DEVELOPMENT OF *PHAEOCYSTIS GLOBOSA* BLOOMS IN THE UPWELLING WATERS OF SOUTH CENTRAL COAST OF VIETNAM

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Abstract

Blooms of haptophyte algae in the southern central coastal waters of Viet Nam often occur in association with upwelling phenomenon during southwest (SW) monsoon. Sometimes the blooms cause damage in wildlife and cultures while other time, with lower magnitude of a bloom, could have been hardly seen an obvious affect on natural communities. Base on data sets of two years investigation on biology, oceanography, and marine chemistry, the present study suggest a conceptual model of the haptophyte *Phaeocystis globosa* success in the waters. At the beginning of the blooms, the upwelling and early rain supply nutrients, especially nitrate, to the water column, and the lower sea temperature would favour development of diatoms. During the blooms, nutrient consumption of diatoms reduce nitrate in the waters, pulse supplying phosphate from upwelling activity, lower temperature, and higher ammonium make *Phaeocystis globosa* become the best competitor to diatoms. At the end of the *Phaeocystis* bloom free cells of this species may be a good food supply to stimulate another bloom of a dinoflagellate species, *Noctiluca scintillans*. During the blooms, phytoplankton decay on sea floor leading to remineralisation of bacteria which reduce dissolved oxygen to a very low concentration, and this condition favouring growth of nitrate-reducing bacteria. A Lagrangian HAB model is implemented driven by a circulation model of the area. The model outputs reflect well transportation of microalgae on surface water during strong and weak SW monsoon periods. The results of the model suggest a good tool for early warning of HAB in Vietnamese coastal waters.

Key words: *Phaeocystis globosa*, bloom, Viet Nam, coastal upwelling, conceptual model, species competition, Lagrangian HAB model.

Introduction

Haptopyte genus *Phaeocystis* has been studied for long time since the first description in 1892. There were six species resently re-described with some other suspected new species (Medlin & Zingone 2007). They are cosmopolitan distributed (Schoemann *et al.* 2005) and exhibited a complex life cycle and morphology (Whipple *et al.*, 2005; Rousseau *et al.*, 2007). There are three species in the genus forming colonies and often forming blooms in cold (*P. antartica, P. pouchetii*) and temperate water (*P. globosa*) (Lancelot *et al.* 1998). The blooms of these species have been reported to have great impacts on global geochemical cycles (Verity *et al.* 2007) and ecosystem functioning (Lancelot, 1995; Nejstgaard *et al.* 2007). However, even *Phaeocystis* spp. have been a research subject for almost a century, there were still limited of knowledge on its role of the life cycle in the ecology and how its impact on ecosystem function (Whipple *et al.*, 2005; Rousseau *et al.*, 2007). There were recently strange blooms of temperated species, *P. globosa*, in subtropical waters (Lu & Huang, 1999) and tropical waters (Doan-Nhu *et al.*, 2003).

Blooms of a haptophyte, *P. globosa*, in coastal waters of Binh Thuan Province have been recorded in 2002, 2005, 2006 and 2007 and in 2008 (Doan *et al.*, 2008). These events have been associated with upwelling phenomenon during the SW monsoon. In July 2002, about 90% of animal and plant species in tidal reefs of Phan Ri Bay were eliminated by the bloom. Lost was estimated to be over VND10 billion (ca. $US 650,000). During this bloom, low diversities of both phytoplankton and zooplankton were reported (Doan *et al.,* 2003). During the blooms in 2005, few in situ data have been recorded (Doan *et al.*, 2008), but there was no field data during the bloom in 2006. However, a more extensive investigation in time and space has been done 2007 -2008 by the Institute of Oceanography Nha Trang. Preliminary results indicate there was a pattern of development of the bloom with change in plankton communities and nutrient stoichiometry. However effects of upwelling activity, nutrient regime, and species competition play a complex role (Doan *et al.*, 2008; Project KC0903 unpublished data). This present paper describes the development of blooms of diatoms, haptophyte species *Phaeocystis globosa* and dinoflagelate *Noctiluca scintillans* with their interaction during the upwelling season in coastal waters of the south centre Viet Nam. Many studies have been questioned about the conditions which stimulate a bloom of certain phytoplankton species. In Viet Nam the blooms of *N. scintillans* has been reported (Nguyen & Doan, 1996; Nguyen *et al.* 1997) without any further explanation how a bloom starts and where it goes. This study is a first try to set up a conceptual model to have a more general view of the development and alternation of the blooms of diatoms, *N. scintillans,* and *P. globosa* in a tropical coastal upwelling system. Both of species forming blooms in south central Viet Nam, *N. scintillans* and *P. globosa,* have capability of buoyancy in the water. The latter species when drifts onshore in a large bloom could cause heavy damage on both nature and culture marine organisms (Doan *et al.,* 2003). Thus, a Lagrangian HAB model is developed to predict the transportation of a bloom in a certain oceanographic condition. This would be a tool for an early warning of HAB in Viet Nam.

Material and method

Sampling and sample analysis

Sampling has been taken monthly during 2007 – 2008 with some months were lacking due to rough sea condition during NE monsoon season. Table 1 presented the sampling periods and numbers of station were visited. At each station, a number of biological, oceanographic and environmental parameters were collected, including: wind direction and speed, currents, temperature, salinity, fluorescent, PAR (CTD 19*plus*, Seabird), macro nutrients, chlorophyll/phaeophytine, total suspended matters, bacteria, phytoplankton, and zooplankton. Figure 1 shows maps of stations and sampling area. Biological and environmental samples were taken from a niskin bottle at surface, near-bottom and chlorophyll maximum layers of the water column.

Characteristics of sampling area

Rainfall

Rainy season in Binh Thuan Province is from May to October with monthly rainfall in 2007-2008 was ca. 200 mm at Phan Thiet station but some twice times higher in Ham Tan station. The total rain during rainy season occupied some 80% of the yearly rainfall at Phan Thiet station, but some 90% at Ham Tan station. The investigated area is influenced with fresh waters from two rivers, Ca Ty river in Phan Thiet and Luy river in Phan Ri. Both of rivers are small with low discharge (ca. 39 $m^3.s^{-1}$) during rainy season. The discharge during dry season is extremely low (Bui *et al.*, 2006)

Wind

The sampling area is within the monsoon climate region with two periods of prevailing monsoon, southwest in June-September and northeast (NE) in October to March of the following year (Fig. 3). During 2007 -2008, the SW monsoon started in May and ended in September. The highest wind speed was ca. 10 m/s for both SW and NE wind in 2007.

Model description

The numerical model consists of a circulation model in which a Lagrangian HAB model is implemented. The circulation model is a three-dimensional baroclinic tidal model based on the Hamburg Shelf Ocean Model (HAMSOM, Backhaus, 1985). It has a resolution of 4 nautical miles and a time step of 300 seconds. With this model, six baroclinic surface circulation fields are constructed for strong and weak NE monsoon, strong a weak SW monsoon and spring and fall inter-monsoon (Hein, 2008). Depending on the intensity of the Southern Oscillation Index (SOI) the velocity fields are linear interpolated in time and in space. These velocity fields drive offline the Lagrangian HAB model which simulated the transport and diffusion by particle tracking. The transport equation for the Lagrangian tracer is

$$\vec{X}_i(x,y,t+\Delta t) = \vec{X}_i(x,y,t) + \Delta t * \left[\vec{U}_L(x,y,t) + \vec{P}*(1-\mu_i) + 0.03*\vec{W}*(1+\lambda_i)\right]$$

where X_i is the two-dimensional Lagrangian coordinate of the i-th tracer, U_L is the surface velocity transformed onto Lagrangian coordinates, P is a band width of turbulent fluctuation, W is the wind speed, and μ_i and λ_i are a random numbers uniformly distributed between zero and unity.. The boundary condition is a reflecting boundary condition at the coast. If a Lagrangian tracer is leaving the model through the open boundary, it is not considered any longer in the computation. The equation is solved numerically with a fourth-order Runge-Kutta method. To ensure a sufficient accuracy in the model, 5000 Lagrangian tracers are considered for the HAB simulation. Details of the numerical procedure can be found in Dippner (2005). Turbulent mixing is assumed to be isotropic, but time dependent and is simulated with Monte Carlo technique. The coordinate X_i of the tracer is subject of random displacement. The turbulent fluctuation is assumed to be proportional to the age τ of the individual tracer: $P \propto \tau^{0.65}$. This approach is equivalent to the 7/3 power law of diffusion of Okubo (1971). A detailed description of this technique is given in Dippner (2005). The surface HAB is assumed to be transported with 3% of the actual wind speed. Gust is simulated as an anisotropic stochastic process in wind direction.

