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# Simulation of advection and vertical distribution of buoyant cyanobacterial colonies in Lake Erie with a Lagrangian particle model for short-term forecasts of harmful algal blooms

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## Short-term forecasts of cyanobacterial harmful algal bloom (CHAB) spatial extent and transport

Cyanobacterial harmful algal blooms (CHABs), primarily *Microcystis*, are a recurring problem during the summer in western Lake Erie. Short-term forecasts of the spatial extent and transport of CHABs are useful to public water systems, anglers, recreational boaters, and beach users. NOAA NCCOS and NOAA GLERL have developed experimental forecast products that indicate the present location and extent of CHABs from satellite remote sensing imagery, then predict the movement of the CHAB five days into the future. These products have used Lagrangian particle tracking models to forecast CHAB transport, forced by currents from a hydrodynamic model and forecast meteorology from NOAA National Weather Service.

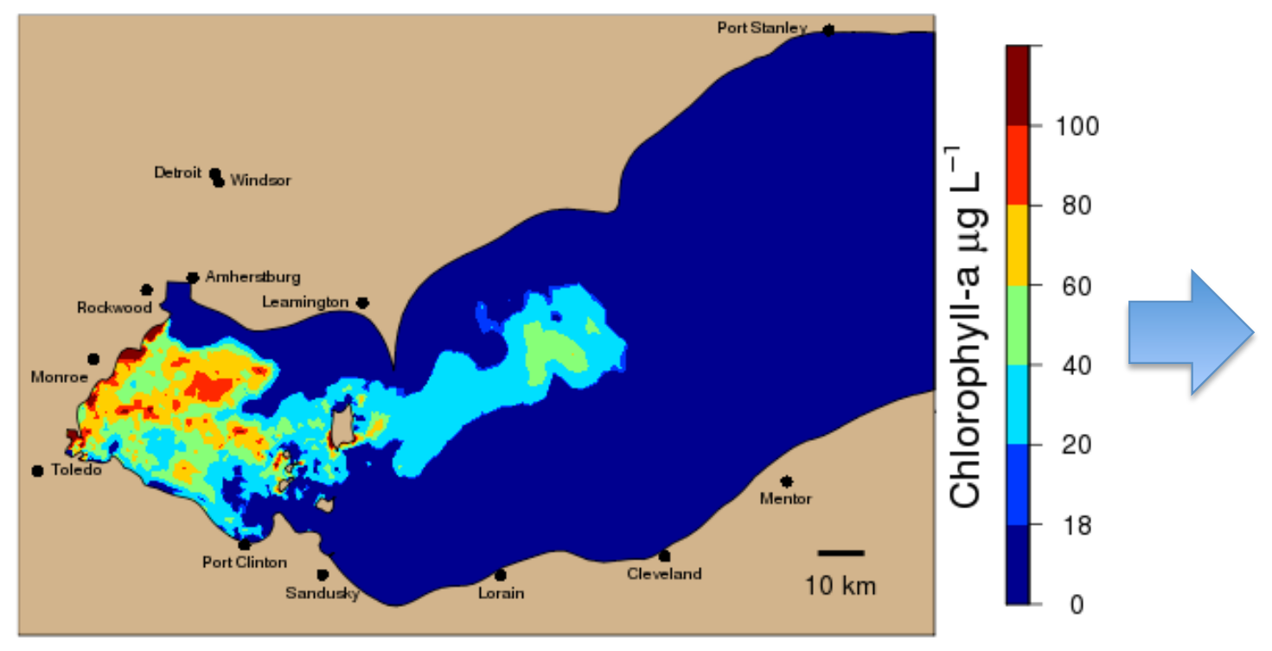
To date, the models have prescribed the CHAB only at the water surface. In nature, the vertical distribution of *Microcystis* colonies in the water column varies according to the balance between turbulent mixing and the buoyant (floating/sinking) velocity of the colonies. We evaluated the ability of a Lagrangian particle model that includes vertical mixing and buoyancy to simulate the variable vertical distribution of *Microcystis* in Lake Erie. Improved simulation of *Microcystis* vertical distribution will, 1) improve comparisons between simulated surface concentration and satellite remote sensing surface concentration, and thereby improve model initial conditions as well as facilitate model skill assessment relative to observed surface concentrations, and 2) improve simulation of bottom concentration near water intakes, which is of interest to public water systems.

This poster shows results of measured *Microcystis* colony size distribution in western Lake Erie, shows the sensitivity of simulated vertical distribution of *Microcystis* to colony buoyant velocity and simulated turbulent diffusivity for a location in western Lake Erie, and shows hindcast skill assessment of a forecast model that includes vertical mixing and buoyancy.

**Links to public products:** **Lake Erie HABs Tracker**, http://www.glerl.noaa.gov/res/HABs_and_Hypoxia/
**Lake Erie Harmful Algal Bloom Bulletin**, http://www2.nccos.noaa.gov/coast/lakeerie/bulletin/bulletin_current.pdf

