al., 2004; Chang et al., 2013) are deemed common upwelling mechanisms in the lee of an island, according to the recent review of De Falco et al. (2022).

Several previous studies focussed on the enhancement in productivity and biomass around islands and the general biological impact of wakes (e.g., Hamner and Hauri, 1981; Hernandez-Leon, 1991; Martinez and Maamaatuaiahutapu, 2004; Hasegawa et al., 2004; Hasegawa et al., 2021). While findings confirmed the enhanced biological production near islands, the studies did not question whether effects other than the island wake itself are responsible for this biological response.

Recently, Kämpf et al. (2023) used a process-oriented coupled physical-biological model to demonstrate that wind events of only a few days of duration can trigger significant phytoplankton growth near larger (>10 km in diameter) tropical reef islands. Simulated vertically integrated chlorophyll-a levels of ~ 10 mg/m² agreed well with observational evidence by Gove et al. (2016) reporting elevated levels of 1–10 mg/m² within 10 km from the coast from 25 in-situ surveys across 21 pacific coral reef islands and atolls. This finding has motivated the current work that explores how current-driven island wakes, not considered by Kämpf et al. (2023), influence the nutrient enrichment and phytoplankton growth around islands.

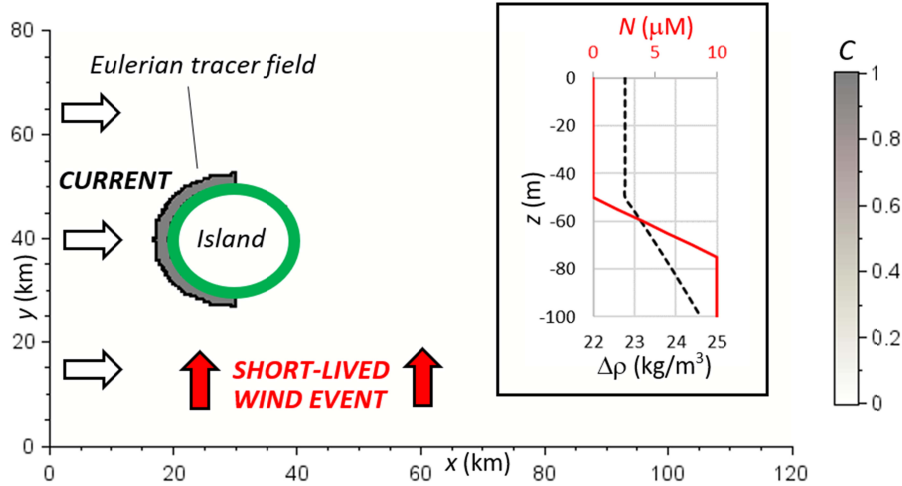


Figure 1: Model domain including a circular island. The ambient current flows from left to right. The direction of short-lived wind events is varied. An Eulerian tracer field C (the initial distribution is displayed) is used to illustrate the horizontal structure of island wakes. The insert shows initial vertical profiles of (dashed black curve) density excess $\Delta\rho$ (kg/m³), relative to 1000 kg/m³, and (red solid curve) dissolved nitrogen concentration N (μM).

2 Methodology

2.1 Model description

Apart from the addition of an ambient current and a larger model domain, this studies applies the same model equations and configuration that Kämpf et al. (2023) used in their control run. Only key features are summarized here. The physical model is a conventional sigma-coordinate model COHERENS (Luyten et al., 1999) that is applied with a horizontal resolution of 500 m and 20 vertical layers to a model domain that extends 120 km in the x -direction and 80 km in the y -direction (**Figure 1**). The island is simplified as a circular vertical cylinder, 20 km in diameter.

Initially, the ocean's density field is assumed to be horizontally uniform, which hinders the creation of baroclinic instabilities that are common features for island wakes (see Dong et al., 2007). The initial density profile exhibits a strong pycnocline at 50 m depth (see Fig. 1 insert) characterized by a stability frequency of $M = 0.0183$ s⁻¹, defined by $M^2 = -g\rho_0 \frac{d\rho}{dz}$, where $g = 0.91$ m/s² is acceleration due to gravity, $\rho_0 = 1026$ kg/m³ and ρ are mean and actual densities,

respectively, and z is the vertical coordinate. The presence of strong stratification hinders the development of deeper flows. This allowed us to limit the total depth of the model domain of 100 m, which significantly reduces the CPU time of model simulations. As in the study by Kämpf et al. (2023), the Coriolis parameter is set to $f = +0.5 \times 10^{-4} \text{ s}^{-1}$, corresponding to tropical seas at a geographical latitude around 20°N . Horizontal turbulence is parameterized using the closure scheme by Smagorinsky (1963). Eddy diffusivity is assumed the same as eddy diffusivity. Vertical turbulence is parameterized with the k - ϵ turbulence closure using standard parameter settings (see Luyten et al., 1999). An advection-diffusion equation is used to predict the evolution of an Eulerian concentration field C with the same eddy diffusivities as the density field. C has initially zero values except in a zone near the island, shown in Fig. 1, where $C = 1$ throughout the simulation.