Results

Oceanographic condition

During the SE monsoon prevailing in both years, 2007 and 2008, distribution of sea surface temperature indicated upwelling waters with low temperature from May to September. The magnitude of upwelling, estimate by area and lower temperature, was varied from time to time and from one another localities event with small scale (Fig. 4). Variation in upwelling activity was also observed from year to year (Fig. 5). 2003 appeared to be a warmer year with weak upwelling activities.

During the investigation in 2007-2008, upwelling activities have also been recorded from May to September. The surface (0.5m depth) temperature and salinity were plotted in Figure 6 showing strong upwelling signals in August. Upwelling signals were also recorded in July 2007 but did not reach to the surface waters.

Nutrients and dissolved oxygen

Average concentration of nitrate of the investigated waters was 31.6 $mg.L^{-1}$ in May, reached its highest to 39.2 $mg.L^{-1}$ in July, and decreasing to 30.1 $mg.L^{-1}$ in October 2007. This was following the upwelling activities during May – September which fuelled the surface waters with nutrients rich deep waters. Another source of nutrients during this time would also come from water-runoff since this was during rainy season. However, due to low water discharge from rivers (Bui et al 2006) nutrient loading from water runoff may be low. Ammonium was low average value (0.6 - 8.0 $mg.L^{-1}$) in May-August, but as high as 68.0 $mg.L^{-1}$ in September. Dissolved oxygen (DO) ranged from 5.7 to 6.4 $mg.L^{-1}$, in May-August and October but as low as 2.7 $mg.L^{-1}$ in some stations in September.

Phytoplankton pigments

Chlorophyll-*a* concentration showed high variation throughout the investigation period. Highest chl-*a* concentration occurred during a bloom in August – September at near shore station (37.8

µg.L^{-1}) with phaeophytin of 9.34 µg.L^{-1}. At the end of the bloom in September 2007, chl-*a* was highest at bottom layer with 18.1 µg.L^{-1} and phaeophytin 9.81 µg.L^{-1}. During May-June average value of chl-*a* was as low as 0.65 µg.L^{-1}. During the high peak of the bloom, with high concentration of microalgae on shore, chl-*a* could be as high as 336 µg.L^{-1} and phaeophytine as 96 µg.L^{-1}.

Bacteria

There was an alternative dominance of different groups of bacteria in the waters. At periods with low phytoplankton biomass (May-June), the nitrifying bacteria group (NB) was dominant compared to denitrifying bacteria (DNB) group with average value of 433 and 81cells.mL^{-1}, respectively. In July to September, 2007 – the average value of DNB showed extremely high, especially in Sep 2007, it reached 2254 cells.mL^{-1}, while NB reduced to 20 cells.mL^{-1}.

Phytoplankton biomass and composition

Observations in the two-year period during the SW monsoon showed a clear pattern of development of phytoplankton biomass versus dominant species along with upwelling activity. The diatom biomass increased from ca. 20.1 µgC.L^{-1} in May –June to ca 35.2 µgC.L^{-1} in July – August 2007 and decreased to 12.0 µgC.L^{-1} in September-October 2007. A similar pattern has occurred in 2008, but with a slightly decrease of diatoms biomass in September (Fig.7A). In 2007, *Phaeocystis globosa* had occurred since August, but had formed bloom at the end of August and beginning September (Fig. 7B). Densities on shore ranged from 1800 – 2200 colonies.L^{-1}, decreased to 1000 and 800 colonies.L^{-1} at 1 and 3 Km offshore, respectively. At 6th September, *Phaeocystis globosa* is already at near late of a bloom periods with some 40% old colonies, estimated biomass from single cell count was 300.1 µgC.L^{-1} (85.2- 694.1 µgC.L^{-1}) among the centre stations of the bloom. At offshore stations, colonies were degrading at bottom layers. To the mid of September 2007 many fractions of *Phaeocystis globosa* colonies were found decaying at near seafloor. Number of colonies found around 10 per litre at station DS5 (close to shore). In 2008, smaller bloom of *P. globosa* was also recorded in August but with lower densities of colonies than in 2007 (900 colonies.L^{-1}).

Noctiluca scintillans also forming blooms during our investigation. They reached high number also after blooms of diatoms in July-August. The high cell densities recorded in September in 2007 and 2008 were 660 and 720 cells.L^{-1}, respectively (Fig. 7C). It was obvious that *N. scintillans* was high in time and space when *P. globosa* was low and vice versa.

The first simulation considers a weak SW monsoon circulation field with no additional wind. In this case no Ekman offshore transport occurs and the patch is transported parallel to the coast with the coastal jet (Fig. 8). The second simulation is a strong SW monsoon circulation field with 6 Bft. wind from SW. In this case, the Ekman transport advects the patch offshore (Fig. 9).

In both simulations the initial conditions are the same: a patch of a size of 10 km located at 11.2°N and 109.2° E. The patch is initialized with a Gaussian distribution in which the +/- one sigma interval has the size of 10 km.

Conceptual model

Base on data of the present study and previous publication, few scenarios of development of the haptophyte *Phaeocystis globosa* is proposed in interaction with several biological and oceanographic conditions (Fig. 10).

Macro nutrients were analysed during the investigation showing the impact of both nitrate and phosphate to the growth and structure of phytoplankton communities. In May to September, the upwelling activities and rainfall supplies most of nutrients for phytoplankton consumption so these nutrients concentrations were slightly changed over the time. In this study, phosphate may be one of the factors stimulate growth of phytoplankton in the investigated waters.

In this study, turbulence is considering as water mixing due to SE wind. The blooms of *Phaeocystis globosa* occurred in periods with low SE wind speed (ca. 2-4 $m.s^{-1}$). With the rather fragile colonies of the species, this suggests that a relatively low disturbing waters could favourite them growth. The blooms of *Noctiluca scintillans* is either before or after the blooms of *Phaeocystis*, larger numbers of them usually found during a stronger SE wind condition (ca. 4-6 $m.s^{-1}$). The stronger cells of this species (compare to *Phaeocystis* colonies) may let them stand better with the turbulence so they may be a better competitor during a mixing condition.

Bacteria grow well with source of carbon from phytoplankton in the waters. At early stage of upwelling activity, nitrate sources from both upwelling and water runoff were important for nitrifying bacteria group (NB). This explained with high biomas of NB during May-June. Decaying processes at the end of diatoms bloom (July-August) reduced dissolved oxygen in waters and favoured growth of denitrifying bacteria group (DNB). This group, in turn, produced ammonium which is one of favourable nutrient for dinoflagellates and *Phaeocystsis*.

Diatoms are a strong competitors for nutrient uptake especially when nitrate available and no limitation with silicate. During our investigations, high concentrations of silicate has been observed (252 ± 108 $\mu g.L^{-1}$). Degradation of high phytoplankton biomass which resulted in high ammonium concentration may be one of the unfavourable conditions for diatoms and hence *Phaeocystis globosa* and *Noctiluca scintillans* become dominant.

Discussion

The sampling periods showed that our investigation over the waters only during SW monsoon periods with some part of spring inter-monsoon. In general, phytoplankton biomass/density from a previous report (Nguyen *et al.*, 2004) reveals a clear pattern of phytoplankton biomass over the year. Most of the plankton biomass/density peak occurred during the high peak of SW monsoon period (Nguyen *et al.*, 2004; Doan-Nhu unpublished data 2003-2004).

