韓國産業應用學會誌, 제5권, 제4호, 347-351, 2002.11
J. Korean Society of Industrial Application, Vol.5, No.4, 347-351, November, 2002

담수성 연안하구의 식물성플랑크톤-영양염 역학에 대한 수리학적 조절

Hydrodynamic controls on phytoplankton-nutrient dynamics in a river-dominated estuarine system

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<요약>

유입되는 담수의 영향을 크게 받는 한 하구 (미국 버지니아주의 요크강)의 크기별 식물성플랑크톤의 역학에 대한 수리역학적 조절에 대한 조사를 위해 플랑크톤 생태계모델이 계발되었다. 모델은 요크강 하류의 상부층에서의 탄소 및 영양염의 분포를 나타내는 12개의 구성체 변수로 이루어져 있다. 빛, 온도, 바람, 해류 그리고 조수와 같이 이송과 혼합을 일으키는 물리적 변수들로 포함하고 있다. 모델은 포트란으로 계발되었고 Runge- Kutta technique을 이용해 미분방정식을 풀었다. 모델분석 결과, 크기가 큰 마이크로 식물성플랑크톤의 수화는 수체내의 생산보다는 이송이나 확산 때문에 나타나는 것임을 알 수 있었다.

Key Words : Ecosystem model, Phytoplankton, Advection and Diffusion, York River

INTRODUCTION

Estuarine systems are considered to be complicated marine environments for scientists struggling to elucidate the ecology of an organism. On the other hand, they are excellent sites for ecological studies since biotic and abiotic factors, varying spatially and temporally, control the dynamics of organisms in the entire system. In addition to the complexity of the systems, estuaries are productive (Ryther 1969[1]) and play a major role in supporting commercial fisheries since they provide habitats and food resources for juvenile commercial fish and shellfish (Smith 1966[2], Levinton 1982[3]).

Environmental disturbance such as eutrophication can impact aquatic food web structure and fisheries by affecting phytoplankton community since phytoplankton are the main source of carbon and nutrients in a food web. Phytoplankton affect water quality, especially dissolved oxygen by photosynthesis and respiration, and can serve as substrates for microbial decomposition resulting in oxygen

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depletion when their ungrazed biomass has accumulated (Sundbaeck et al. 1990[4]). In addition, plankton are also light-absorbing particles which can limit their own growth, i.e., self-shading (Kirk 1994[5]), and the depth of light penetration.

Phytoplankton production in aquatic environments may be regulated by bottom-up controls, nutrient fluxes associated with physical variability and top-down controls, biotic, trophic interactions (Alpine and Cloern 1992[6], Kivi et al.1993[7]).

In estuarine environments, these controlling mechanisms interact with phytoplankton in complex ways, mainly because of freshwater and tidal energy inputs into the system (Cloern 1996[8]). Physical processes including advection and diffusion play an important role in estuarine plankton population dynamics (Haas etal 1981[9], Delgadillo-Hinojosa et al. 1997[10], Shen et al. 1999[11]). In this context, understanding of the relationship between physical processes and plankton population dynamics in coastal estuarine systems is important to better understand phytoplankton dynamics and then to better manage water quality in estuarine environments. An ecosystem model was developed and used to explore the relationship between hydrodynamic processes and phytoplankton-nutrient dynamics in the mesohaline zone of the York River estuary, a river-dominated subestuary of the Chesapeake Bay (U.S.A.).

MATERIALS AND METHODS

The conceptual ecosystem model includes 12 state variables for describing the distribution of carbon and nutrients in the surface mixed-layer of the mesohaline zone in the York River estuary (Fig. 1). The state variables consist of autotrophs including pico- (<3 μm), nano- (>3 and <20 μm), and micro-phytoplankton (>20 μm); heterotrophs including bacteria, flagellates+ciliates, microzooplankton (>70 and <202 μm), and mesozooplankton (>202 μm); the nutrients $NO_2^- + NO_3^-$, NH_4^+, and PO_4^{-3}, and non-living organic materials, DOC (dissolved organic carbon), and POC (particulate organic carbon). Groupings of autotrophs and heterotrophs are based on cell size and ecological hierarchy; mixotrophy was not considered in the model.