**Nowcast**

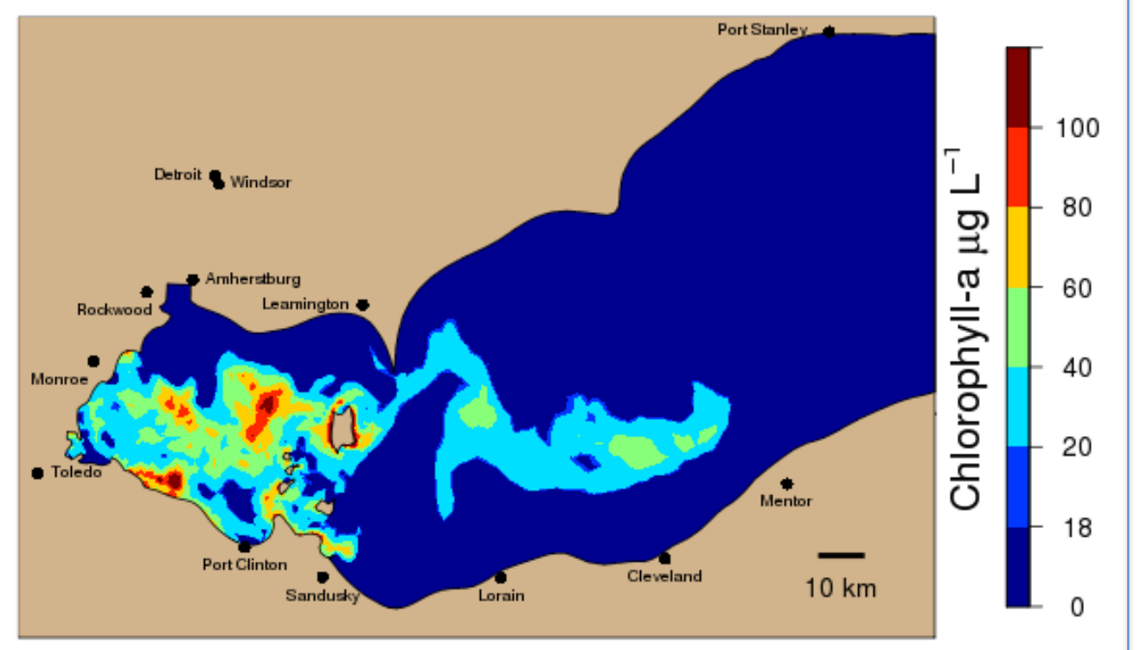
2015-08-23 20:00 EDT



Initialize CHAB bloom location and intensity in a Lagrangian particle tracking model based on satellite remote sensing imagery

**Five-day forecast**

2015-08-29 21:00 EDT



Five-day forecast of bloom intensity and location based on

1. Forecast meteorology
2. Currents from a hydrodynamic model
3. Lagrangian particle tracking model

## *Microcystis* colony size distribution and buoyant velocity in Lake Erie

The highest concentrations of *Microcystis* colonies and their associated toxins occur when buoyant colonies concentrate at the surface. *Microcystis* colonies are composed of spherical cells of ~5 µm diameter surrounded by a mucus sheath (Fig. 1). Colony diameters commonly range from ~50 – 500 µm. The buoyant velocity of a colony increases with colony diameter, for a given density difference, so colony size distribution is an important variable in determining the buoyant velocity and vertical distribution of *Microcystis*.

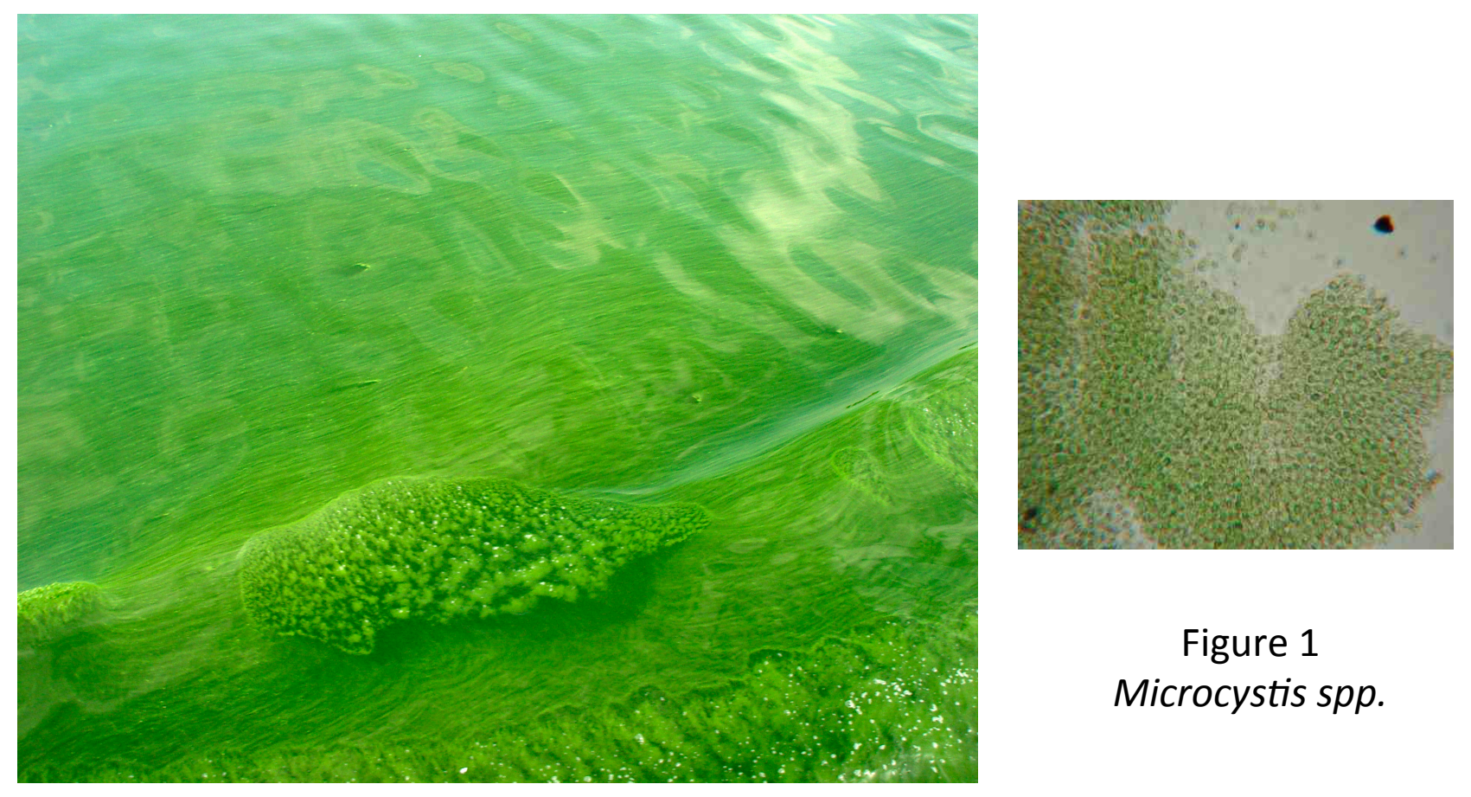


Figure 1
*Microcystis spp.*

We measured *Microcystis* colony diameter for samples collected from western Lake Erie in the summers of 2012, 2013, and 2014. In 2012 and 2013 colony diameters were measured microscopically. In 2014 we used the FlowCam (Fluid Imaging Technologies). The FlowCam captures images of individual colonies and estimates their equivalent spherical diameter (ESD) by image analysis. The irregularly-shaped particles in Figure 2 are images of *Microcystis* colonies captured by the FlowCam from a sample collected at the Toledo water intake on August 4, 2014. The pink lines indicate the colony outline identified by the image analysis algorithm, which was calibrated to identify the colony outline including the mucus sheath.