In 1999, there was a very similar pattern compared to our observation of yearly variation of diatoms biomass (Nguyen *et al.*, 2004). The diatoms biomass almost reached 50 µC/. L^{-1} at the beginning of upwelling season (SW monsoon) in June – July. The dinoflagellates came up in mid September with biomass as high as diatoms (Nguyen *et al.*, 2004). However, this investigation in 1999 was only in Ca Na Bay which is at northern transect of our study area (at station 1, see Fig. 1).

During 1998 -2003, several investigations took place in different time of the year. It was shown that biomass/density during the NE monsoon periods were 2-6 folds lower that that during the SW monsoon periods. However, daily chlorophyll-a satellite images provided by SEAWIFS (http://oceancolor.gsfc.nasa.gov) also indicate blooms during NE monsoon in quite narrow bands close to the shoreline (images are not shown).

During the blooms in 2007 and 2008, phytoplankton decay on sea floor leading to remineralisation of bacteria which reduce dissolved oxygen to a very low concentration, and this condition favouring growth of nitrate-reducing bacteria. The activities of bacteria resulted in higher ammonium concentration in the water. Both ammonium and bacteria biomass would be essential for triggering either *Phaeocystis* and *Noctiluca* blooms. However a combination of much more factors may be involved in this progress. Our results would lead to a suggestion that the magnitude of turbulence (mixing condition due to SW wind) would be one of the main factors that favour the bloom of *Phaeocystis* (low turbulence) or *Noctiluca* (moderate turbulence). One biological factor may be importance that the grazing impact, which is not analysed in this studies, would be a subject for future research in the area. The blooms of *Phaeocystis* and/or *Noctiluca* after the bloom of diatoms is one of the tropical proofs for many previous research in temperate waters (e.g. Lancelot *et al.*, 2005).

Whipper *et al.* (2005) presented a conceptual model of *Phaeocystis* in which the author considered variation of physical factors (water temperature, light, advection, turbulence, and sedimentation), chemical (dissolved nutrients, inorganic and organic (N), and chemical signals), and biological factors (DNA, genetic mechanisms, grazing, seed particles, viral infection, viral lysis, and non-viral lysis (NVL) on *Phaeocystis* life cycle. Whipper *et al.* (2005) have discribed quite details of the effects of each factor. In this study, more interaction among biological factors of an *in situ* case, in a specific waters (upwelling system) has been explained.

In this conceptual model, we could not check whether turbulence would stimulate *Phaeocystis* blooms from its benthic stage. Even the benthic form of this species is one of the subject for future research. Because, there are apparently no current methods, would applied *in situ*, to check the present of *Phaeocystis* species.

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References

Anonymous, 2004. Admiralty Tide Tables Volume 3: Indian Ocean and South China Sea (including tidal stream tables). United Kingdom Hydrographic Office, 357pp.

Backhaus, J. O., 1985. A Three-Dimensional Model for the Simulation of Shelf Sea Dynamics. *Dt. hydrogr. Z. (38)*. 165-187

Bui, H.V., Ho, V.B., & Pham, V. T., 2006. Hydrochemical characteristics and quality of coastal waters in Binh Thuan Province. Journal of Geology, Series A, 297: 38-50. (in Vietnamese with English abstract).

Dippner, J.W., 2005. Mathematical modelling of the transport of pollution in the water. In: Mathematical Models, ed J.A. Filar, in: Encyclopedia of Life Support System (EOLSS) developed under the auspices of the UNESCO, EOLSS Publisher, Oxford UK.

Doan, N.H., Nguyen, N.L., Nguyen, t. M-A., Ho, V.T., & Nguyen, N.T.G., 2008. Red tides in south central coast of Vietnam: biodiversity and planktonic community structure consequences. Poster presentation at XIII HAB conference, Hong Kong, November 2008.

Doan-Nhu, H., Nguyen-Ngoc, L., Nguyen, C., Ho-Van, T., & Nguyen-Thi, M.A., 2003. Plankton assemblages during the late bloom of Haptophyte Algae in Binh Thuan province, Southern central Vietnam, in July 2002. Collection of Marine Research Works, XIII: 105 – 118

Hein, H., 2008. Vietnam upwelling – analysis of the upwelling and related processes in the coastal area off South Vietnam. Ph.D. Thesis, University Hamburg, 163pp.

Lancelot, C., 1995. The mucilage phenomenon in the continental coastal waters of the North Sea. Sci. Total Environ. 165, 83–112.

Lancelot, C., Keller, M., Rousseau, V., Smith Jr.,W.O., Mathot, S., 1998. Autoecology of the marine haptophyte Phaeocystis sp. In: Anderson, D.A., Cembella, A.M., G., Hallegraef

(Eds.), NATO Advanced Workshop on the Physiological Ecology of Harmful Algal Blooms. NATO-ASI Series, Series G. Ecological Science, vol. 41, pp. 209–224.

Lancelot, C., Spitz, Y., Gypens, N., Ruddick, K., Becquevort, S., Rousseau, V., Lacroix, G., Billen, G., 2005. Modelling diatom and Phaeocystis blooms and nutrient cycles in the Southern Bight of the North Sea: the MIRO model. Mar. Ecol., Prog. Ser. 289, 63–78.

Lu, D. & Huang, W., 1997. *Phaeocystis* bloom in southeast China coastal waters 1997. Harmful Algal News 19: 9.

Medlin, L. & Zingone, A., 2007. A taxonomic review of the genus Phaeocystis. Biogeochemistry 83:3–18. DOI 10.1007/s10533-007-9087-1 13.

Nejstgaard, J.C., Tang, K.W., Steinke, M., Dutz, J., Koski, M., Antajan, E., Long, J.D., 2007. Zooplankton grazing on Phaeocystis: a quantitative review and future challenges. Biogeochemistry 83, 147–172.

Nguyen, N.L., Doan, N.H., Andersen, P., Ho, V.T., Skov, J., Chu, V.T., & Do, T.B.L., 2004. Occurrence of potentially toxic algae in Vietnamese coastal waters. *In*. Larsen, J. & L.N. Nguyen (eds): Guide to identification of Potentially harmful algae in coastal waters of Viet Nam. Opera Botanica, Copenhagen, Denmark, No. 140, 159-180.

Nguyen, N.L. & Doan, N.H., 1996. Harmful marine phytoplankton in Vietnam waters. Pages 45-48 *In* Yasumoto T., Oshima Y. & Fukuyo Y. (eds.). Harmful and Toxic Algal Blooms. Intergovernmental Oceanographic Commission of UNESCO, 586 pp.

Nguyen, N.L., Doan, N.H. & Pham, T.V., 1997. Outbreak of *Noctiluca scin-tillans* (Mac.) Ehr. Related to Eutrophication in Vanphong-Bengoi Bay, Central Vietnam. Pages IX-29- IX- 35, *in* Viger G., K.S. Ong, C. McPherson, N. Millson, I. Watson and A. Tang (eds.), ASEAN Mar. Env. Management: Quality Criteria and Monitoring for Aquatic Life and Human Health

Protection. Proceeding of the ASEAN-Canada Technical Conference on Marine Science (24-28 June, 1996), Penang, Malaysia. EVS Environment Consultant, North Vancouver and Dept. of Fisheries Malaysia.

Okubo, A., 1971. Oceanic diffusion diagrams. *Deep Sea Research*, 18:789-802.

Rousseau, V., Chrétiénnot-Dinet, M.-J., Jacobsen, A., Verity, P., Whipple, S., 2007. The life cycle of Phaeocystis: state of knowledge and presumptive role in ecology. Biogeochemistry 83, 29–47.

Schoemann, V., Becquevort, S., Stefels, J., Rousseau, V., Lancelot, C., 2005. Phaeocystis blooms in the global ocean and their controlling mechanisms: a review. J. Sea Res. 53, 43–66.