The physical model is directly coupled to a Nitrogen-Phytoplankton (NP) model which exclusively focusses on the initial phytoplankton growth and ignores effects due to zooplankton grazing and bacterial nutrient-recycling. The surface mixed layer is initially devoid of nitrogen (see Fig. 1 insert). Dissolved nitrate concentration increases below the surface mixed layer linearly to a maximum of $10 \text{ } \mu\text{M}$ at a depth of 75 m, with constant values underneath. This initial nitrogen field is chosen such that exclusively upwelling-induced vertical displacements of the nutricline rather than vertical diffusion initiate phytoplankton growth. The conservation equations for dissolved nitrogen concentration (N) and phytoplankton concentration (P) are given by:

$$\partial N / \partial t + \text{Adv}(N) = \text{Diff}(N) - \frac{\mu_* N}{(K_N + N)} P \quad (1)$$

$$\partial P / \partial t + \text{Adv}(P) = \text{Diff}(P) + \left[\frac{\mu_* N}{(K_N + N)} - \lambda \right] P \quad (2)$$

where t is time, $\text{Adv}(\cdot)$ and $\text{Diff}(\cdot)$ are three-dimensional advection and diffusion operators, μ_* is the largest possible phytoplankton growth rate under saturated nutrient conditions, K_N the half saturation constant of phytoplankton uptake of nitrogen, taken as $1.0 \text{ } \mu\text{M-N}$, and λ is the mortality rate, set to 0.05 day^{-1} . The growth rate μ_* is controlled a prescribed day-night cycle of radiance based on the method described by Ji et al. (2007). Kämpf et al. (2023) present the resultant vertical profile of daily-averaged maximum net growth rates of phytoplankton that attain a maximum of 0.55 day^{-1} at a depth of 10 m, and become negative at depths $> 45 \text{ m}$. Chlorophyll- a values in units of mg/m^3 are calculated from predicted phytoplankton concentrations in units $\mu\text{M-N}$ on the basis of an average C:chl- a ratio of 50:1 (see Jakobsen and Markager 2016) and a Redfield ratio of C:N of 106:16. Results are presented as vertically integrated chlorophyll- a concentrations (mg/m^2) for comparison with values reported by Gove et al. (2016)

2.2 Experimental design

The ambient barotropic current is created by prescribing a sea-level difference of 5 cm between the northern and southern boundaries with a linear adjustment over the first simulation day. This creates an eastward flow of a speed of $\sim 0.3 \text{ m/s}$. Zero-gradient conditions are used for all variables at all boundaries otherwise. In addition, a short-lived wind event is prescribed during the first 4 days of simulation. The wind field of events is spatially uniform. It is linearly

adjusted from zero to its final value of 10 m/s over the first simulation day and then switched off after 4 days. Standard bulk formulae are used to calculate wind stresses. For comparison, five different wind forcing scenarios are considered with either easterly, southerly, westerly, or northerly wind direction, or no wind at all. The total simulation time for each scenario is 20 days.

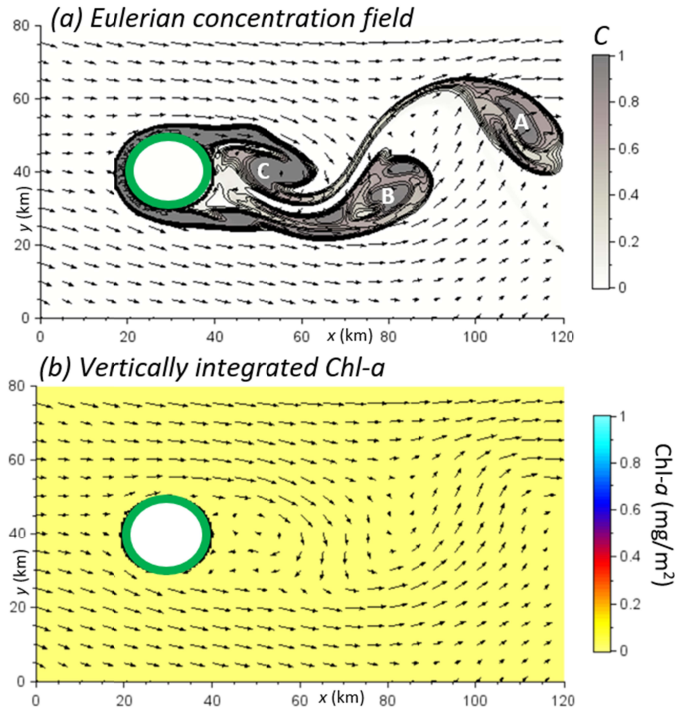


Figure 2: Simulation without wind forcing. Horizontal distributions of a) the Eulerian concentration field C ; three individual patches of high Eulerian concentration, named A, B and C, can be identified; and b) vertically integrated chlorophyll-a values (mg/m^2) after 15 days of simulation. Arrows show horizontal velocity vectors (only every 10th vector is shown). Note that chlorophyll-a values remain zero throughout the domain.

