A HYDROBIOLOGICAL MODEL AS A TOOL FOR THE DETECTION OF HARMFUL ALGAL BLOOM (HAB) EPISODES: APPLICATION TO THERMAIKOS GULF

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ABSTRACT

Algal blooms constitute one of the most important environmental phenomena in coastal areas; particularly if these blooms contain potential toxic algae populations. As Dinophysis spp. had been recorded in low population densities, all over the year in Thermaikos Gulf, a mathematical model was developed to simulate critical conditions for the appearance of an algal bloom episode and the population's dispersion in space and time. The model is constituted from two parts, a mechanical which computes the hydrodynamics and the matter transfer of the investigated area as well as a biological part which computes the cells growth rate and the cells decay.

The application of the model simulations were based on: (a) different starting population densities, (b) different positions in the Gulf as sources of initial population, (c) different wind direction and speed.

The results show that population densities above a number of 500-1000 cells/L with mean wind speed of 5 m/sec and low grazing rates may regulate the appearance of a HAB in Thermaikos Gulf. The dispersion of algae population was finally found to be regulated by wind velocity, filter feeder's abundance.

It was found that if an episode starts in the inner part of the Gulf, under the influence of the prevailing north and south winds over the area of the Gulf, the population hardly reaches to the outer part of the Gulf, while an episode in the outer area of the Gulf leads to a variety of pattern dispersions depending on the different wind conditions.

KEYWORDS: Phytoplankton growth, hydro-biological model, phytoplankton dispersion, Thermaikos Gulf

INTRODUCTION

Thermaikos Gulf (NW Aegean Sea, Greece) is a semi-enclosed and eutrophic area, receiving high nutrient inputs from rivers, urban and industrial runoff [1]. The shellfish farming activity, especially in the NW area of the gulf, reaches 85% of the total Greek production [2]. As primary producers respond to increased nutrient loads increasing their production, algal blooms constitute one of the most important environmental phenomena in coastal areas; particularly if these blooms contain potential toxic algal populations.

Since 2000, harmful algal blooms (HABs) have been recorded repeatedly in Thermaikos Gulf and the causative organisms have been identified as *Dinophysis acuminata, Prorocentrum micans, P. dentatum, Gymnodinium* sp., *Scrippsiella trochoidea*, and *Noctiluca scintillans*. One of the most serious HAB events was recorded during the winter of 2000, when *D. acuminata* reached $8.5 \cdot 10^4$ cells L^{-1} [3, 4]. Species belonging to the genus *Dinophysis* produce toxins consisting mostly of okadaic acid (OA) and/or dinophysistoxin-1 (DTX-1) [5]. The human consumption of toxin-contaminated shellfish causes gastrointestinal symptoms known in literature as Diarrhetic Shellfish Poison (DSP) [6]. Due to this reason, during HABs, the harvest in mussel cultures is not allowed, causing a substantial socio-economic impact in the area.

Hence, it is obvious that HABs represent a serious and widespread threat to marine ecosystems, fishery resources and human health. There is, therefore, a need to understand better their population dynamics in order to improve our capability to predict and manage these episodes. In this effort, the study of the involved physical and biological interactions may play a particular and important role [7, 8].

As living cysts and low population densities of *Dinophysis* sp were found in the whole area of the Gulf, all over the year [9, 10], a mathematical model was developed to simulate critical conditions for the appearance of an algal bloom episode and the population's dispersion in space within a short time period (7 days).

MATERIALS AND METHODS

MODEL DESCRIPTION

A 2D-depth averaged hydrodynamic mathematical model coupled with a transport model is applied for the description of the algal dispersion in the Thermaikos basin.

According to the principles of mass and momentum conservation, the hydrodynamic model is based on the following equations [11]:

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}=-g\frac{\partial \zeta}{\partial x}+fV+\frac{\tau_{sx}}{\rho h}-\frac{\tau_{bx}}{\rho h}+\nu_h\frac{\partial^2 U}{\partial x^2}+\nu_h\frac{\partial^2 U}{\partial y^2}$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}=-g\frac{\partial \zeta}{\partial y}-fU+\frac{\tau_{sy}}{\rho h}-\frac{\tau_{by}}{\rho h}+\nu_h\frac{\partial^2 V}{\partial x^2}+\nu_h\frac{\partial^2 V}{\partial y^2}$$

$$\frac{\partial \zeta}{\partial t}+\frac{\partial (Uh)}{\partial x}+\frac{\partial (Vh)}{\partial y}=0$$

where, h is the depth of the water column, U & V the vertically averaged horizontal current velocities, ζ is the surface elevation, f the Coriollis parameter, τ_{sx} & τ_{sy} the wind surface shear stresses and τ_{bx} & τ_{by} the bottom shear stresses, ν_h is the dispersion coefficient, ρ the seawater density. and g the gravity acceleration.

The study area was discretized with a grid of 41×42 cells. The spatial step was dx = 1 nm (1852 m) while the time step was dt = 20 s.