Forcing functions include incident radiation, temperature, tide, wind stress, and mean flow. Incident radiation and temperature were estimated using empirical equations for Gloucester Point, VA. Salinity and wind stress data were collected by the Virginia Institute of Marine Science at Gloucester Point, VA. Daily river discharge rates at the fall line were collected by US Geological Survey. The surface boundary condition is specified by a zero flux condition for all state variables at the atmosphere- water interface. Vertical transport by advection and diffusion, sinking for organisms, and fluxes for nutrients were incorporated into the model as the bottom boundary condition, in which the flux of organisms and nutrients was specified by vertical exchange or sinking rate times biomass and nutrient flux from bottom water respectively. Chlorophyll *a* and nutrients collected from bottom water over an annual cycle and presented in Sin et al. (2000)[12] were used as input data for the bottom boundary condition. The model was developed in Fortran90 (Microsoft Fortran Power Station) and differential equations were solved using the 4th order Runge-Kutta technique. Mathematical Structure for hydrodynamic, biological and chemical processes was described in Sin and Wetzel (2002)[13].

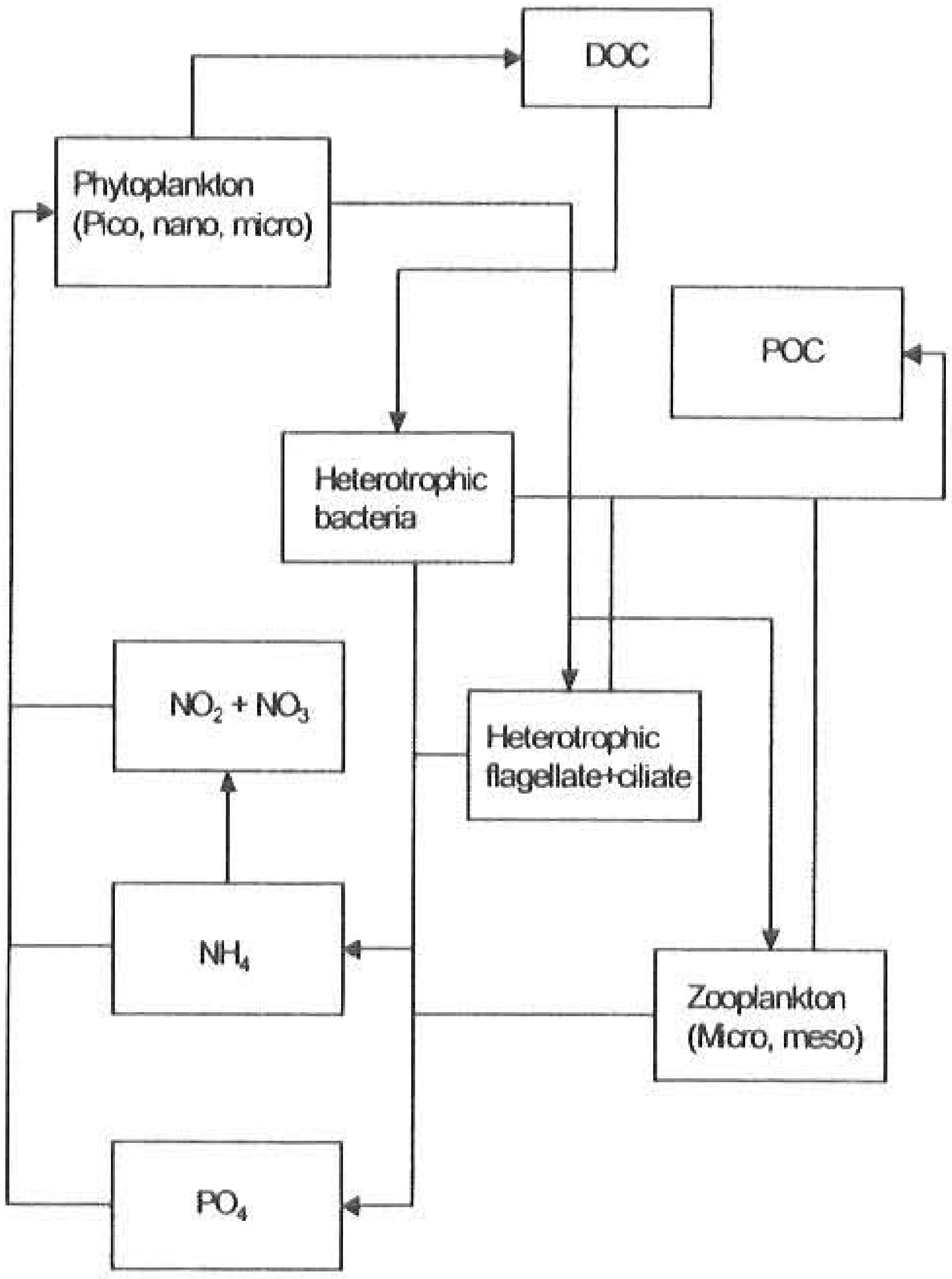

Fig. 1 Diagram for state variables and interaction between the state variables in the York River ecosystem model.