3 Results and Discussion

In the absence of wind effects, the ambient current leads to the formation of a classical island wake (**Figure 2a**). The structure of the island wake is displayed in terms of zones of low and high concentrations of the Eulerian tracer that is released on the upstream side of the island. The island wake consists of a retention zone in the lee of the island, and oscillating flow that occasionally discharges seawaters from the retention zone as individual patches into the ambient ocean. Three of such patches of 10-20 km diameter have formed during 15 days of simulation. The Eulerian concentration field also reveals the existence of elongated structures, known as filaments.

Despite some perturbations of the flow, the island wake is devoid of dynamic instabilities that could induce upward nutrient fluxes. Due to the absence of the latter, the scenario without wind effects fails to create any phytoplankton growth (**Figure 2b**). The reason for this failure is that the horizontal flow does neither create upwelling near the island, nor does it meet conditions essential for the development of baroclinic or barotropic instabilities.

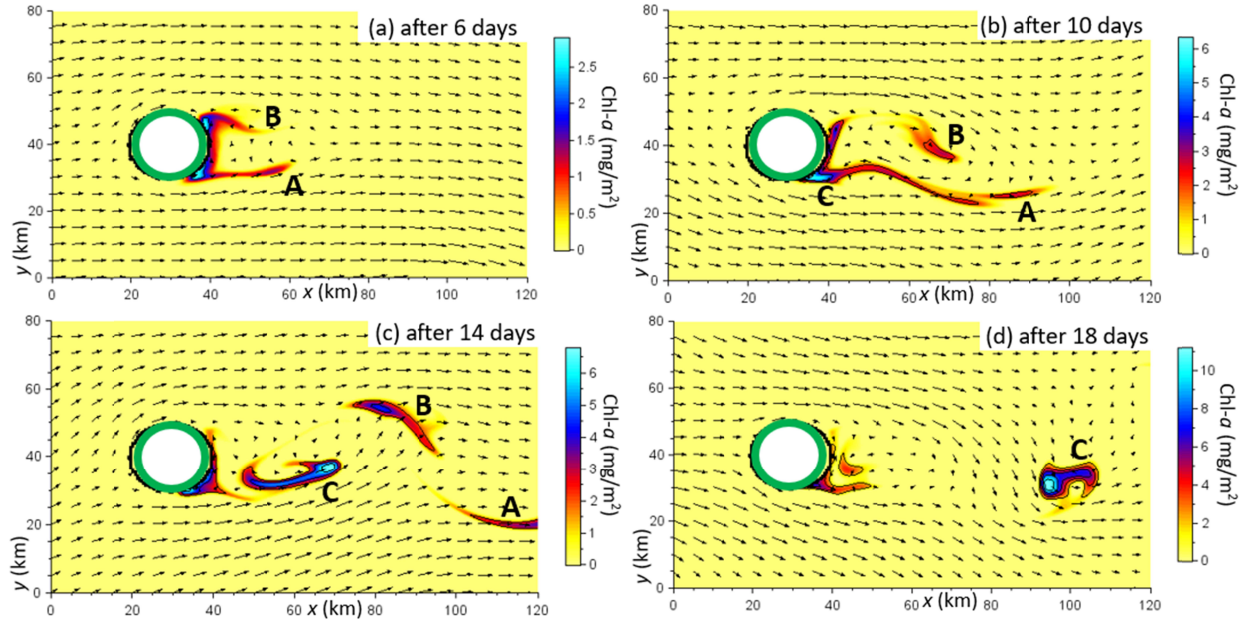


Figure 3: Simulation with an initial easterly wind burst. Horizontal distributions of vertically integrated chlorophyll-*a* values (mg/m^2) after a) 6, 10, 14 and 18 days. Arrows show horizontal velocity vectors (only every 10th vector is shown). Capital letters mark individual plankton patches.