Verity, P.G., Brussaard, C.P.D., Nejstgaard, J.C., Van Leeuwe, M.A., Lancelot, C., Medlin, L.K., 2007. Current understanding of Phaeocystis ecology and biogeochemistry, and perspectives for future research. Biogeochemistry 83, 311–330.

Whipple, S.J., Patten, B.C., Verity P.G., 2005. Life cycle of the marine alga Phaeocystis: A conceptual model to summarize literature and guide research. J Mar Syst 57:83–110.

Figure captions

Figure 1. Map showing sampling location and stations

Figure 2. Monthly precipitation in 2007-2008 at Phan Thiet meteorological station, Binh Thuan Province. (Source: Statistical Yearbook 2008, Binh Thuan Province)

Figure 3. Daily wind speed and direction at 108.75E - 10.476N, in 2007-2008, source: http://iridl.ldeo.columbia.edu

Figure 4. Sea surface temperature in SE monsoon season in 2002-2006. Source: http://www7320.nrlssc.navy.mil

Figure 5. Sea surface temperature in 2007, Source: http://www7320.nrlssc.navy.mil

Figure 6. In situ temperature (left graphs) and salinity (right graphs) in May, August and September 2007.

Figure 7. Variation in diatoms biomass (µgC.L-1), *Phaeocystis globoa* colony density (colonies. L^{-1}) and maximal density of *Noctiluca scintillans* (cells. L^{-1}) in 2007-2008. 9*, is indicated sampling in 6-7/September when heavy bloom of *P. globosa* and number of sampling stations were fewer.

Figure 8. The simulation of development of a surface bloom of microalgae (initial path at 11.2°N and 109.2° E, diameter 10 km, black/dark dots) in a strong SW monsoon with 6 Bft. wind from SW. In this case the Ekman transport advects the patch (red/gray dots) offshore (A), and the corresponding surface velocity field (B). The color scale in the velocity field marks the relative vorticity times 10^{-5}.

Figure 9. The simulation of development of a surface bloom of microalgae (initial path at 11.2°N and 109.2° E, diameter 10 km, black/dark dots) in a weak SW monsoon with no wind. In this case no Ekman offshore transport occurs and the patch is transported parallel to the coast (red/gray dots) with the coastal jet (A), and the corresponding surface velocity field (B). The color scale in the velocity field marks the relative vorticity times 10^{-5}.

Figure 10. Conceptual model of development of blooms in Binh Thuan Province, Viet Nam, during SE monsoon season.

Table 1. Sampling time and number of visited stations. (9* - an extra sampling trip during bloom of *Phaeocystis globosa*, this sampling including 3 stations at beach in Phan Thiet region and other 3 stations from boat – DS5, 13 and 15).

Year	2007							2008					
Month	5	6	7	8	9*	9	10	4	5	6	7	8	9
No. of stations	20	20	21	24	6	21	14	16	20	16	21	21	17

Figure 1
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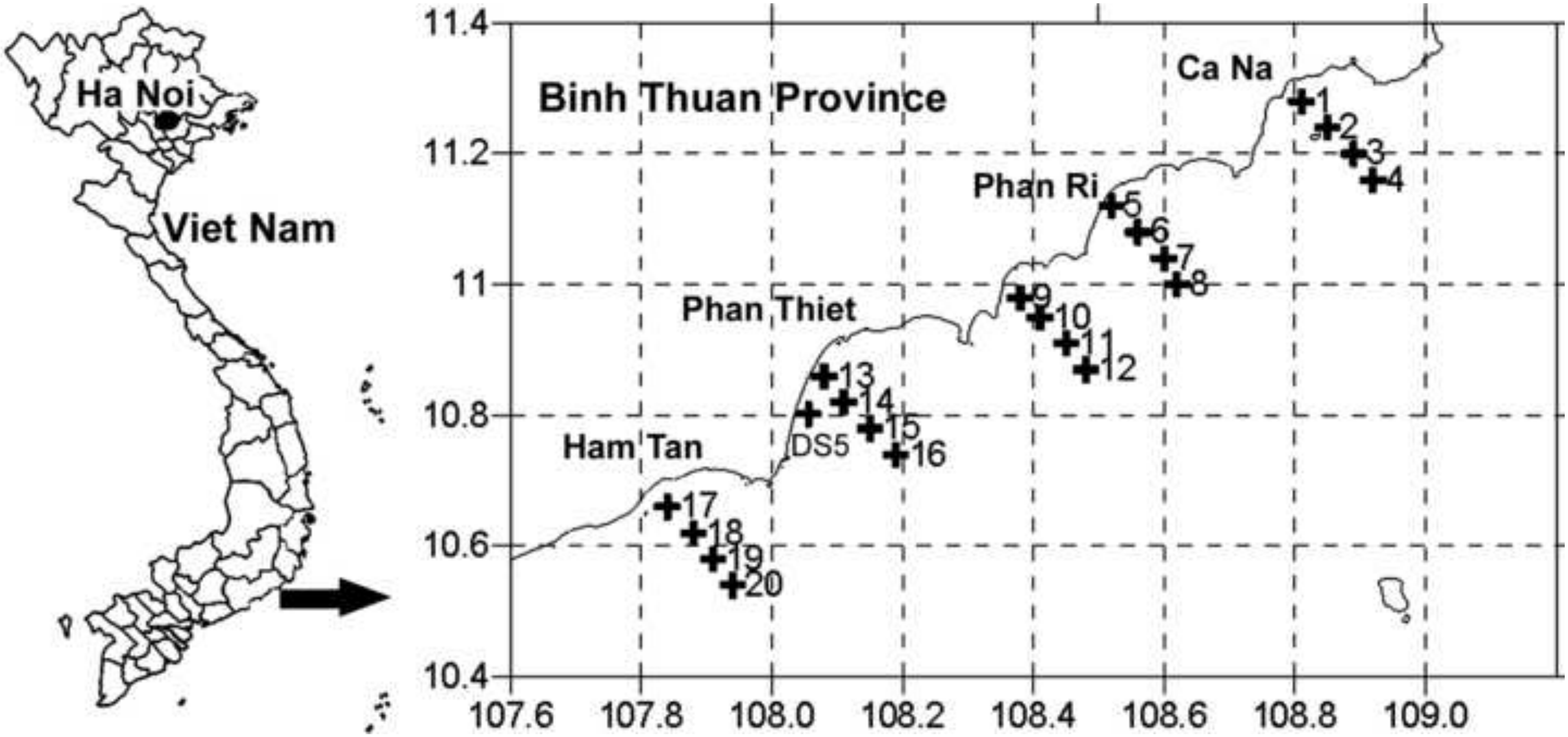