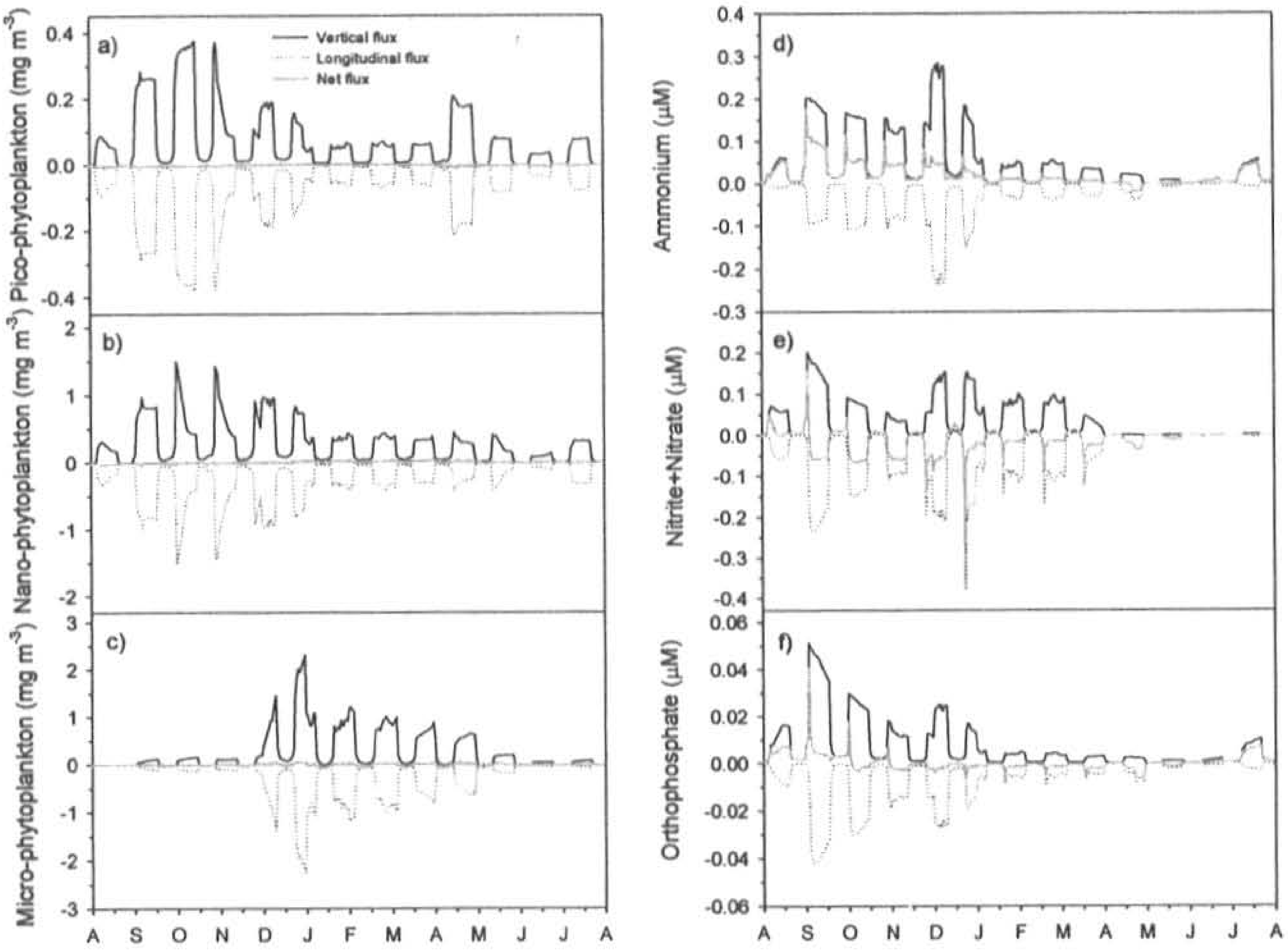

Fig. 2 Temporal distributions of daily changes in abundances of pico-, nano-, and micro-phytoplankton (mg chl *a* m^{-3}) and nutrient (ammonium, nitrite+nitrate, orthophosphate, mM) due to vertical advection/diffusion and longitudinal advection from Aug. 1996 to Aug. 1997. Net fluxes due to the hydrodynamic processes were also presented.