Concerning the transport model, the horizontal positions of the particles are computed from the superposition of the deterministic and stochastic displacements, according to the following relationships:

$$x_i^{n+1}=x_i^n+\Delta x_i^n+\Delta x_i^{n\prime} \text{ and } y_i^{n+1}=y_i^n+\Delta y_i^n+\Delta y_i^{n\prime}$$

where $\Delta x_i^n = u_i^n(x_i^n, t^n)dt$ is the deterministic displacement, and $\Delta x_i^{n\prime} = u_i^{n\prime}\, dt\, rnd[-1,1]$ the stochastic displacement for x-axis with $u_i^n(x_i^n, t^n)$ the deterministic velocity at time t^n at the location x_i^n of the i particle and $u_i^{n\prime}$ the random (stochastic) horizontal velocities at time t^n at the location x_i, with $u_i^{n\prime}=\sqrt{6D_h/dt}$, D_h is the horizontal sediment diffusion coefficient and *rnd* is a random variable distributed uniformly between -1 and +1. Similar relationships are considered, respectively, for the velocities on y-axis. The spatial particle distribution resulting from the above process can then lead to the computation of particle concentrations, relative to the number of particles in each grid box.

Each one of the above particles is considered to be a *Dinophysis* spp. cell following exponential growth:

$$N = N_0 e^{\mu},$$

where N_0 is the starting population and μ is the net growth rate, usually limited by temperature, light, nutrients, predation, competition and sinking [12-14].

In this simulation, we take into account the following two assumptions coming from literature:

a) Although cell abundance in the peak of the blooms exceeds the number of 10^4 cells L^{-1}, a minimum of 0.5 - 1.2 $\cdot 10^3$ cells L^{-1} is a threshold for restrictions in fisheries [7]. So, in our model, a number of 2,000 cells of *Dinophysis* spp are considered to be the minimum population for the starting of a bloom episode.

b) In almost all the studies, before a bloom episode, *Dinophysis* cell abundance is usually less than 200 cells L^{-1}. For this reason, we consider, in this simulation, N_o = 150 cells L^{-1}.

Concerning the application of the model, we consider a) two different positions for the starting point, the first one, position A, in the inner part of the gulf, and the second one, position B, in the outer gulf as depicted in Fig. 1, and b) simulation time of 7 days.

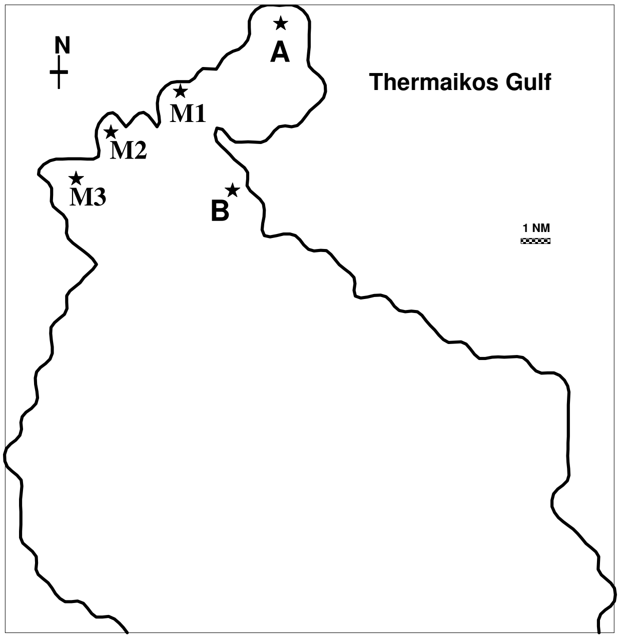

FIGURE 1 - Thermaikos Gulf, Greece. A and B are the starting points of the simulation, A is the area close to the harbor of Thessaloniki, M1, M2 and M3 are mussel cultures areas.

RESULTS AND DISCUSSION

Model simulation started with low phytoplankton net growth rate (0.3 div day^{-1}). HAB episodes appeared when net growth rate takes values close to 1.0 div day^{-1}.

For the inner part of the Gulf (point A), we consider 4 cases of different wind speed (2, 5, 7 and 10 m/s) and

4 cases for the most frequent wind directions N, NW, S, and SE [15]. Figure 2 depicts the computer outcomes for the simulation of a 7-days time period, under the influence of N winds. It is shown that the appearance of a bloom is favored by low wind velocities (Figs. 2a and b). As wind velocities increase, population density decreases while the spread of dispersion increases. With wind speed higher than 5 m/s, high population densities could be observed in the whole area of the inner part of the gulf (Figs. 2 c and d) with maximum population densities close to 2300 cells L^{-1}; in such cases, the transfer of large amount of *Dinophysis* spp cells close to shellfish cultures could be expected (M1 in Fig. 1).