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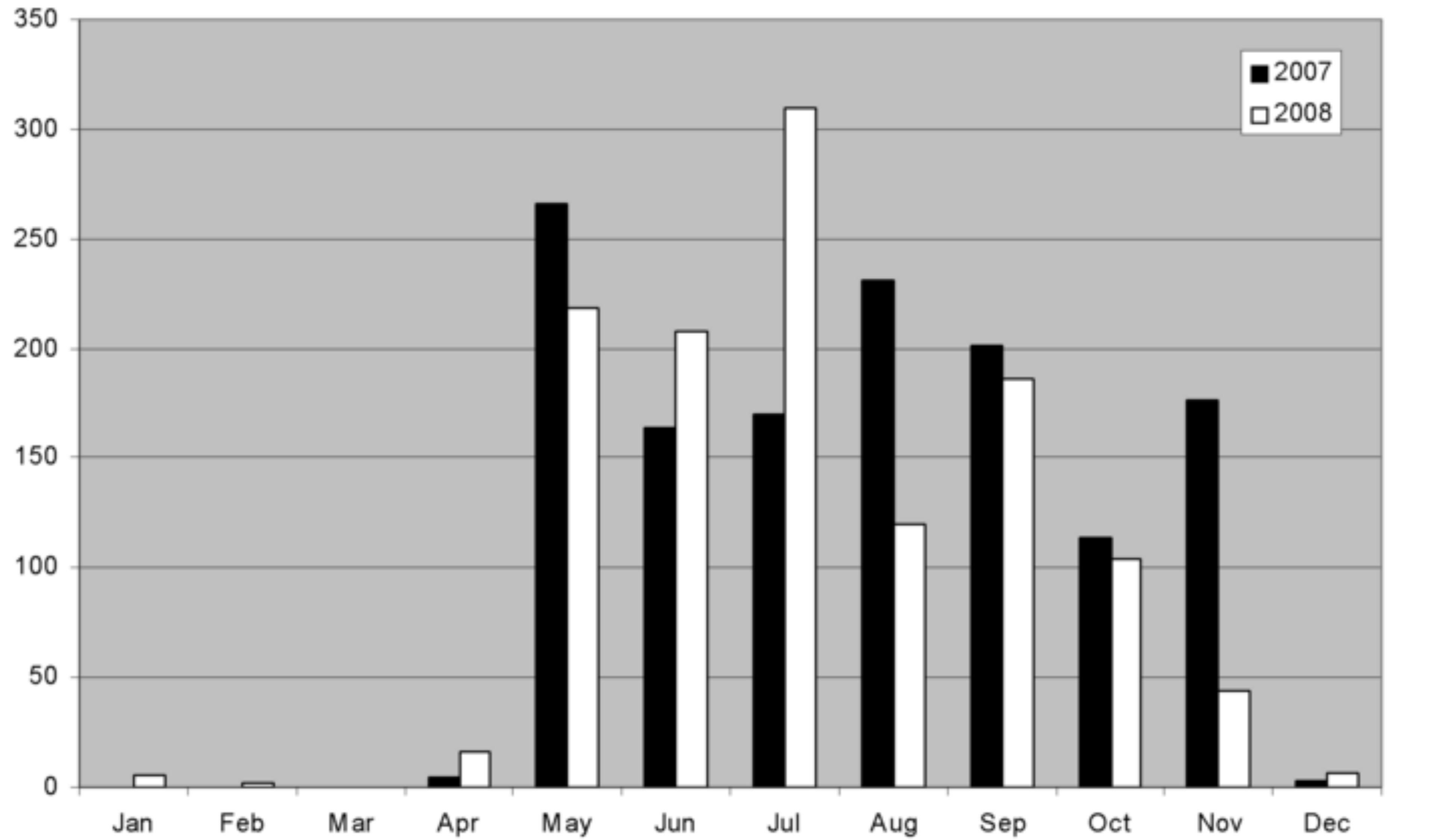

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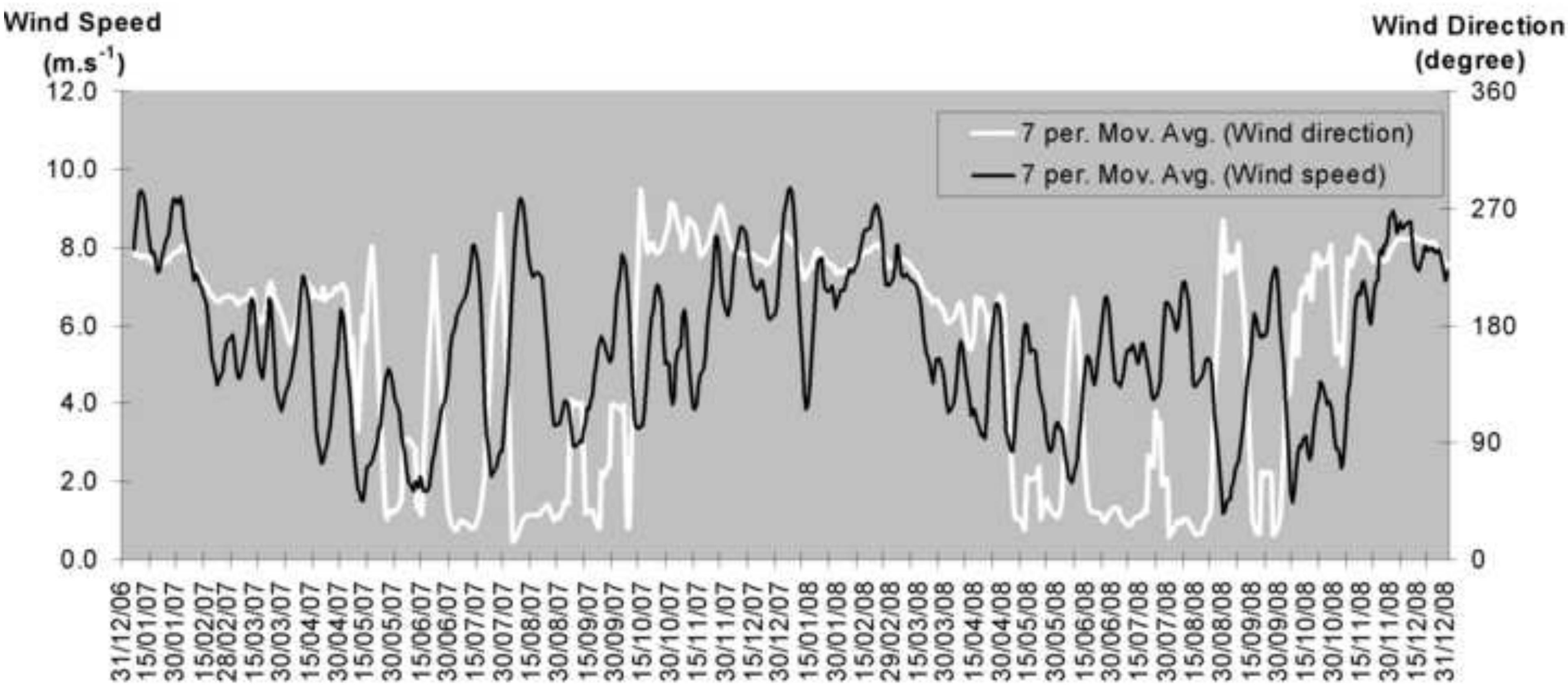