Figure 2. FlowCam images of *Microcystis* colonies

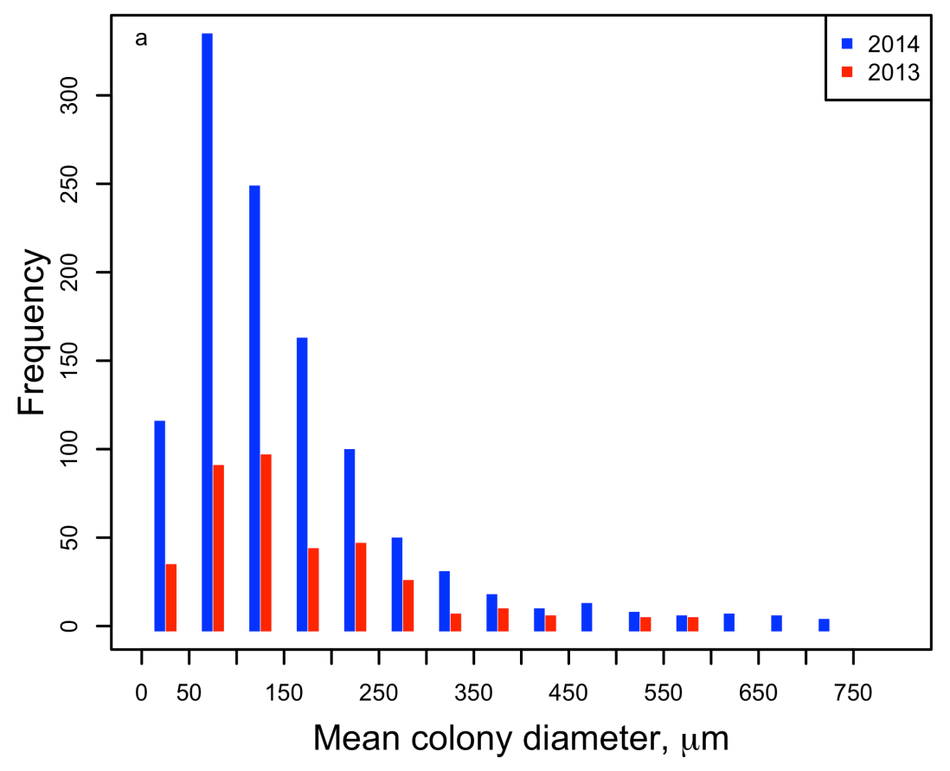


Figure 3. The *Microcystis* colony size distribution for surface samples collected in 2012 and 2013 was similar to the sample collected on August 4, 2014, and analyzed by FlowCam.

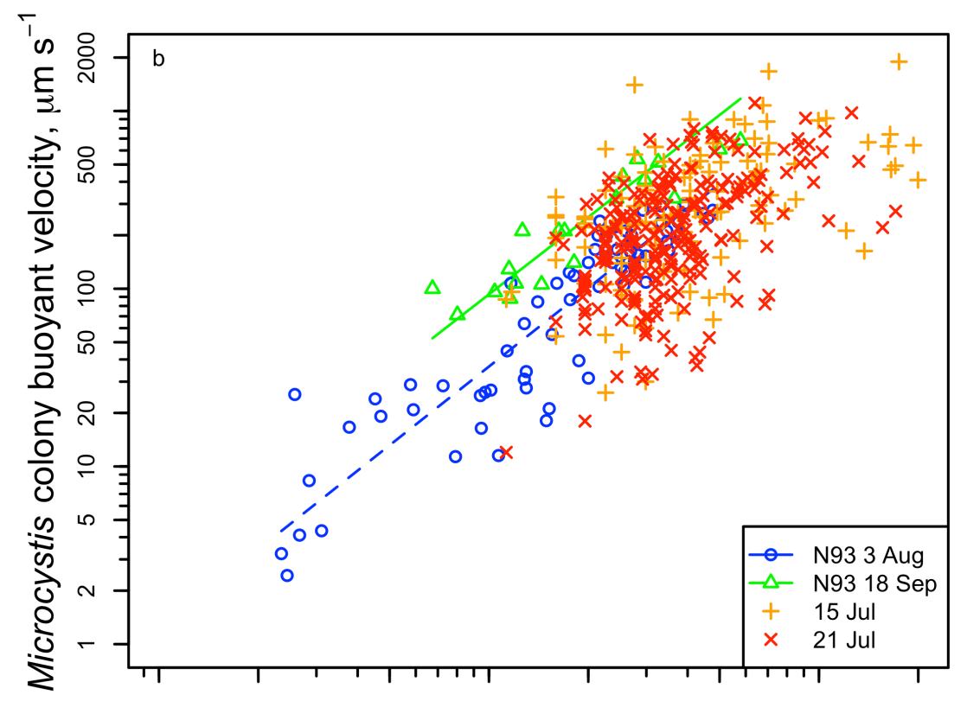


Figure 4. We measured *Microcystis* colony vertical velocity due to buoyancy by microscopic videography on two dates in 2015 (15 Jul., 21 Jul.) from samples collected in Lake Erie. Our measurements were comparable to those made by Nakamura et al. (1993) in a Lake in Japan.

Future work will determine buoyant velocity over a greater size range, and evaluate the influence of variables such as season, preceding light exposure, and nutrient status.