NW winds show similar patterns with N winds concerning the maximum growth rate and the population density of phytoplankton, but they differ in the way they influence its dispersion. While N and NW winds with speed 2 m/s show similar patterns of dispersion (Fig. 3a), a quite different pattern appeared when their velocity reaches the value of 5 m/s (Figs. 1b and 2b). Further more, winds with speed higher than 5 m/s may force large amount of the algal population, close to the mussel cultures area M1 in a 7-days period (Figs. 3 c and d).

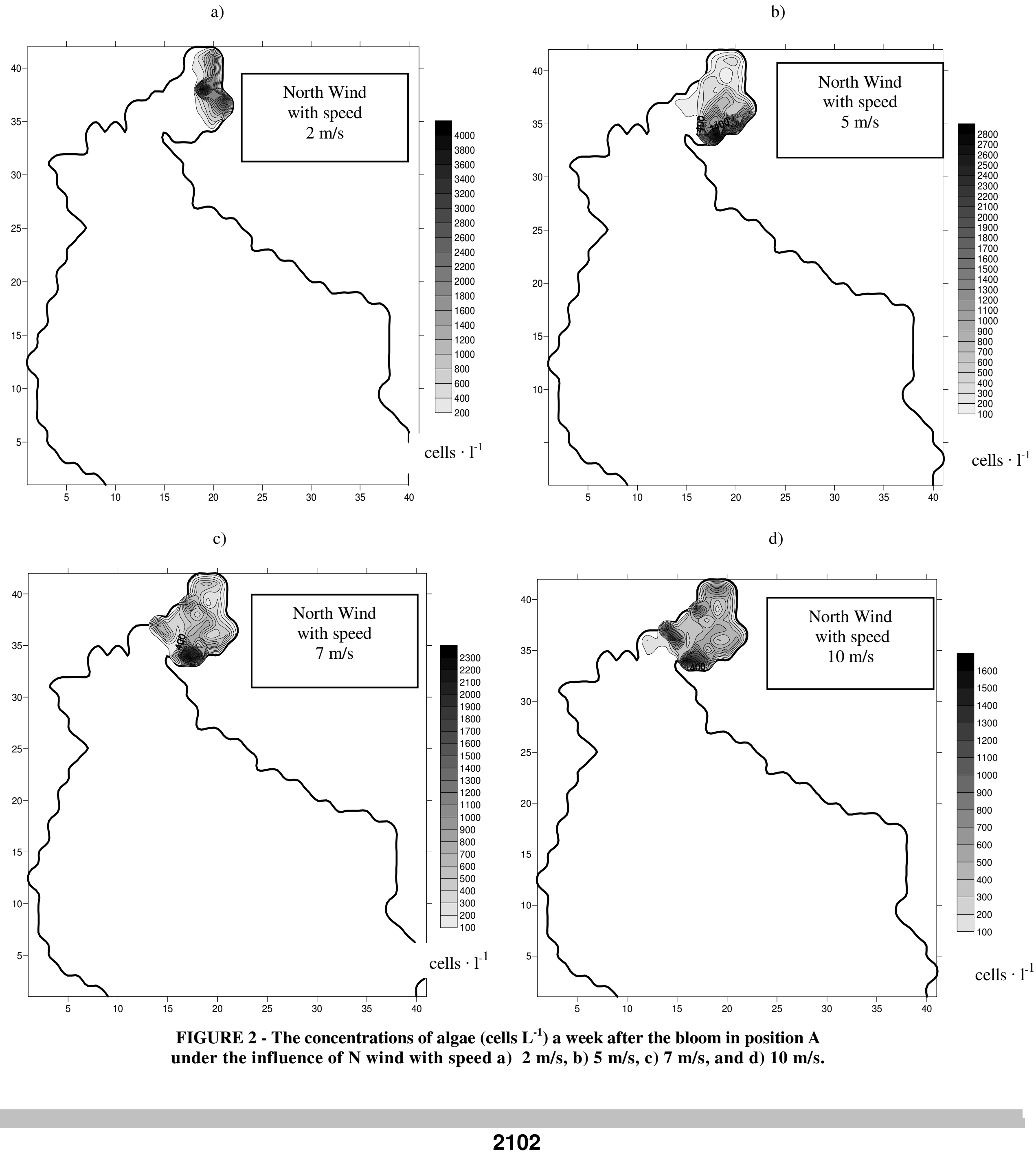

FIGURE 2 - The concentrations of algae (cells L^{-1}) a week after the bloom in position A under the influence of N wind with speed a) 2 m/s, b) 5 m/s, c) 7 m/s, and d) 10 m/s.