Field data collected over an annual cycle (Sin et al. 2000[12]) were used as validation data for the three size-structured phytoplankton populations and nutrients. EPA monitoring data collected at the station (WE4.2) nearby the mouth of the York River were used for model validation of micro- and meso-zooplankton. Field data collected at the Virginia Institute of Marine Science, VA (U.S.A.) were used for the other state variables.

Effects of physical processes including diffusion and advection on phytoplankton and nutrient dynamics were assessed by removing diffusion, longitudinal advection, vertical advection and diffusion + advection processes from the model in the sensitivity analyses. Since removal of one or two hydrodynamic processes are not physically realizable scenarios, it is necessary to examine the time series of each term for vertical flux (advection and diffusion) including sinking, longitudinal import/export (advection) and *in situ* production in order to investigate their relative importance.

RESULTS AND DISCUSSIONS

Figure 2 shows the changes in concentrations of phytoplankton and nutrients due to vertical advection and diffusion vs. longitudinal advection. It is evident that vertical flux serves as a source for phytoplankton and nutrients whereas longitudinal transport serves as a sink in the model suggesting these two terms are offsetting in the model simulation. The scale or magnitude of the source and sink terms also varies with season, cell size and nutrient species. Seasonality of microphytoplantkon is prominent (Fig. 2c) ; high during the cold season but low during the warm season. Vertical flux is more important than longitudinal advection for ammonium and orthophosphate pools during the warm season whereas longitudinal advection is more important for nitrite+nirate pools during the cold season (Fig. 2d, 2e, 2f).

The direct effects of the combined hydrodynamic processes were compared with *in situ* production of phytoplankton and nutrients to

