Sensitivity of simulated *Microcystis* colony vertical distribution to turbulent mixing and buoyancy in a model for short-term forecasts of cyanobacterial harmful algal blooms in Lake Erie

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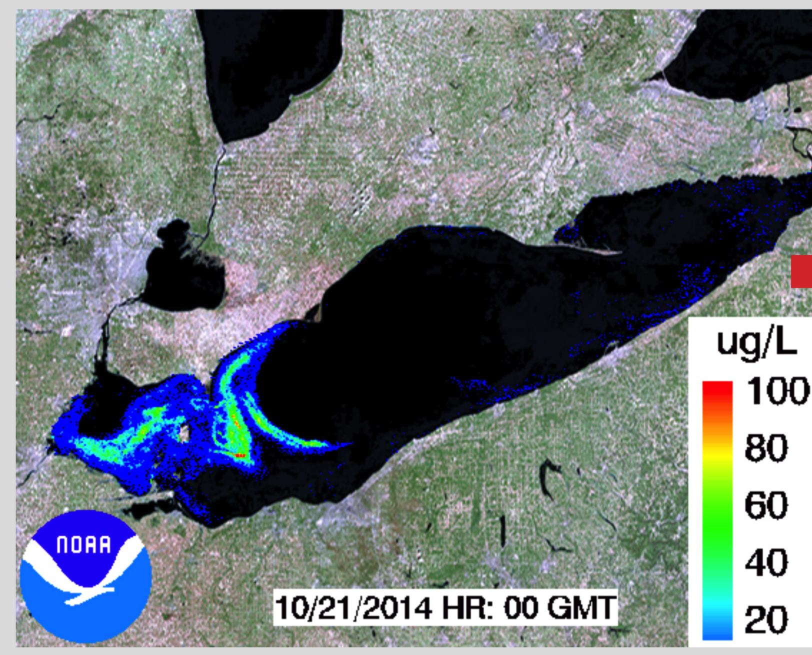
Short-term forecasts of CHAB extent and location

Cyanobacterial harmful algal blooms (CHABs), primarily *Microcystis*, are a recurring problem during the summer in western Lake Erie. Short-term forecasts of the extent and location of CHABs are potentially useful to water treatment plant operators, 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 National Weather Service.

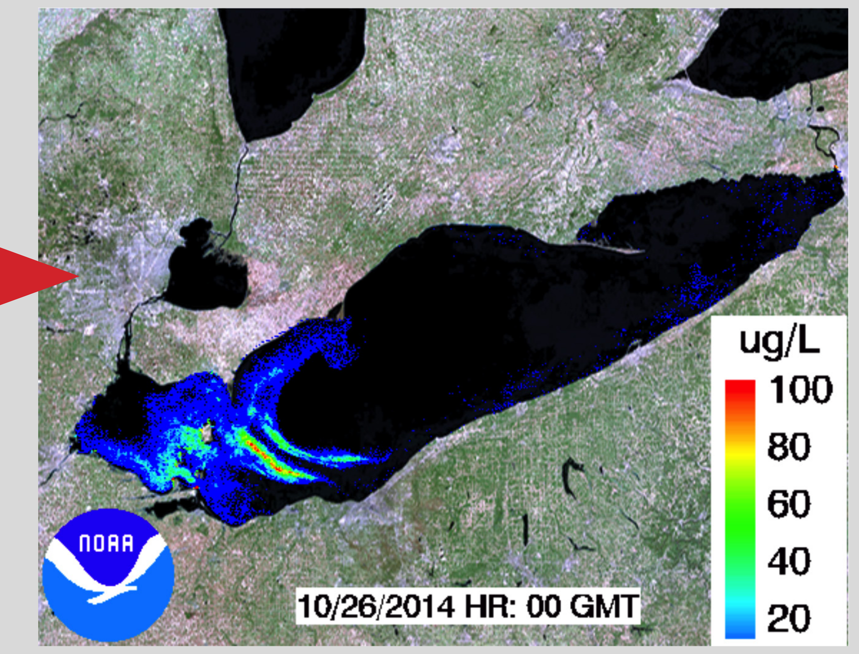
To date, the models have prescribed the CHAB only at the water surface. In nature, the vertical distribution of *Microcystis* colonies in the water column varies according to the balance between turbulent mixing and the buoyant (floating/sinking) velocity of the colonies. We are evaluating the ability 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 could, 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 may be of interest to managers.