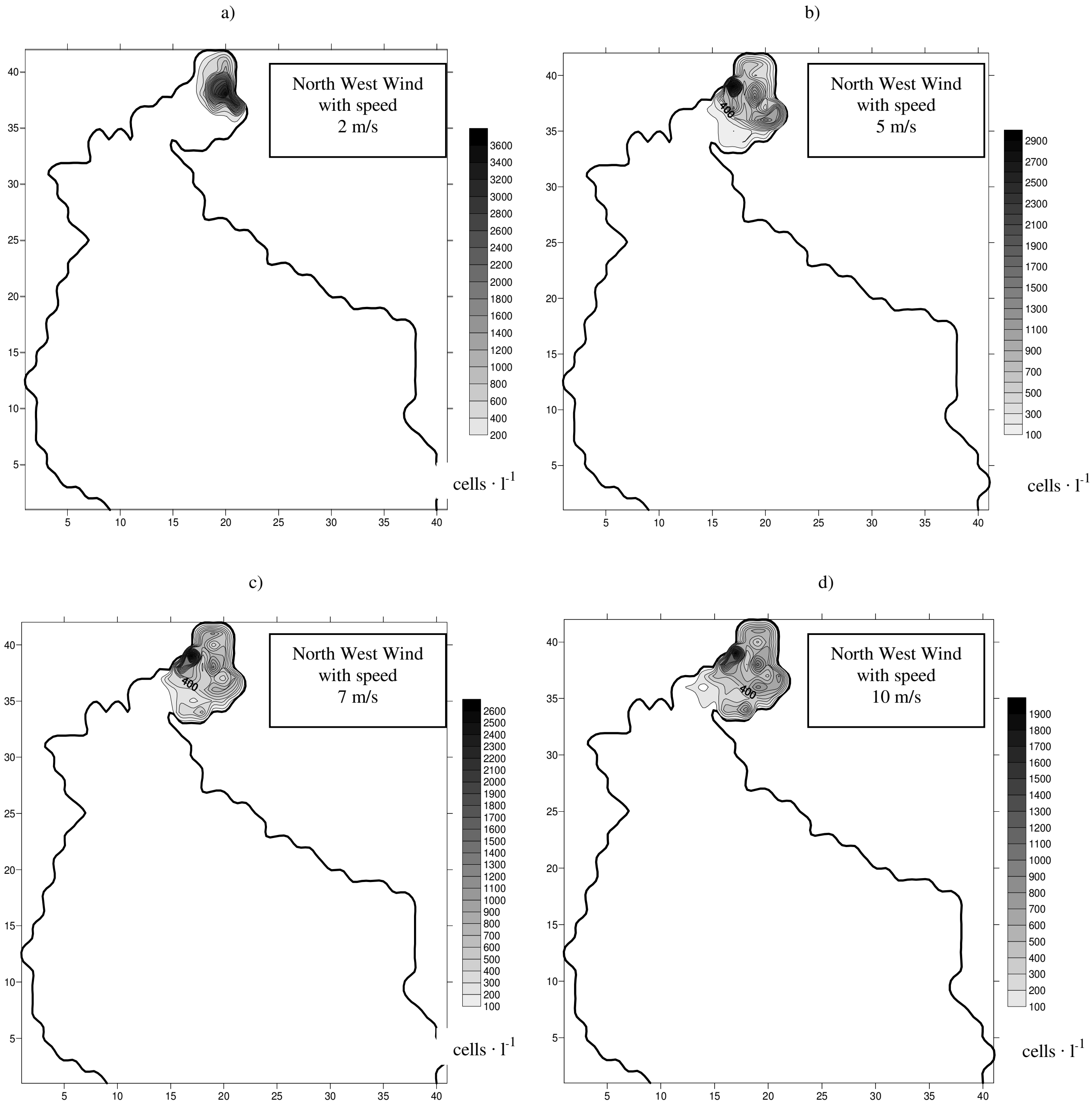

FIGURE 3 - The concentrations of algae (cells L^{-1}) a week after the bloom in position A under the influence of NW wind with speed a) 2 m/s, b) 5 m/s, c) 7 m/s,and d) 10 m/s.

With S direction winds, HABs appeared only when the winds have a speed close to 2 m/s. The maximum population level reaches a value of 5000 cells L^{-1}, enough higher compared with the estimating values with N and NW winds (Figs. 2a, 3a, and 4a). In this case, HAB is forced in the inner part of the Gulf close to the harbor (Figs. 1 and 4a). Winds with speed 5 m/s or more do not favor the appearance of a bloom, as population levels always are lower than 2000 cells L^{-1} (Figs. 4 b, c and d). In such cases, phytoplankton cells are dispersed in the whole area of the inner part of Thermaikos Gulf.

South-east winds cause the most serious HAB appearance, meaning that in all cases phytoplankton population overcomes the critical value of 2000 cells L^{-1} (Figs. 5 a-d). Low speed winds (lower than 5 m/s) show similar patterns of dispersion, forcing the HAB to the southwestern areas of the harbor (Figs. 5a, b). Winds with speed higher than 5 m/s force a large number of phytoplankton cells close to shellfish farming area M1.