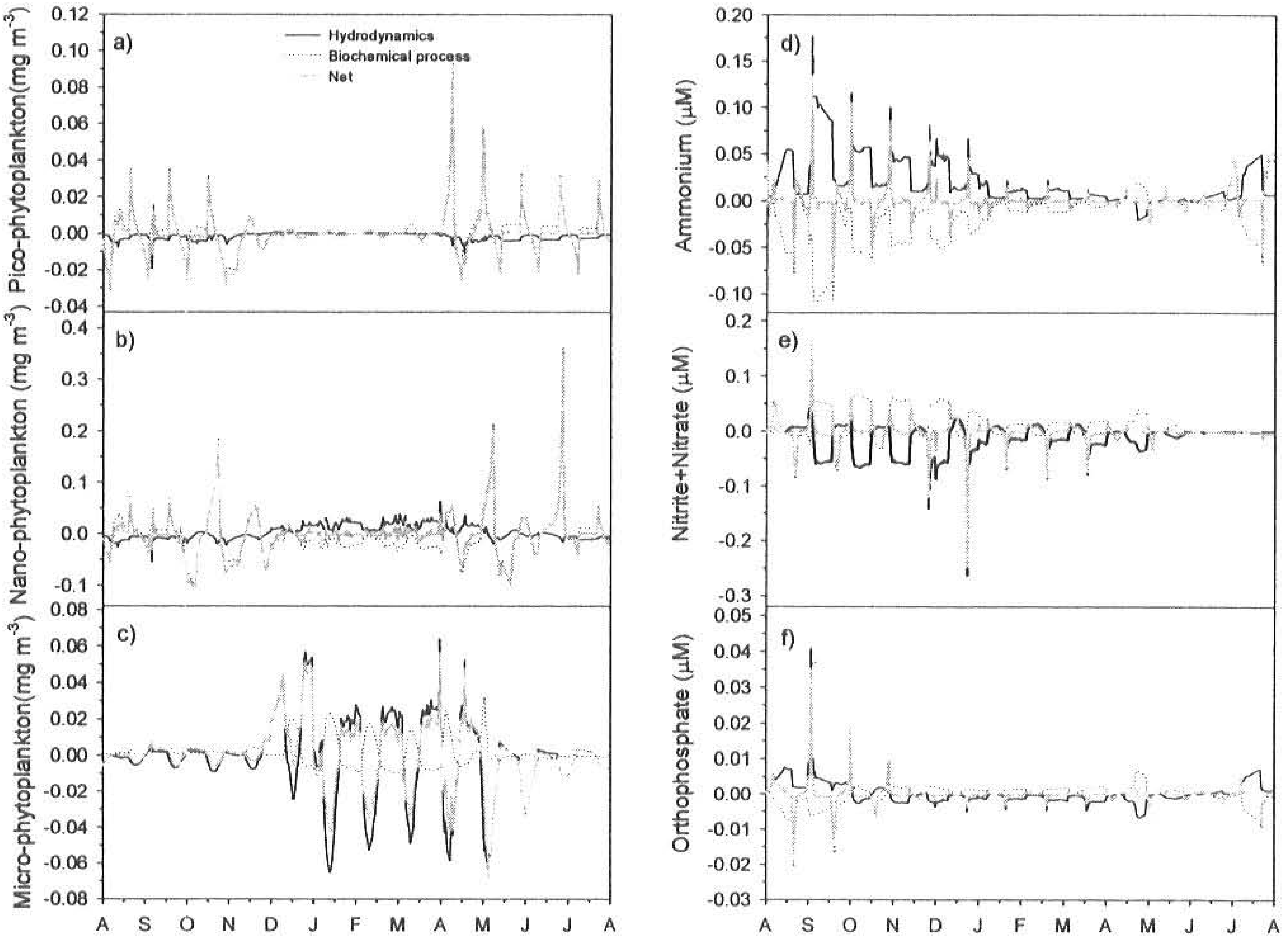

Fig. 3 Temporal distributions of daily changes in abundances of pico-, nano-, and micro-chlorophyll *a* (mg m-3) and nutrient (ammonium, nitrite+nitrate, orthophosphate, μM) due to hydrodynamic mechanisms (advection + vertical diffusion) and biochemical processes from Aug. 1996 to Aug. 1997. Net fluxes between the hydrodynamic and biochemical processes were also given.

determine the role of hydrodynamics and biological-chemical processes in water column dynamics of the York River system (Fig. 3). Since vertical advection/diffusion serves as a source mechanism and longitudinal advection is a sink mechanism in most cases (see Fig. 2), positive values represent vertical flux alone and negative values denote longitudinal export. Changes in pico- and nanophytoplankton biomass due to hydrodynamic processes are small and vary little over time whereas *in situ* production of the small cells is large and fluctuates greatly except for the winter-spring time (Fig. 3a, 3b). However, changes in microphytoplankton biomass due to hydrodynamics are relatively large and fluctuate greatly between source and sink at the scale of neap-spring tidal cycles during the winter-spring (Fig. 3c). *In situ* production also fluctuates during the winter-spring but is small compared to hydrodynamic processes although the effects of the two are inversely related. The results suggest that *in situ* production is more important than hydrodynamic controls for small cells whereas hydrodynamic processes are more important for large cells.

Hydrodynamics also play a role as a source mechanism for ammonium throughout the season, especially summer and fall whereas biochemical processes generally serve as a sink mechanism especially during winter season (Fig. 3d). The pattern is reversed for nitrite+nitrate; hydrodynamics serve as a sink and biochemical processes serve as a source mechanism (Fig.3e). For orthophosphate, hydrodynamics play a role as a source and biochemical processes serve as a sink mechanism during summer and fall but the roles are reversed during winter and spring (Fig. 3f).

In conclusion, I used a tidally-averaged ecosystem model that incorporated physical mechanisms including advection and diffusion with a neap-spring, fortnightly tidal cycle to investigate the relationship between hydrodynamic processes and size-structured phytoplankton and nutrient dynamics in the mesohaline zone of the York River estuary. The simulated high-frequency fluctuations (days) of small cell population densities were phased with the neap-spring tidal cycle (fortnight) indicating that growth of cells over shorter time frames may be controlled by light availability coupled with water column stratification-destratification, and supported by the input of benthic-regenerated nutrients into the surface water through vertical mixing especially during the warm season in the mesohaline zone. Their growth may be limited by light availability during destratification (tidal mixing) because vertical mixing increases the mixed layer depth and decreases light. In contrast to small cells, biomass accumulation (algal blooms) of large cells may be a consequence of vertical and horizontal transport of cells through advection and diffusion from upriver and bottom water rather than *in-situ* production. This study suggests that it is important to refine the hydrodynamic processes in the ecosystem for better understanding of phytoplankton dynamics and for better management of water quality in coastal estuarine environments.

ACKNOWLEDGEMENTS

I thank Dr. Richard Wetzel, Dr. Hugh Ducklow and Dr. Harry Wang for their insights on this work. This research was supported in part by the US EPA Chesapeake Bay Program and Mokpo National Maritime University.

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(2002년 9월 11일 접수, 2002년 11월 9일 채택)