This poster shows results of measured *Microcystis* colony size distribution in western Lake Erie, and the sensitivity of simulated vertical distribution of *Microcystis* colonies to variable colony buoyant velocity and simulated turbulent diffusivity for a location in western Lake Erie.

Lake Erie HABs Tracker (NOAA GLERL), http://www.glerl.noaa.gov/res/waterQuality/
Lake Erie Harmful Algal Bloom Bulletin (NOAA NCCOS and NOAA GLERL) www2.nccos.noaa.gov/coast/lakeerie/bulletin/bulletin_current.pdf



Lake Erie HABs Tracker nowcast position of CHAB extent and location in Lake Erie on October 21, 2014, based on MODIS satellite imagery.



Five-day forecast of CHAB extent and location in Lake Erie on October 26, 2014. The forecast indicated movement of the bloom to the southeast, based on National Weather Service forecast meteorology, currents from the Finite Volume Coastal Ocean model, and a Lagrangian particle dispersion model.

Random-walk vertical mixing in Lagrangian particle models

Lagrangian particle models attempt to simulate the trajectories of individual particles in the water column. These particles may represent actual particles (e.g., *Microcystis* colonies), but they may also be used to represent arbitrary "parcels" of water or dissolved constituents. Concentration may be calculated in a Lagrangian model by summing the total mass of particles within a selected volume. In contrast, Eulerian models simulate the evolution of concentration fields directly without attempting to track individual particles. Lagrangian models have certain advantages over Eulerian models; for example simulation of plumes on a scale finer than the model grid, and the ability to track the history of individual particle exposure to variables such as light, temperature, and nutrients, which can be useful in biological models.

A 3D Lagrangian particle model simulates advection and dispersion in two separate steps. Advection refers to movement due to 3D currents that are resolved on the grid of the hydrodynamic model, while dispersion represents movement due to the turbulent motions that are not resolved. The vertical turbulent motions are almost entirely unresolved in hydrodynamic models with a horizontal resolution of ~1km, so appropriate simulation of vertical dispersion is important to achieve realistic results in 3D Lagrangian models. This poster focuses on the vertical dispersion portion of a 3D Lagrangian particle model.

Vertical turbulent motions of particles in a Lagrangian model can be described by the following stochastic differential equation (Grawe et al. 2011).

$$dz(t) = (w + \partial_z K_z(z))dt + \sqrt{2K_z(z)}dW(t)$$

$dz(t)$: vertical displacement of the particle
w : Stoke's terminal buoyancy velocity (floating/sinking)
$\partial_z K_z(z)$: vertical gradient in turbulent diffusivity
dt : random walk time step
$K_z(z)$: vertical turbulent diffusivity
$W(t)$: Gaussian random variable with zero mean and standard deviation $\sqrt{dt}$

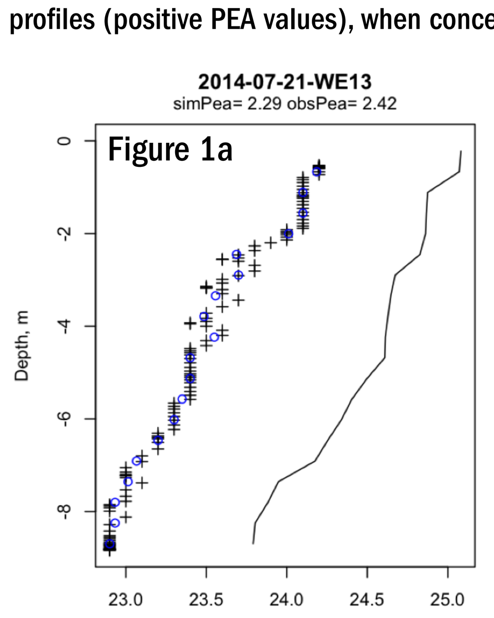
The term that includes the vertical gradient in turbulent diffusivity is important. Without it particles would accumulate in low diffusivity areas, resulting in artifacts that are easy to mis-interpret as features of interest. Similar artifacts can result from selecting an inappropriate time step. Several numerical schemes are available to solve the stochastic differential equation. The simulations in this poster used the Visser (1997) scheme, implemented in a Lagrangian particle model developed for use with FVCOM, called "ptraj" (Gilbert et al., 2010). We are evaluating additional schemes to determine which will work best in the 3D model of Lake Erie.