All the above-mentioned results show that a HAB episode in the inner part of Thermaikos gulf could appear with a net growth rate close to 1.0 div/day even if starting population has low values (less than 200 cells L^{-1}). Furthermore, the dispersion of the HAB is affected by the winds' velocity [16] which plays a very important role to the pattern of circulation in a basin. The role of eddies (as a characteristic element of the hydrodynamic circulation) on the appearance of HAB coastal events is reported by Xie et al. [17]. More generally, it is well-known that matter transfer is closely related with the hydrodynamics in a coastal basin [18, 19].

When the source is located at the position B in the outer Gulf (northwest of the Epanomi coasts), in almost all cases with a net growth rate close to 1.0 div day^{-1}, only winds with very low speed (2 m/s) can favour the appearance of a HAB episode. With higher winds' speed a HAB can occur only when net growth rate take values higher than 1.3 div day^{-1}.

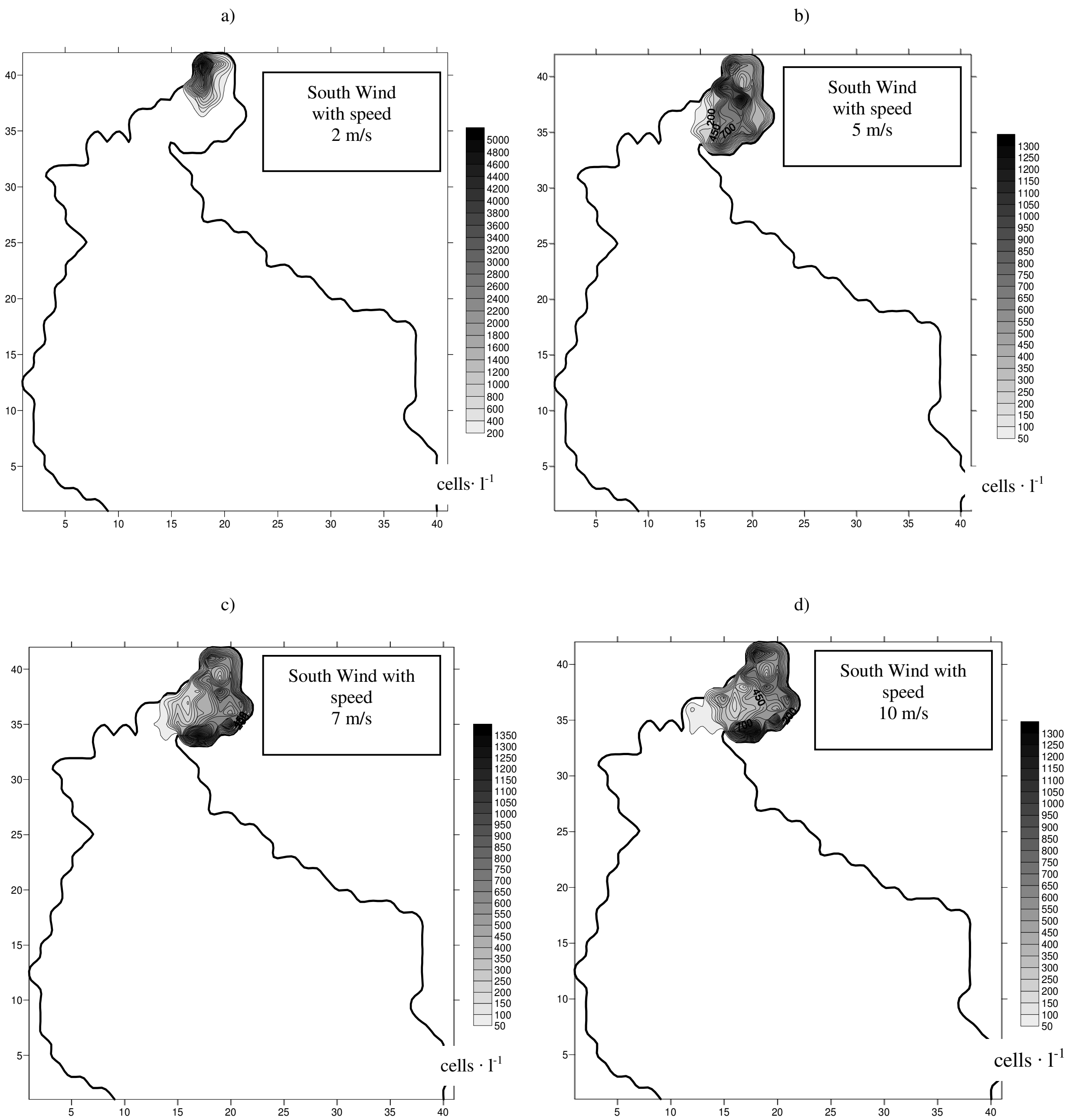

FIGURE 4 - The concentrations of algae (cells L^{-1}) a week after the bloom in position A under the influence of S wind with speed a) 2 m/s, b) 5 m/s, c) 7 m/s, and d) 10 m/s.