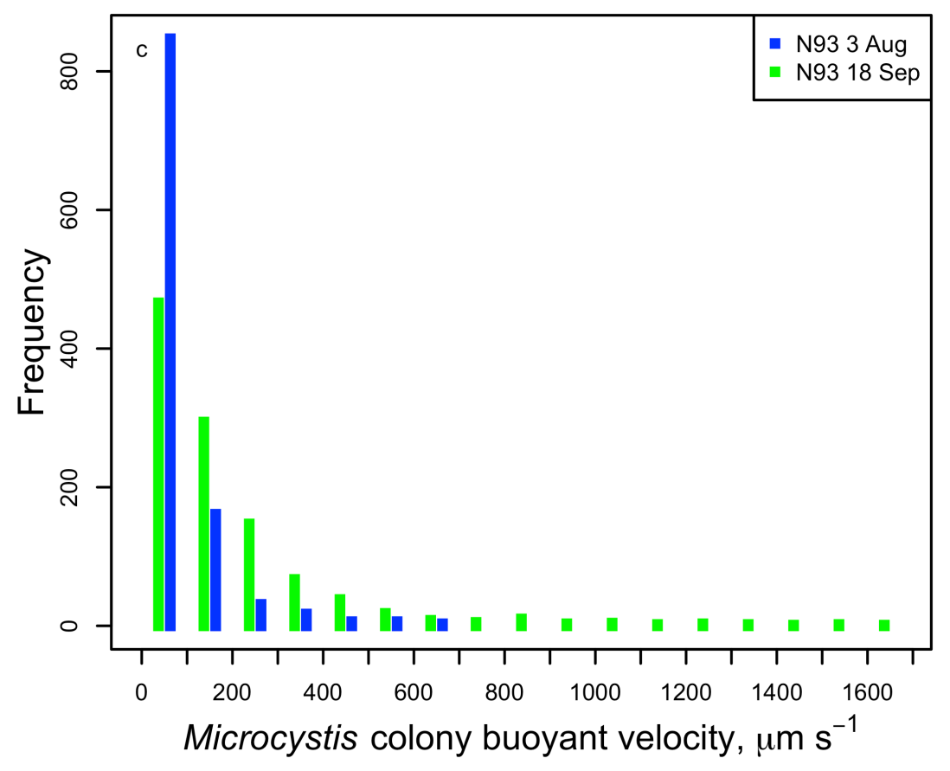


Figure 5. We estimated the frequency distribution of colony buoyant velocity for use in the Lagrangian particle model by applying an empirical relationship (Fig. 4) between *Microcystis* colony diameter and buoyant velocity (Nakamura et al., 1993) to the colony size distribution that we measured in Lake Erie (Fig. 3).

## Simulating vertical distribution of *Microcystis* colonies with the Finite Volume Coastal Ocean Model (FVCOM) and a Lagrangian particle tracking model

Western Lake Erie is polymictic, meaning that it does not continuously stratify during the summer owing to shallow bathymetry and exposure to wind. Temperature profiles simulated by the Finite Volume Community Ocean Model (FVCOM) show periods of temporary stratification that are strongest during calm afternoons when the surface is warmed by the sun and warm summer air (Figure 6a, 19-20 Aug.). At night, cooling of the surface often causes deepening of the surface mixed layer by convection. This diel cycle can be overpowered by shear-induced mixing during windy periods (Fig. 6a, 21-22 Aug.).

Turbulent diffusivity simulated by the FVCOM hydrodynamic model reflects the net effect of wind stress at the surface and static stability of the water column on turbulent mixing (Fig. 6b), and provides the forcing for the vertical random-walk mixing routine in the Lagrangian particle model. Turbulent diffusivity is strongest near the surface, in periods of high wind, and at night when the water surface is cooled, resulting in convection.

When a random-walk vertical mixing simulation is initiated with a uniform distribution of neutral-buoyancy particles, the theoretical result is a uniform concentration profile at all times, regardless of the diffusivity profile. However, random-walk simulations are susceptible to particle accumulation artifacts in the presence of sharp gradients in diffusivity if an inappropriate time step is used (Fig. 6c, 2011-08-24)

We modified the random walk mixing routine to calculate and apply the time step criterion of Visser et al. (1997), in order to avoid formation of particle accumulation artifacts by using a short time step in the presence of sharp diffusivity gradients, while maintaining a computationally efficient longer time step when conditions allowed (Fig. 6d).

In this simulation, particles were assigned buoyant velocity from the distribution shown in Figure 5 (N93 3 Aug), representing *Microcystis* colonies with a size distribution similar to the field sample collected near the Toledo water intake on August 4, 2014. The simulation produced dynamic concentration profiles that vary over periods of several hours from a uniform profile to surface concentrations of up to three times the column-mean concentration (Fig. 6e).