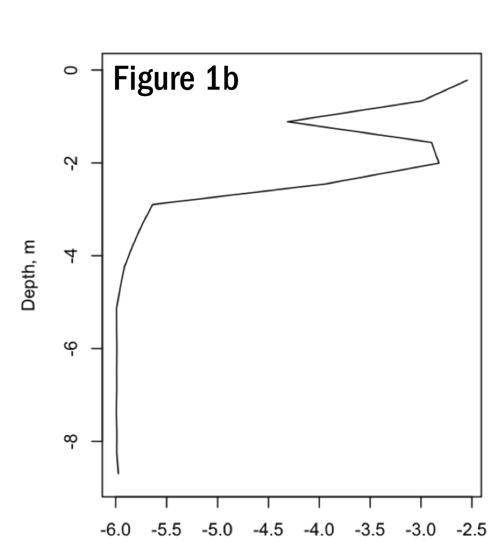
Skill assessment of simulated temperature profiles and water column stability in western Lake Erie

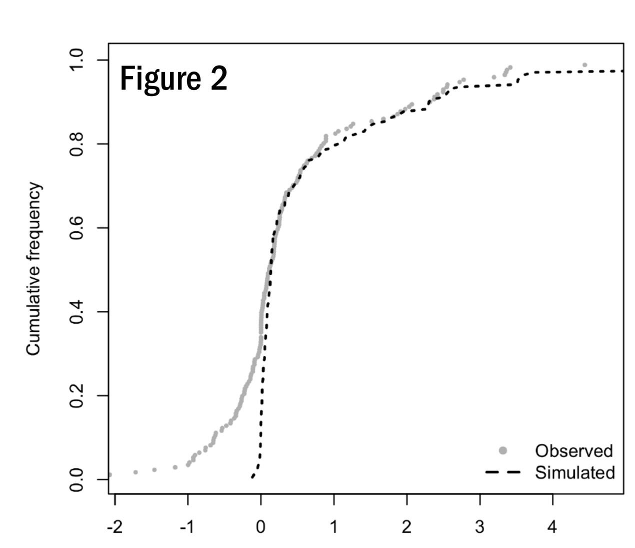
Turbulent diffusivity in the water column is a balance between processes that produce turbulence and processes that inhibit turbulence. Turbulence is produced by shear, which includes wind stress on the surface and horizontal currents with varying speed and direction by height in the water column. Static stability of the water column refers to the vertical gradient of density in the water column, which is a function of temperature for fresh water. Warming of the surface produces a stable water column, which suppresses turbulence. Cooling of the surface can cause an unstable, convective water column and enhance turbulence. One measure of the static stability of the water column is the potential energy anomaly (PEA), which is a measure of the mechanical work energy that would be required to mix a stratified water column to a uniform temperature.

Because accurate simulation of temperature profiles is critical to simulation of turbulent diffusivity, we evaluated the skill of the FVCOM hydrodynamic model in simulating static stability of the water column during the summer in western Lake Erie. Western Lake Erie is shallow, so it alternates between stratified and well-mixed profiles depending on wind and surface heat flux. Figure 1a compares a simulated temperature profile (solid line) to measurements (symbols). The temperature varies by only 1°C over the water column, but this small temperature gradient causes diffusivity to vary over orders of magnitude (Figure 1b). The model had a warm bias of about one degree, but the static stability was accurately simulated, which is the quantity of primary importance in this application (simulated PEA of 2.29 vs. observed PEA of 2.42).

Figure 2 shows the results of 273 comparisons of simulated to observed temperature profiles in western Lake Erie, similar to the one shown in Figure 1, for the summers of 2013 and 2014. The FVCOM hydrodynamic model accurately captured the frequency of occurrence of stable profiles (positive PEA values), when concentration of buoyant *Microcystis* colonies near the surface is likely to occur.