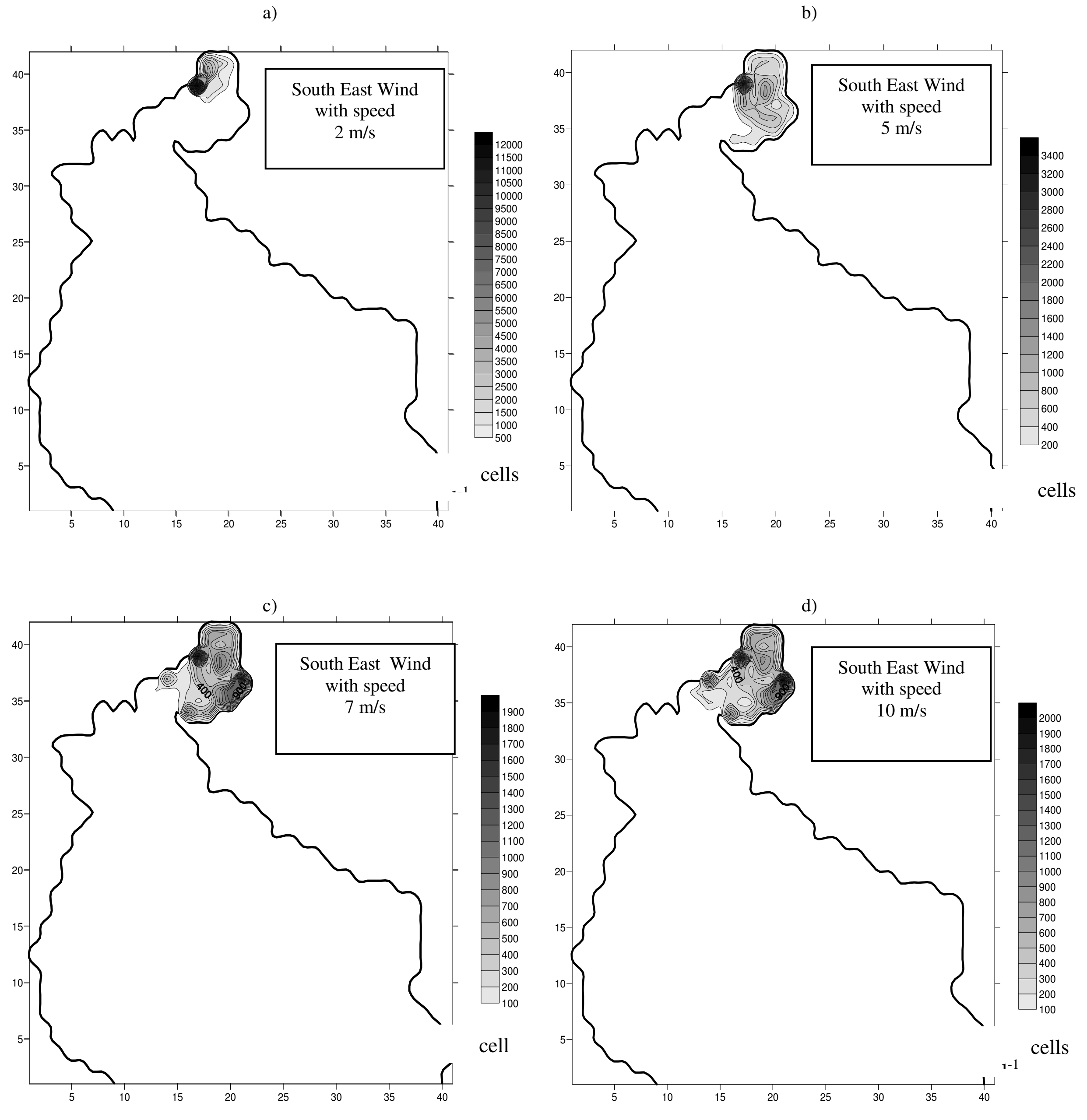

FIGURE 5 - The concentrations of algae (cells L^{-1}) a week after the bloom in position A under the influence of SE wind with speed a) 2 m/s, b) 5 m/s, c) 7 m/s, and d) 10 m/s.

As NW and SE winds show similar patterns of dispersion with these of N and S winds, in this case, we present the results of the two most frequent wind directions (N and S). According to the model output (Figs. 6 a-d), when the source is located at the station B in the outer Gulf, north winds do not seem to cause transport and dispersion of phytoplankton cells at the inner Gulf during the period of a week. On the other hand, cells can be found at the east of the outer Gulf. In that case (the source at the station B), HABs do not seem to be observed, except only under the influence of low winds (~2 m/s).

South winds may transfer and disperse phytoplankton cells in the inner Gulf and close to mussel's cultures areas after a period of a week, but phytoplankton abundance in all cases seems to be lower than 1000 cells L^{-1} (Figs 7 a-d).