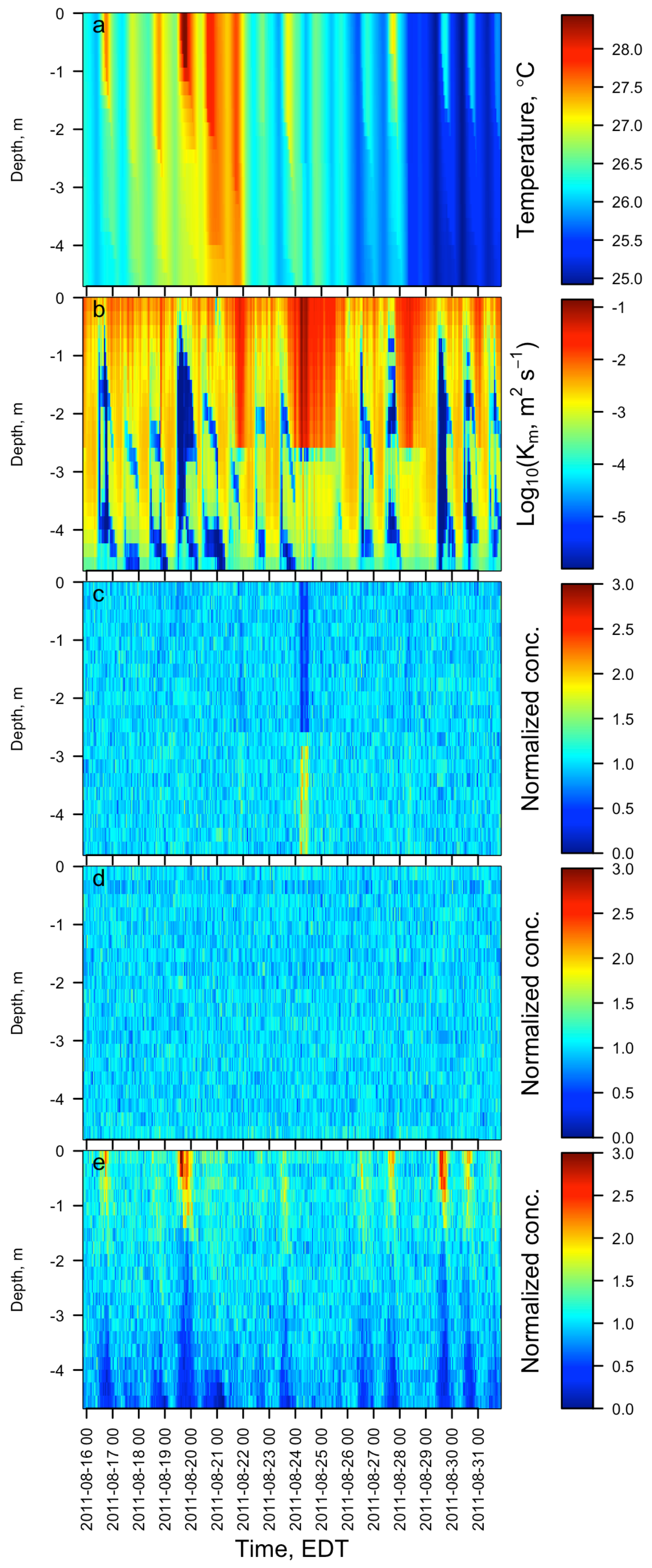


Figure 6. Model results showing time series of vertical profiles in the water column at a 5-m deep location in Western Lake Erie over a two-week period in August, 2011.

## Conclusion

1. We described an approach to simulate the vertical and spatial distribution of buoyant *Microcystis* colonies in the turbulent water column of a polymictic lake using a Lagrangian particle tracking model. The random-walk vertical mixing model using the Milstein scheme (Gräwe, U. 2011) and variable time step meeting the Visser (1997) criterion efficiently avoided particle accumulation artifacts that are a known issue in the presence of sharp gradients in diffusivity, in a way that is suitable for use throughout a 3D model domain with large spatial and temporal variability in Peclet number.
2. We estimated the frequency distribution of *Microcystis* buoyant velocity using measured size distributions and direct measurements of buoyant velocity, and showed that simulated vertical distributions were consistent with in-situ profiles of cyanobacterial concentration.
3. We incorporated the approach into to a Lagrangian particle model for short-term forecasts of harmful algal blooms (CHABs) in Lake Erie and showed significantly improved model skill in predicting changes in spatial distribution of CHABs observed by satellite remote sensing compared to an advection-only model, and improved skill over a persistence forecast through simulation day 6.

## Skill assessment of simulated cyanobacterial chlorophyll profiles in western Lake Erie

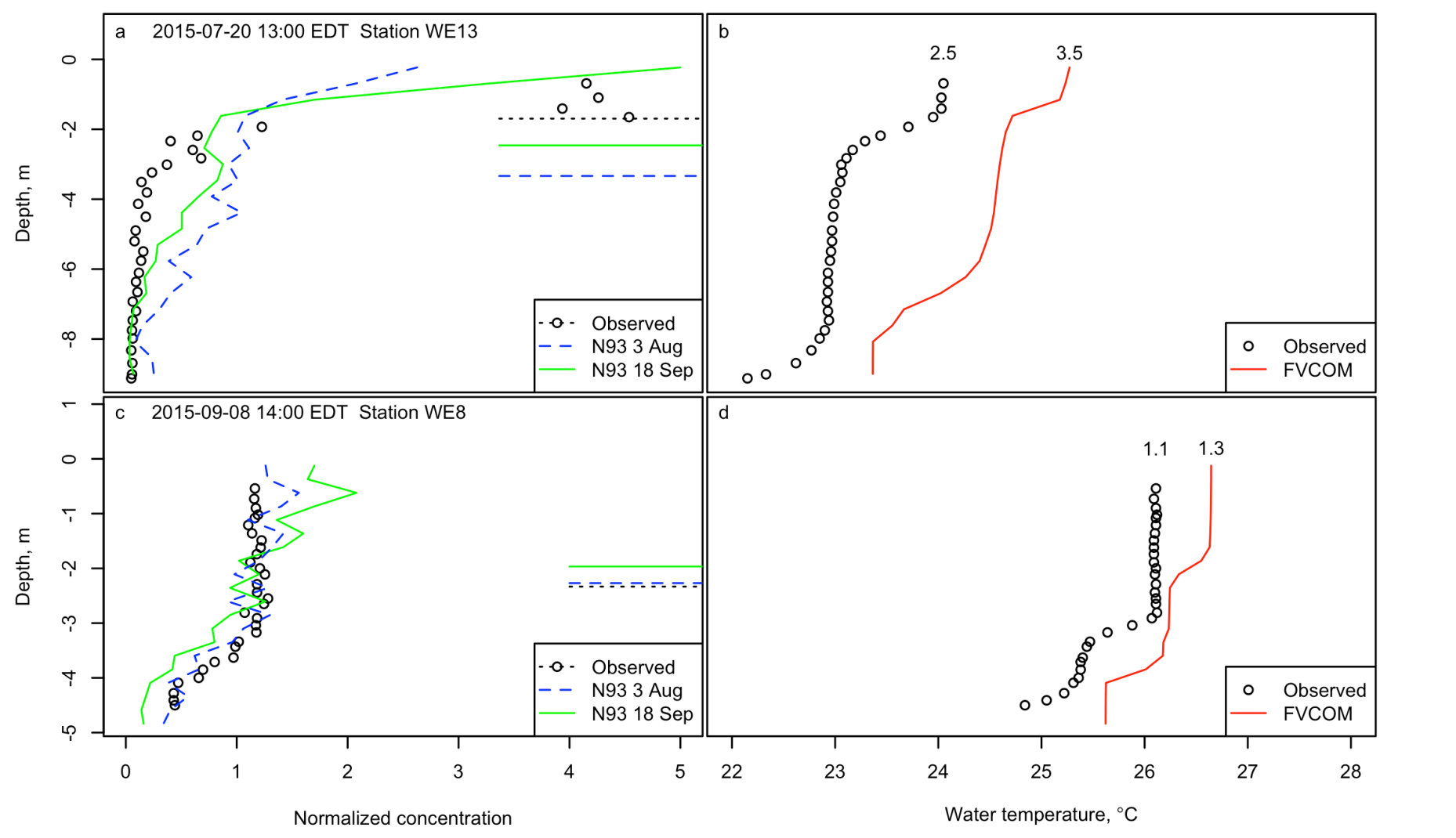


Figure 7. Vertical profiles of cyanobacterial chlorophyll concentration (Fluoroprobe, bbe Moldaenke, GmbH) and temperature in western Lake Erie, compared to model simulations

We tested the ability of the random-walk model with buoyancy to simulate realistic *Microcystis* concentration profiles by comparing measured profiles of cyanobacterial chlorophyll concentration from Lake Erie (predominantly *Microcystis*) to corresponding 1D simulations (Fig. 7a). On 20 July, the concentration profile showed strong accumulation within the surface two meters (Fig. 7a), which corresponded to a surface mixed layer defined by a weak thermocline at 2-m depth (Fig. 7b). A second profile was measured on 9 September, which showed concentration enrichment within a 3-m thick surface mixed layer (Fig. 7c), which was similarly defined by a weak thermocline at 3-m depth (Fig. 7d). The frequency distribution of simulated and observed concentration and temperature profiles compared reasonably well, as represented by the vertical center of mass of the concentration profile and static stability of the temperature profile (Fig. 8).