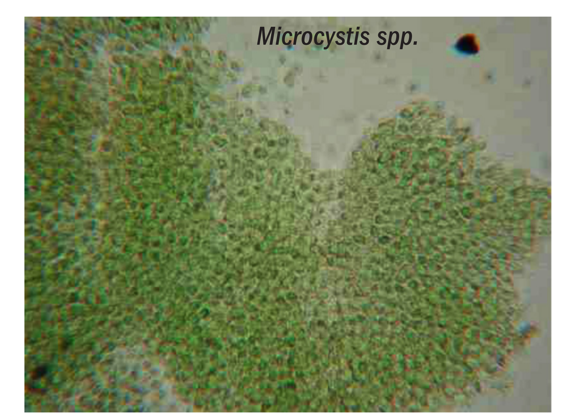






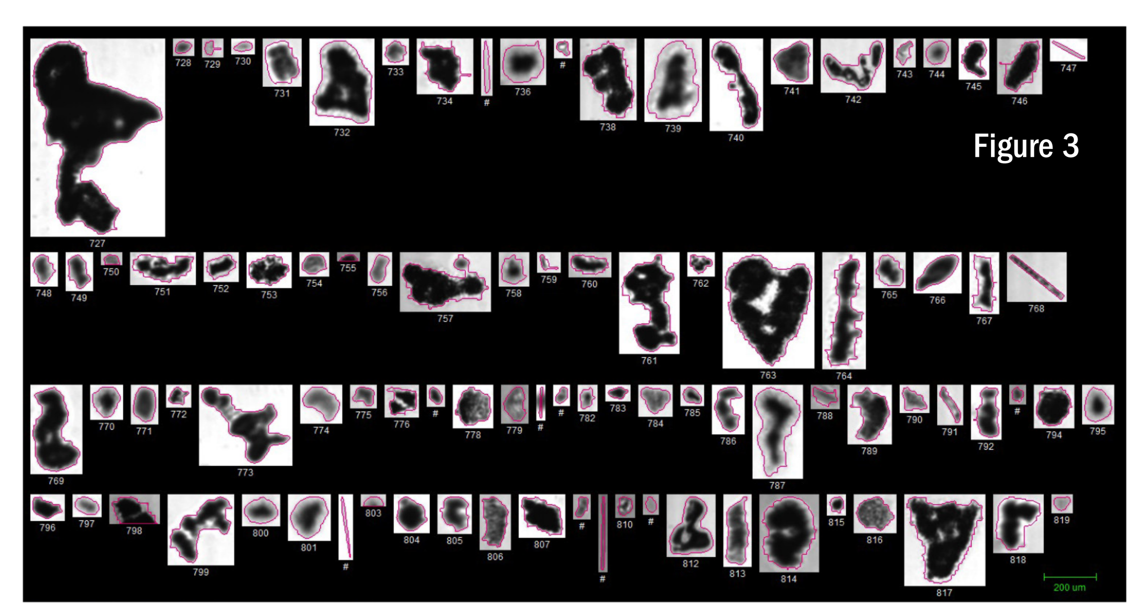
Microcystis colony size distribution and estimated distribution of colony buoyant velocity in Lake Erie

The highest concentrations of *Microcystis* colonies and their associated toxins occur when buoyant colonies concentrate at the surface.



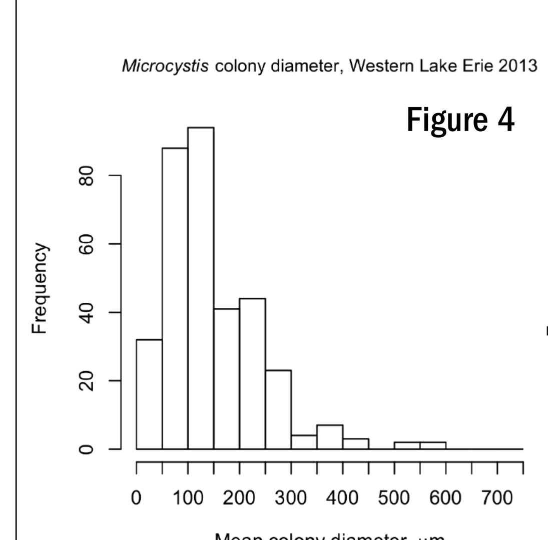
Microcystis colonies are composed of spherical cells of ~5 μm diameter surrounded by a mucus sheath. Colony diameters commonly range from ~50-500 μm. The buoyant velocity of a particle is proportional to diameter squared, for a given density difference, so colony size distribution is an important variable in determining the buoyant velocity and vertical distribution.

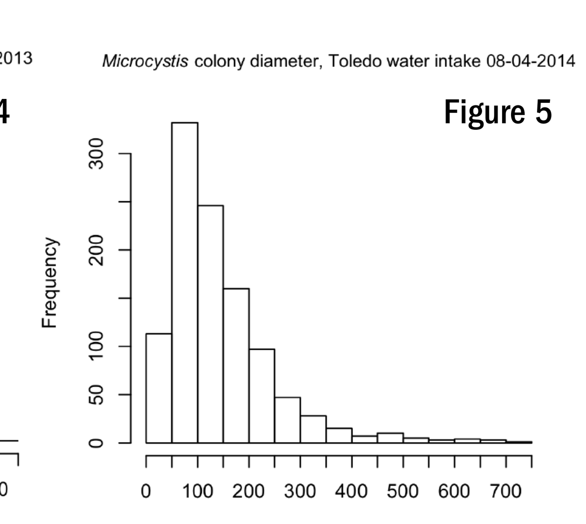
We measured *Microcystis* colony diameter for samples collected from western Lake Erie in the summers of 2012, 2013, and 2014. In 2012 and 2013 colony diameters were measured microscopically. In 2014 we used the FlowCam (Fluid Imaging Technologies). The FlowCam captures images of individual colonies and estimates their equivalent spherical diameter (ESD) by image analysis. The irregularly-shaped particles in Figure 3 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.