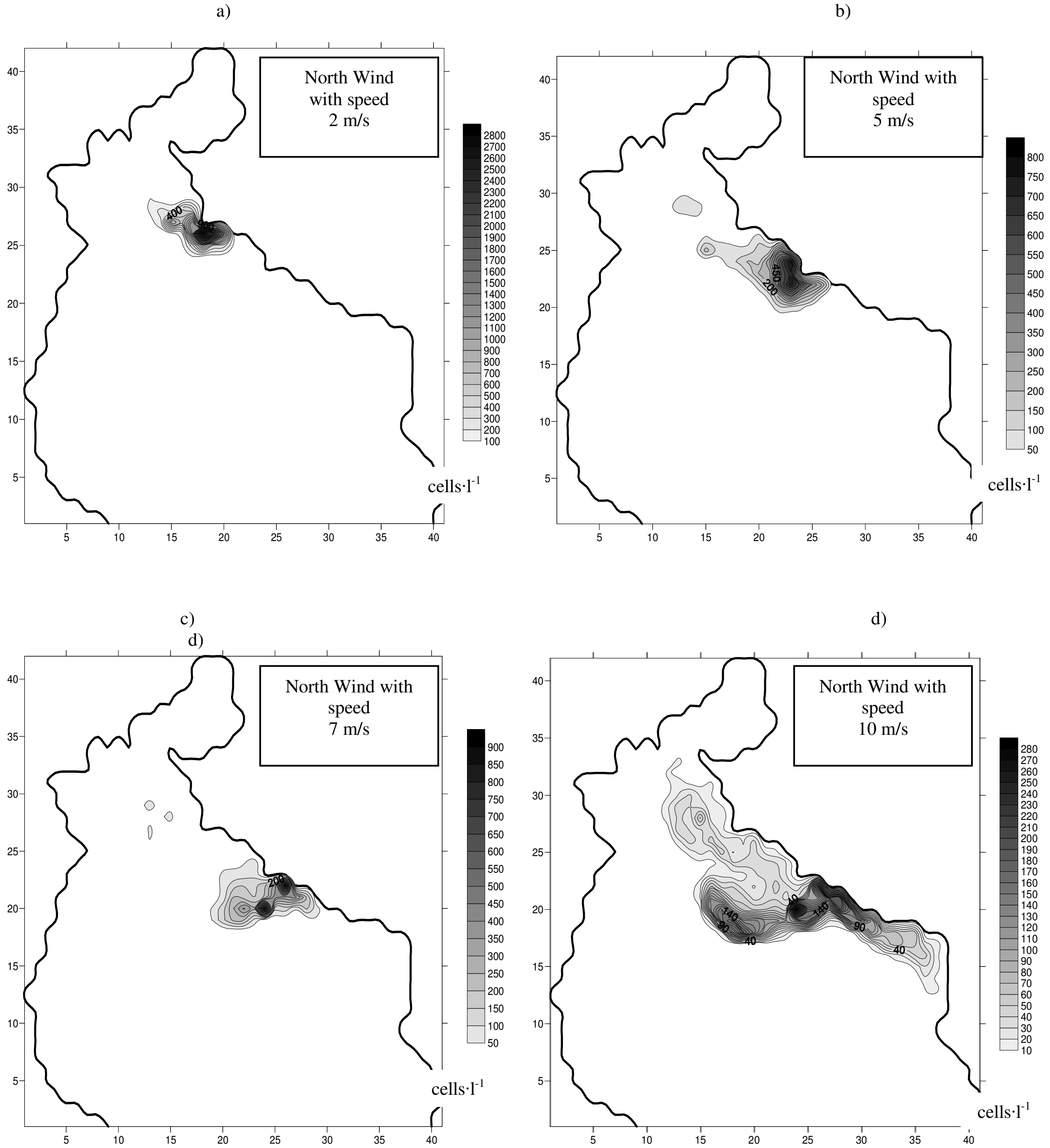

FIGURE 6 - The concentrations of algae (cells L^{-1}) a week after the bloom in position B under the influence of N wind with speed a) 2 m/s, b) 5 m/s, c) 7 m/s, and d) 10 m/s.