In contrast, transient wind forcing induces vertical nutrient fluxes that trigger phytoplankton growth near the island (**Figure 3a**). Kämpf et al. (2023) discusses this phytoplankton production in the absence of island wakes. Here, the upwelled water and its phytoplankton load is occasionally discharged into ambient ocean as filaments and mesoscale patches with diameters of ~ 10 km (**Figure 3b-d**). In comparison with the simulation without wind forcing (see Fig. 2) it is obvious that wind-induced upwelling effects near the island are essential in the creation of the plankton patches. We can also see that the phytoplankton concentration continues to increase in floating plankton patches. For instance, patch C had an initial vertically integrated chlorophyll-*a* value of $\sim 6 \text{ mg}/\text{m}^2$ after 12 days of simulation. This increased to $> 10 \text{ mg}/\text{m}^2$ during the subsequent 6 days. (see Fig. 3d). This increase is possible because (i) the upwelled water has an excess in nitrogen, and (ii) the ambient currents transports both this upwelled water and the phytoplankton it contains. To the end, the phytoplankton patches can be characterized as “floating islands” of individual marine food webs. Note that the phytoplankton patches, simulated here, are vertically mixed throughout the surface mixed layer.

The creation of plankton patches is invariant of the direction of the initial wind event (**Figure 4**), but there are variations of their shapes and magnitudes. Without ambient currents, phytoplankton starts to form first in the region where the Ekman transport is perpendicular to the coast (see Kämpf et al., 2023). Later, the nutrient enrichment zone moves around the island as a coastal Kelvin wave. Here, the ambient currents operates to trap the phytoplankton growth in the retention zone in the lee of the island. Note that a westerly wind event has the strongest response in terms of phytoplankton growth. This scenario creates a spiral-shaped phytoplankton patch, ~ 20 km in diameter, with a vertically integrated chlorophyll-*a* content of $\sim 8 \text{ mg}/\text{m}^2$ after 10 days of simulation (see Fig. 4c).

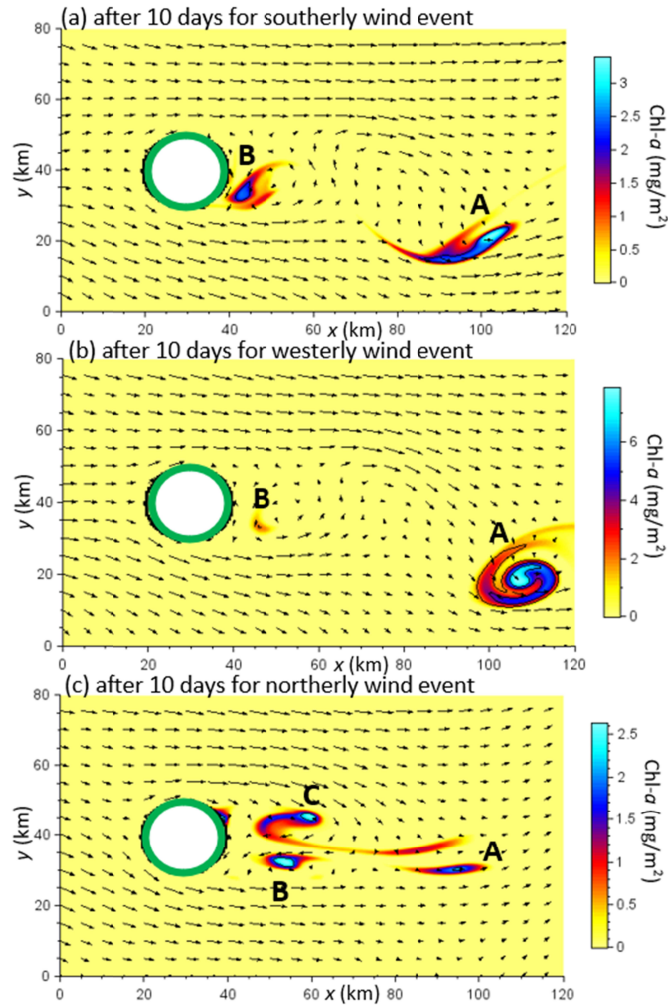


Figure 4: Horizontal distributions of vertically integrated chlorophyll-a values (mg/m^2) after 10 days for simulations with different directions of initial wind bursts; namely a) southerly, b) westerly, and c) northerly. Arrows show horizontal velocity vectors (only every 10th vector is shown). Capital letters mark individual plankton patches.

4 Conclusions

This study reveals that short-lived wind events can trigger the creation of mesoscale phytoplankton patches in interaction with island wakes. The plankton patches are related to the periodic release of previously upwelled water from the retention zone formed in the lee of the island. Vertical nutrient fluxes triggering the subsequent plankton growth exclusively occur as an upwelling pulse during the wind event. Mesoscale eddies that are the common explanation of plankton patches (see De Falco et al., 2022). The patches discussed here are created in the absence of eddies. Hence this work presents a significant advance of the understanding of physical processes that create plankton heterogeneity in the oceans. Future studies should investigate the interaction of island wakes for multiple islands such as island arcs.

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Open Research

This work did not make use of data. The Fortran model code will be deposited to a FAIR compliant repository at acceptance of this paper.

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