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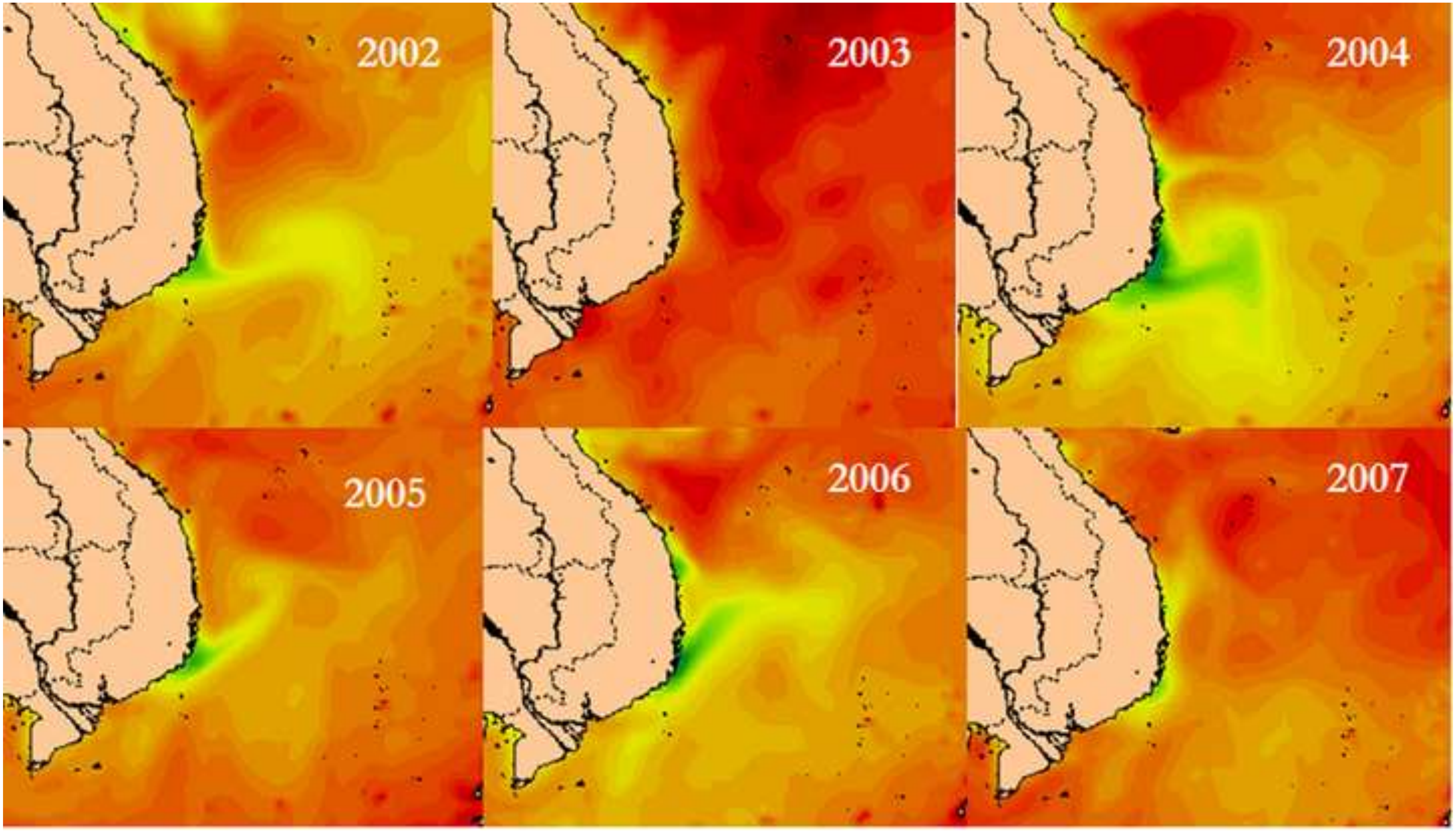

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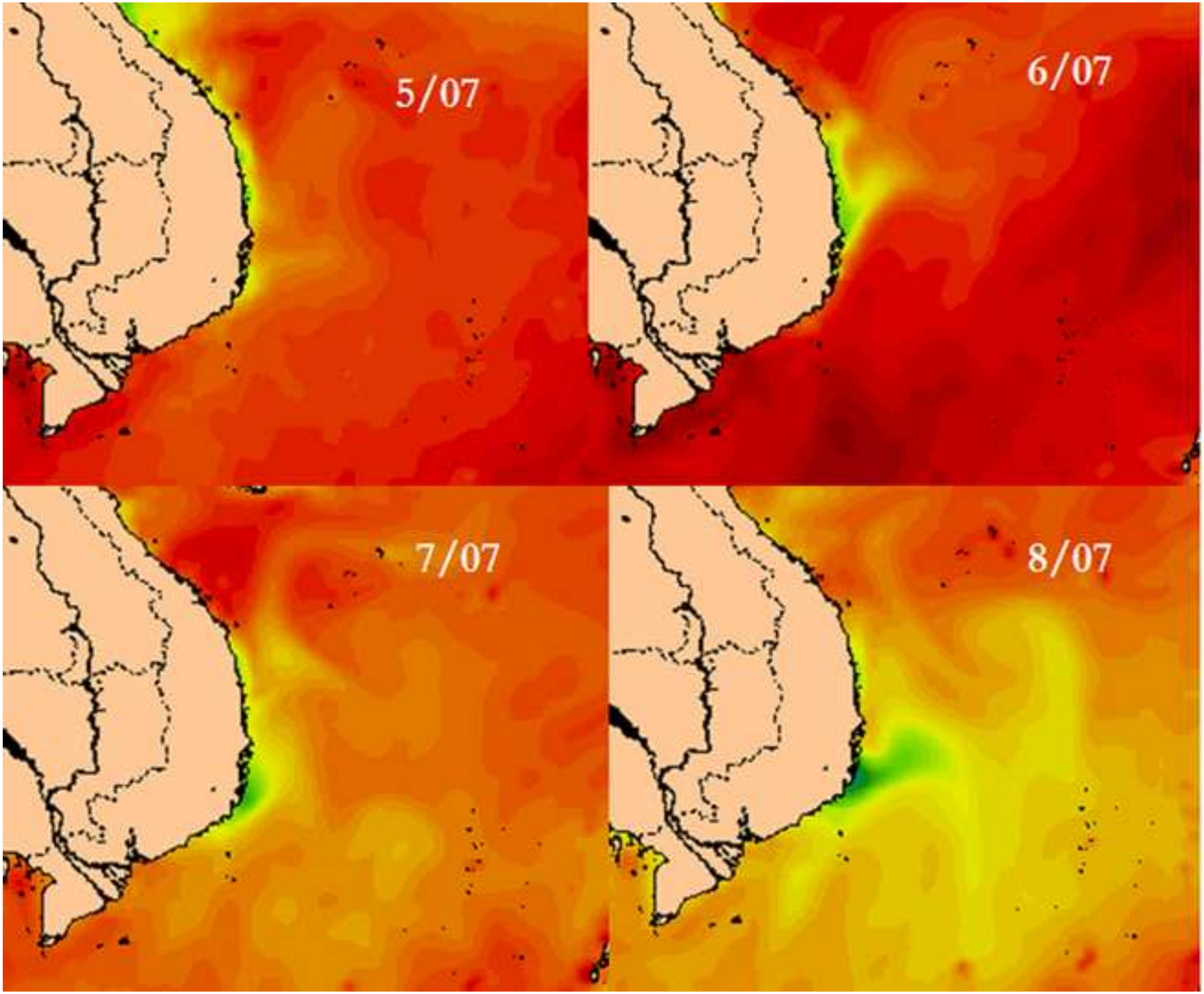

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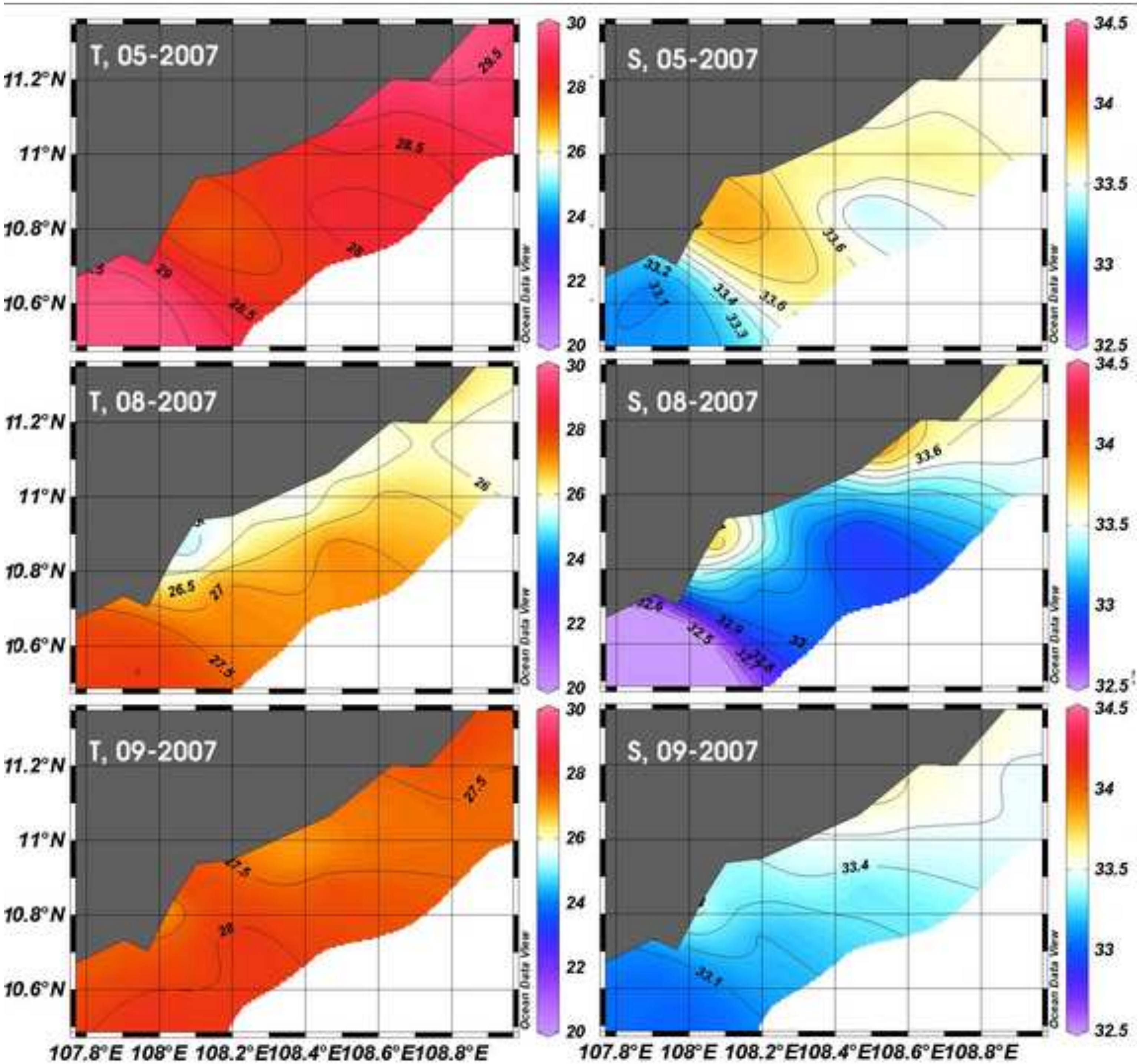