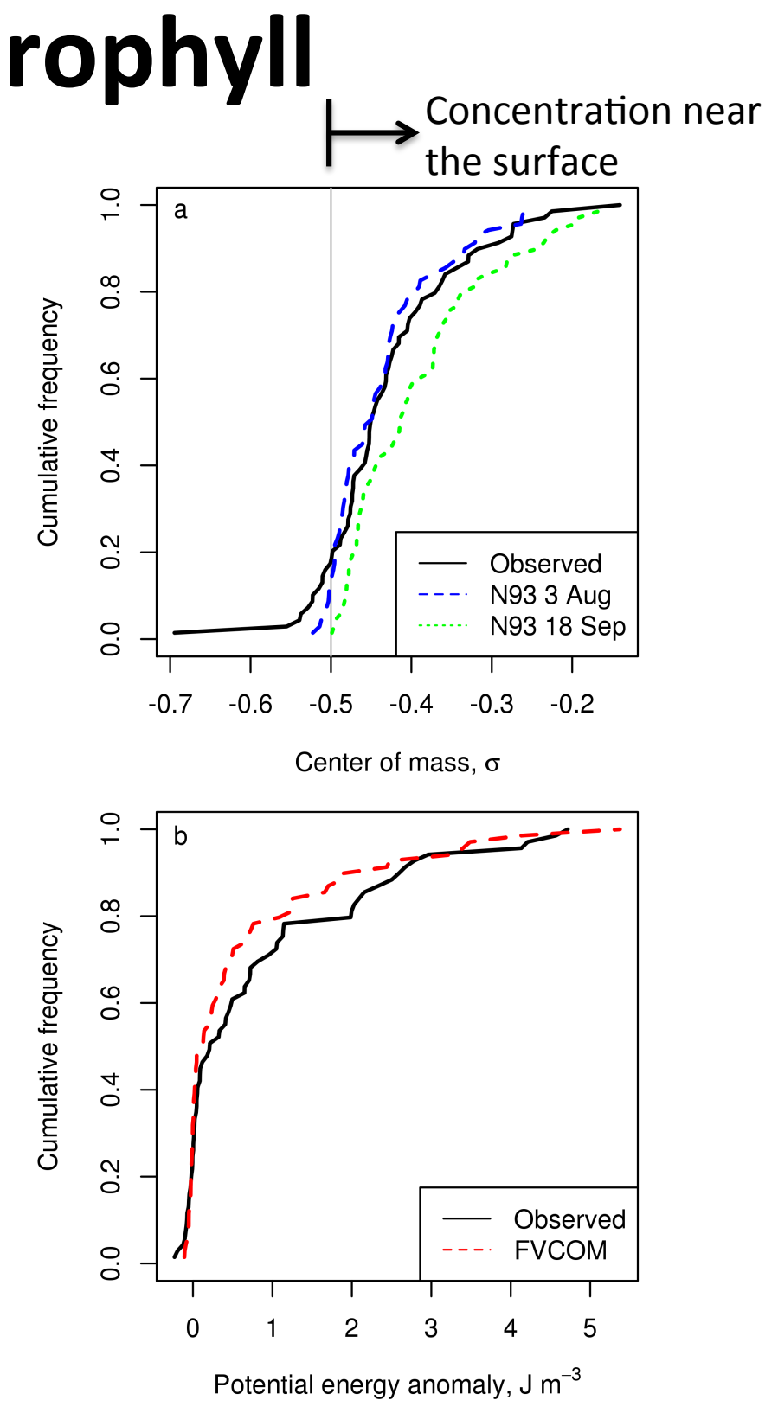


Figure 8. Cumulative frequency distributions of simulated and observed a) center of mass of the normalized cyanobacteria concentration profile, and b) potential energy anomaly (static stability) of the temperature profile for 69 profiles collected in July - September of 2015 at stations in western Lake Erie.

## Hindcast skill assessment of the CHAB transport forecast model

We compared skill statistics for CHAB presence/absence for the 2D (surface transport only) and 3D (with vertical mixing) models in hindcast simulations initialized from satellite-derived cyanobacterial chlorophyll concentration on 26 dates during the record 2011 CHAB season. Subsequent satellite images were used for model skill assessment. The frequency bias (B) gives the ratio of the number of forecasts of occurrence to the number of observed occurrences, and the Pierce Skill Score (PSS) gives the hit rate minus the false alarm rate. An unbiased forecast has a frequency bias B = 1.0. PSS values range from -1.0 to 1.0, with positive values indicating that the hit rate was greater than the false positive rate, and therefore the model had greater skill than a random forecast or constant CHAB or no-CHAB prediction.

In one example, a hindcast simulation was initialized on 6 August, which was a calm day (wind < 5 m s$^{-1}$) with an intense CHAB event throughout the central western basin (Fig. 9a). On the following day, wind increased (5-10 m s$^{-1}$), and a second satellite image indicated reduced surface CHAB intensity and distribution (Fig. 9d). The 3D simulation captured the reduced surface CHAB intensity on 7 August, while the 2D model did not, which can be seen qualitatively by comparing Figures 9e and 9f, and was indicated quantitatively by reduced frequency bias (B) of the 3D simulation compared to the 2D simulation (3D B = 1.10; 2D B = 1.34). On day 9 (15 Aug.), the simulated CHAB distribution was distinctly different between the 2D and 3D models (Fig. 9h,i). In comparison to the 2D model, the 3D model CHAB distribution was more similar to the observed distribution (3D PSS = 0.56; 2D PSS = 0.41), having less CHAB coverage in the central basin east of Sandusky and more continuous coverage along the coast from Monroe to Toledo. Both 2D and 3D models simulated the advection of CHAB to Port Clinton (Fig 9b,c and h,i), which was minimally affected by CHAB on 6 August and fully covered on 15 August (Fig. 9a,g).