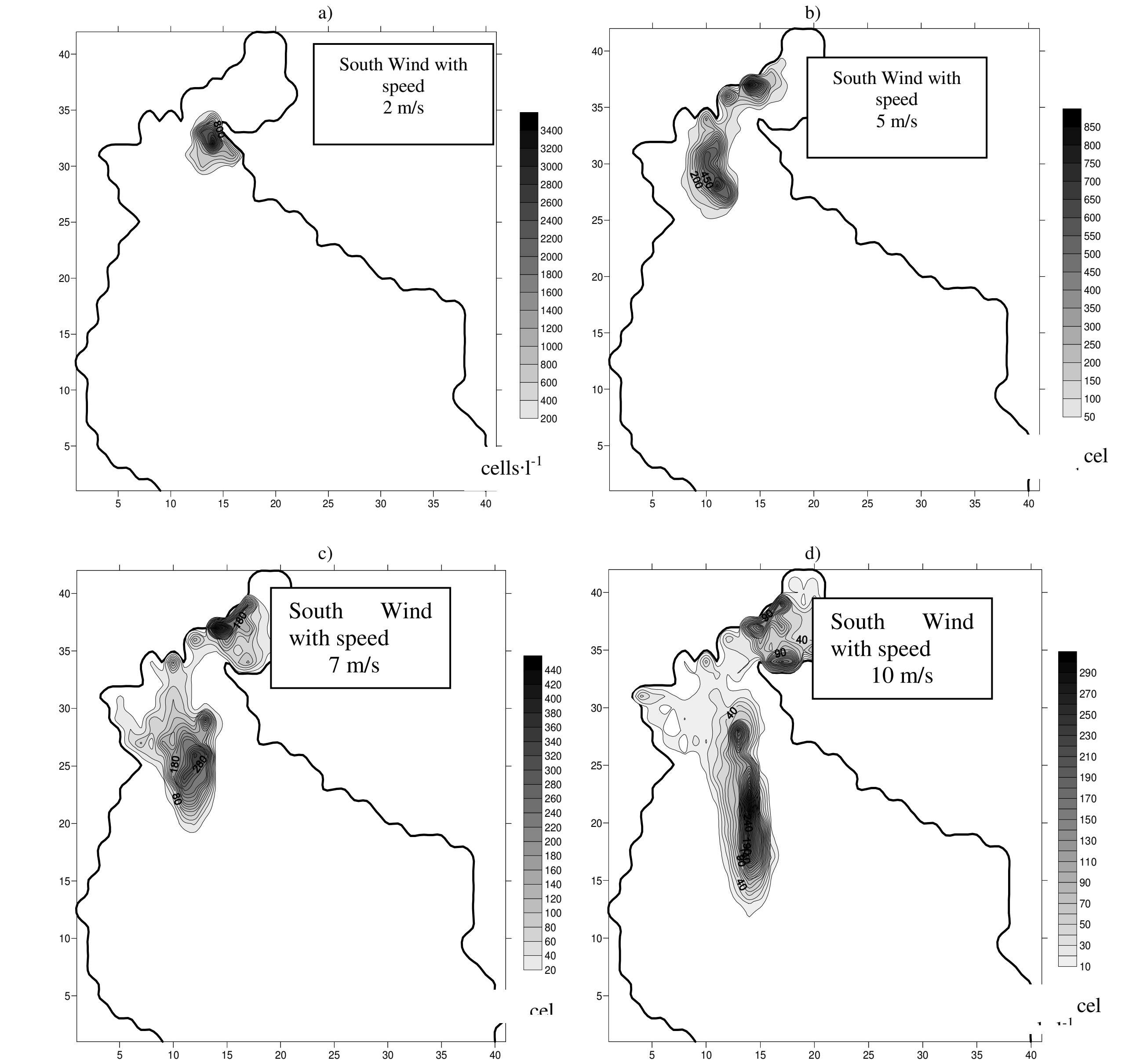

FIGURE 7 - The concentrations of algae (cells L^{-1}) a week after the bloom in position B under the influence of S wind with speed a) 2 m/s, b) 5 m/s, c) 7 m/s, and d) 10 m/s.

CONCLUSIONS

As dinoflagellate maximum growth rate shows an annually spatial and temporal variation in Thermaikos Gulf with a range of 0.09-2.1 divisions day^{-1} [12, 13], the present analysis shows that:

(A) For the case of the algal bloom in the Inner Thermaikos Gulf

1. A Dinophysis spp outbreak is possible to start with low population (150 cells L^{-1}) and a net growth rate close to 1.0 div·day^{-1}, in a short time period (6-7 days).

2. The wind speed and direction play an important role for an algal bloom appearance and its dispersion. S and SE winds with speed 2-5 m/s can cause higher cell concentrations than N and NW winds with the same speed (Fig. 2-5 a and b).

3. When the source is close to position A, the dispersion of the bloom in the outer part of the Gulf is rather rear.

(B) For the case of the algal bloom in Outer Thermaikos Gulf

1. An algal bloom may appear only when wind speed is low (~2 m/s) (Figs. 6 and 7).

2. S winds may cause dispersion of phytoplankton cells in the inner Gulf.

The geographical characteristics of the starting position may play an important role for the appearance and the dispersion of a bloom as winds with the same speed give different patterns of dispersion and different phytoplankton abundance in places A and B (Figs. 2 - 6).

As the maximum growth rate exceeds the threshold of 1.0 divisions day^{-1}, more than 200 days annually [12, 13] grazing, competition and sinking may also play an important role in the regulation of algal populations. In such cases, the model seems to be a useful tool for restrictions if high cell concentrations are forced close to mussel cultures.

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