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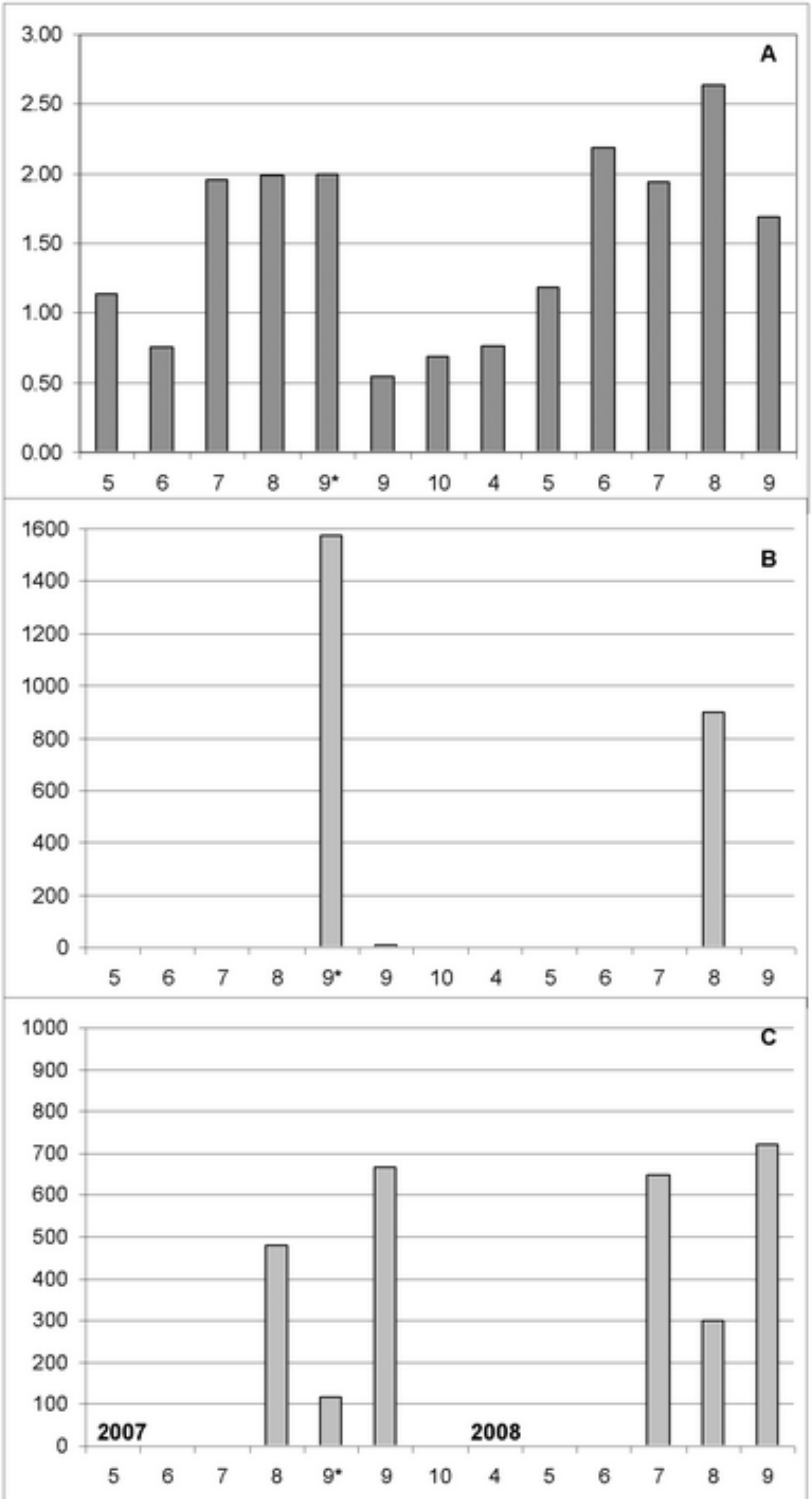

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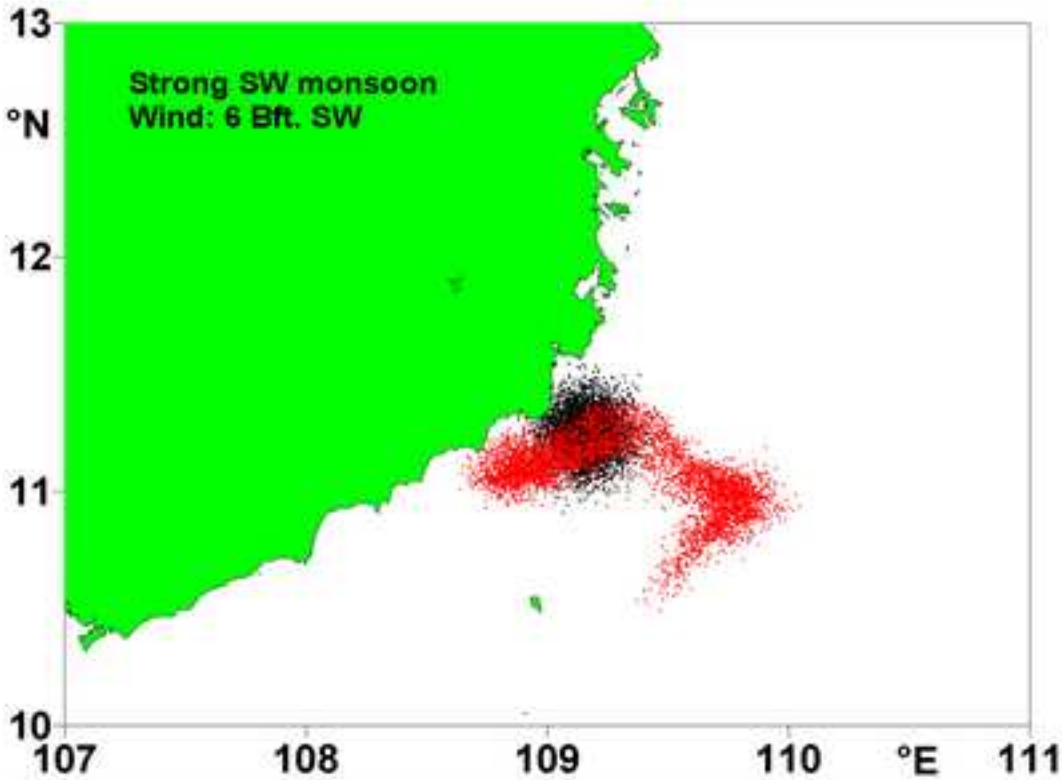