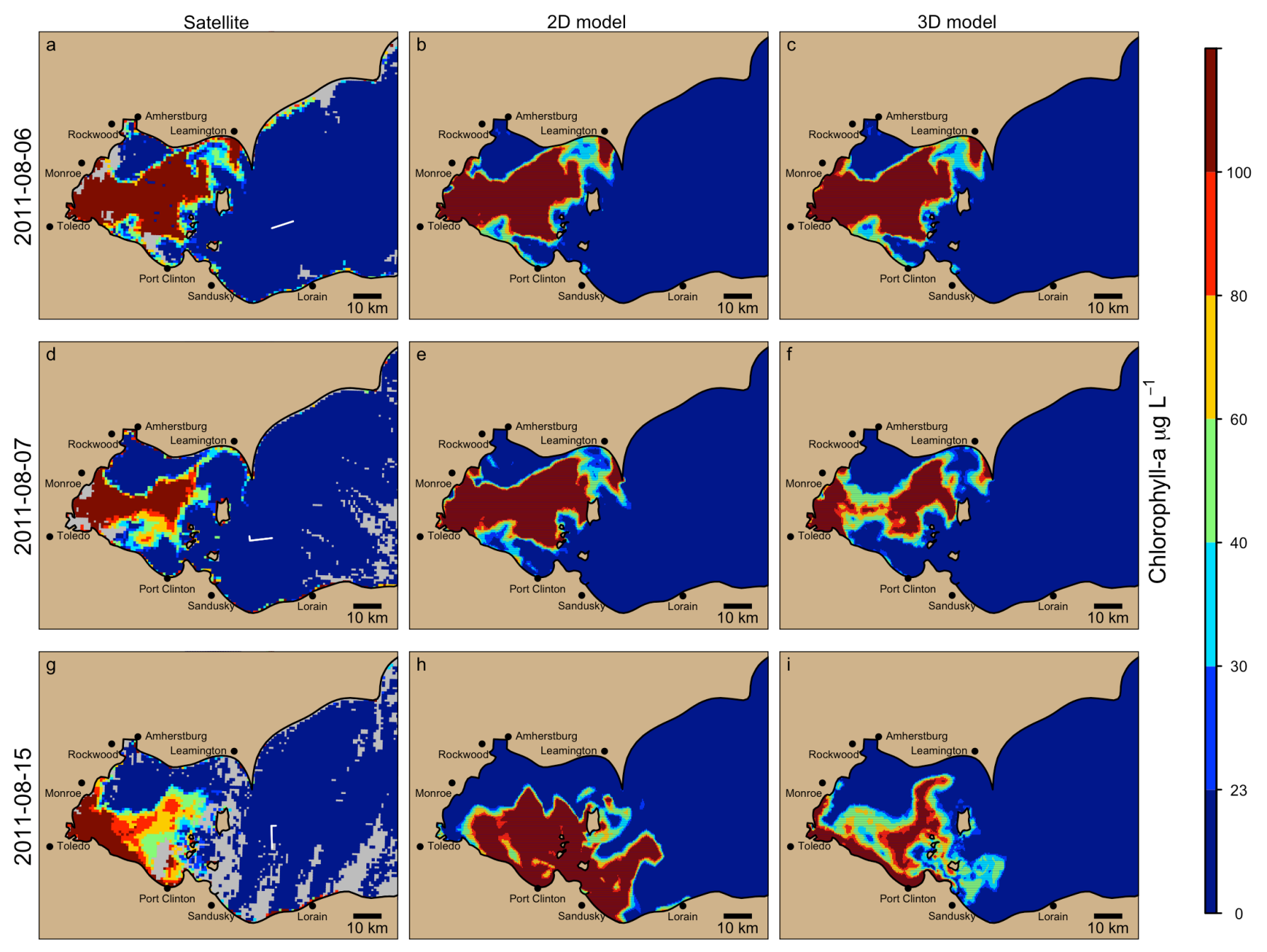


Figure 9. Comparison of 2D and 3D hindcast simulations initialized on 6 August 2011. Gray color indicates missing data.

In a second example, a hindcast simulation was initialized on 29 August, which was a date with only partial coverage by the satellite image, leaving no data over much of the western basin (Fig. 10a). Output from a previous model run was used to initialize the CHAB distribution in the western basin (Fig. 10b,c). On simulation day four (2 Sept.) a second partial satellite image indicated extensive CHAB coverage in the western basin (Fig. 10d), consistent with both models. Both 2D and 3D models underestimated the CHAB coverage, although the 3D model better matched the observed coverage (2D B = 0.81, PSS = 0.76; 3D B = 0.90, PSS = 0.84; Fig. 10d,e,f). The partial image on 2 September did not show the extensive CHAB outbreak into the central basin east of Leamington, Ontario, although it was simulated by both 2D and 3D models (Fig. 10e,f), and was revealed the following day in the 3 September satellite image (Fig. 10g). The 3D model better simulated the CHAB distribution on simulation day 5 (3 Sept.) than the 2D model (2D B = 0.79, PSS = 0.68; 3D B = 0.99, PSS = 0.80; Fig. 10g,h,i).

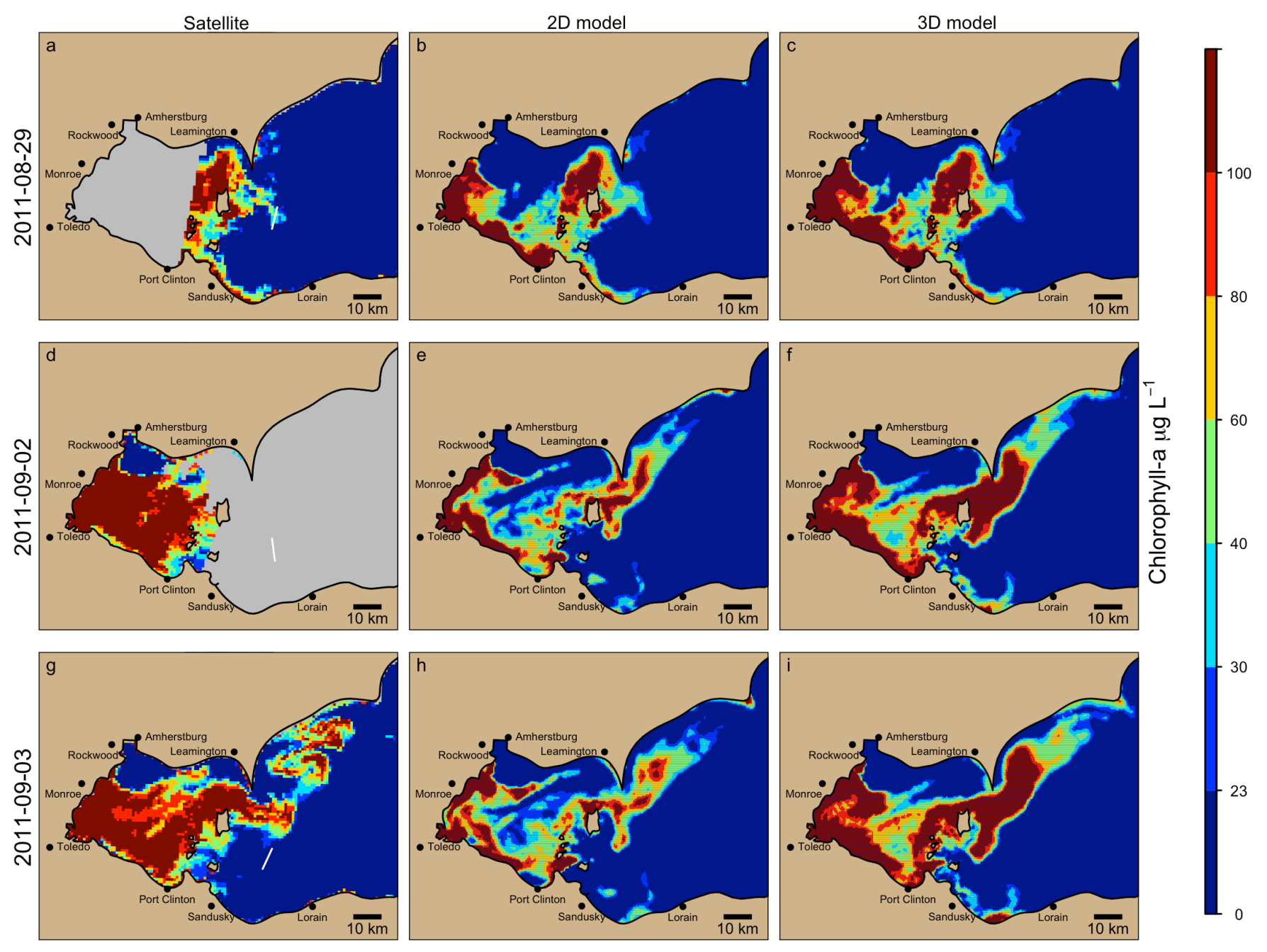


Figure 10. Comparison of 2D and 3D hindcast simulations initialized on 29 August 2011. Gray color indicates missing data.

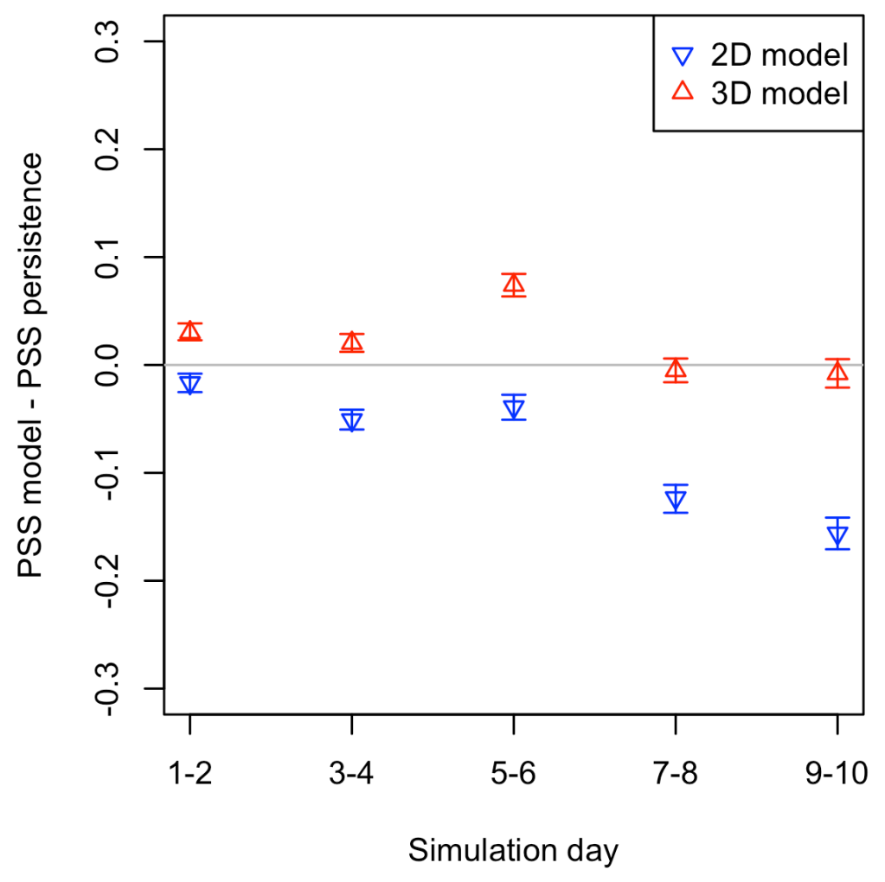


Figure 11. Pierce skill score (PSS) of the model minus PSS of the persistence forecast. The persistence forecast is a benchmark that assumes no change from the initial satellite image. Positive values indicate greater skill for the model than for the persistence forecast. Error bars indicate the 95% bootstrap confidence interval on the difference in PSS for the 26 hindcast simulations from the 2011 CHAB season, grouped into two-day intervals. The 3D model (including vertical mixing with buoyancy) had greater skill than the 2D model (advection only) and greater skill than the persistence forecast through day 6 and comparable skill out to day 10.

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