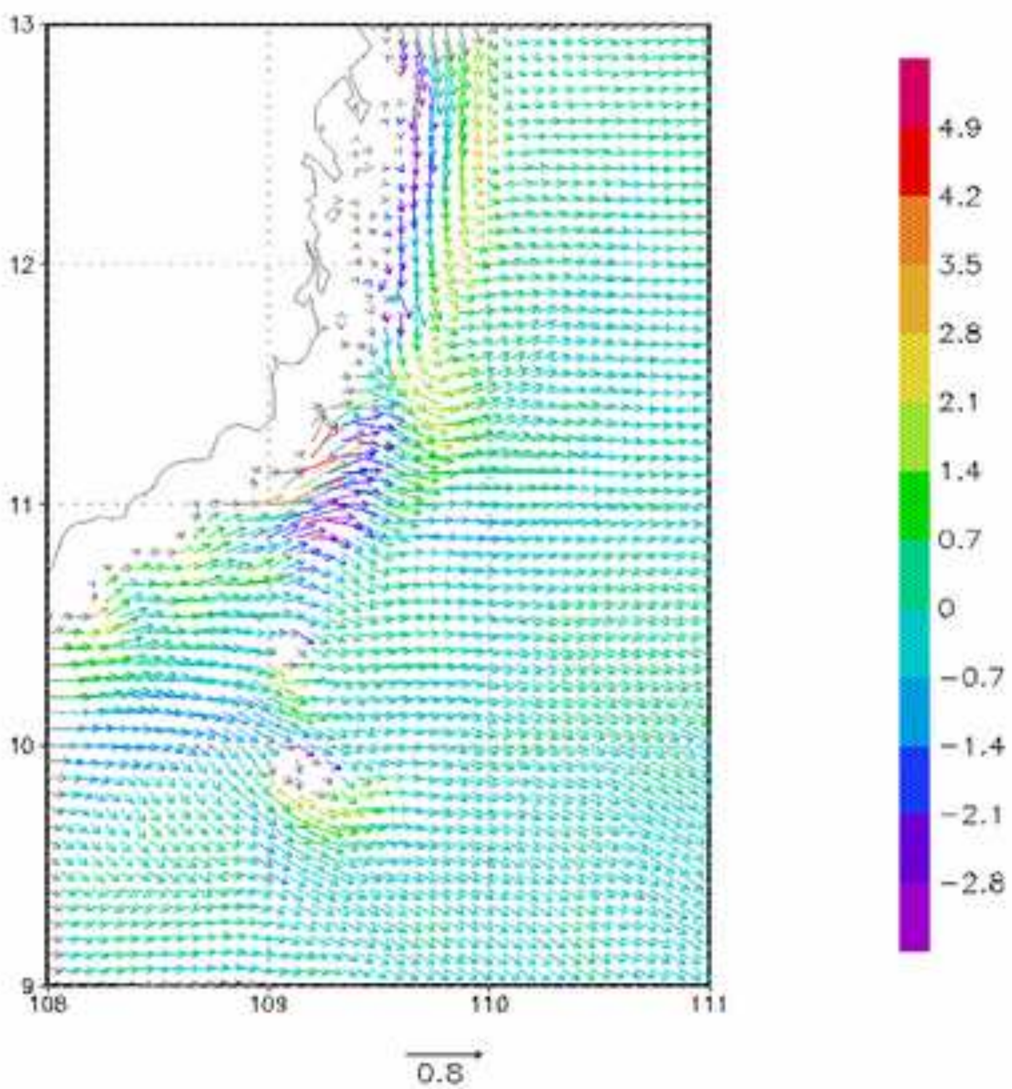

Figure 9
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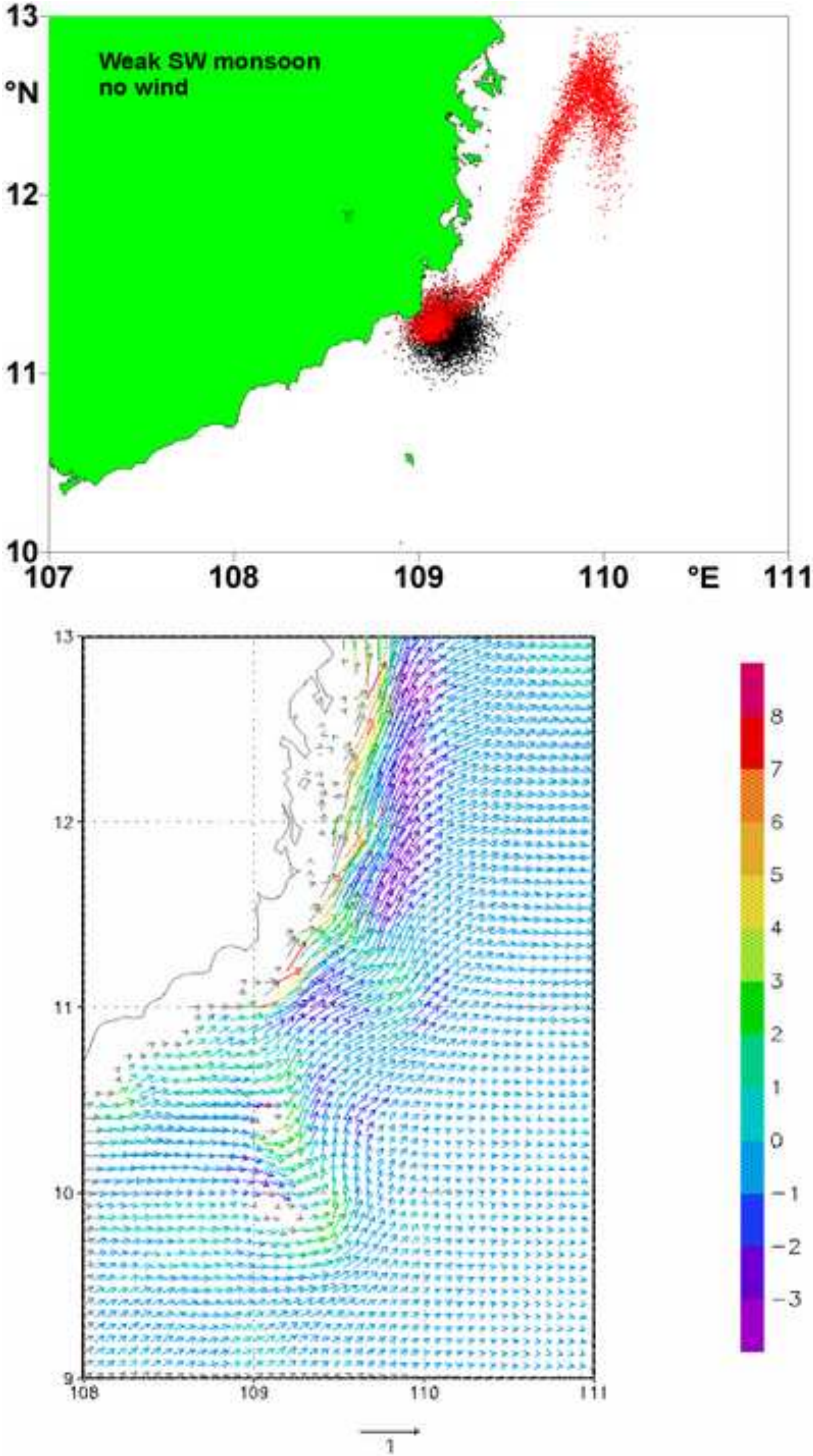

Figure 10
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