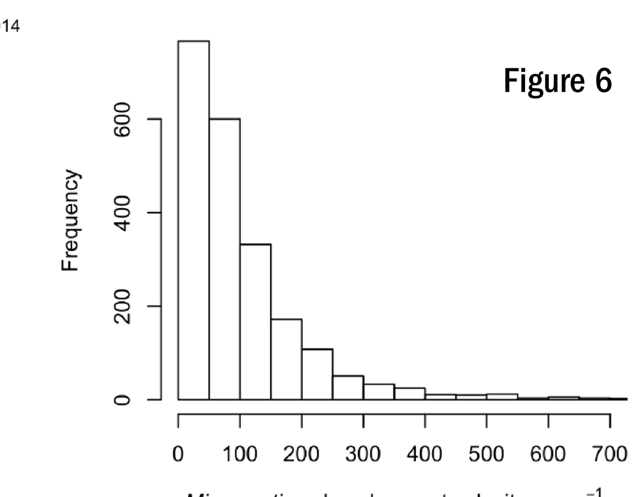


The colony size distribution for samples collected in 2012 and 2013 (Figure 4) was similar to the sample collected on August 4, 2014, and analyzed by FlowCam (Figure 5). Figure 4 represents a total of 340 colonies collected on two dates in 2012 and 11 dates in 2013. Figure 4 represents 1071 colonies collected on one date.

We estimated a distribution of colony buoyant velocity for use in the Lagrangian particle model by applying an empirical relationship between *Microcystis* colony diameter and buoyant velocity (Nakamura et al., 1993) to the size distribution of Figure 5. The estimated distribution of buoyant velocity is shown in Figure 6.

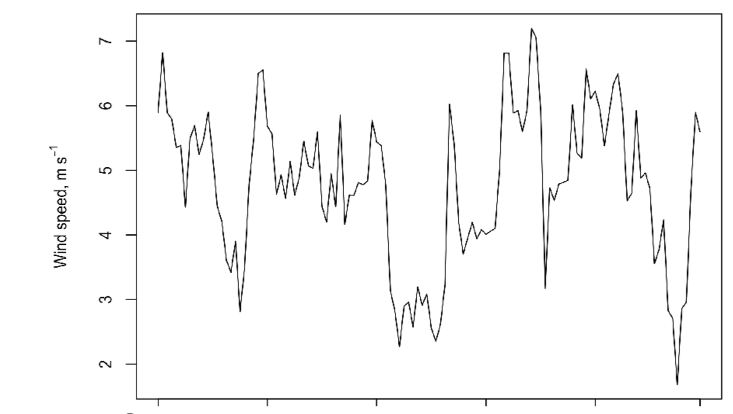




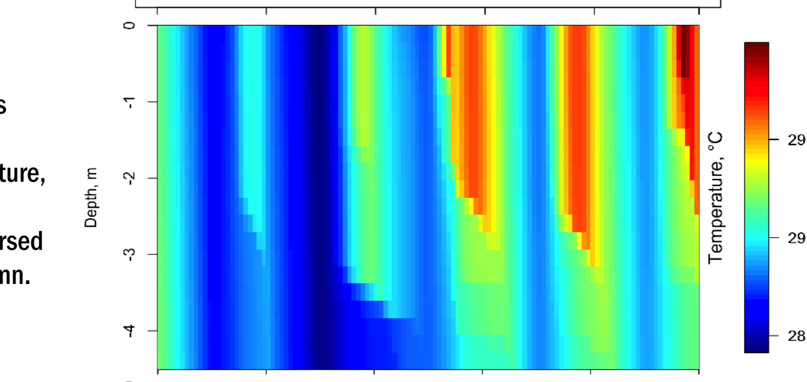


Simulating vertical distribution of *Microcystis* colonies with the Finite Volume Coastal Ocean Model (FVCOM) and a Lagrangian particle dispersion model

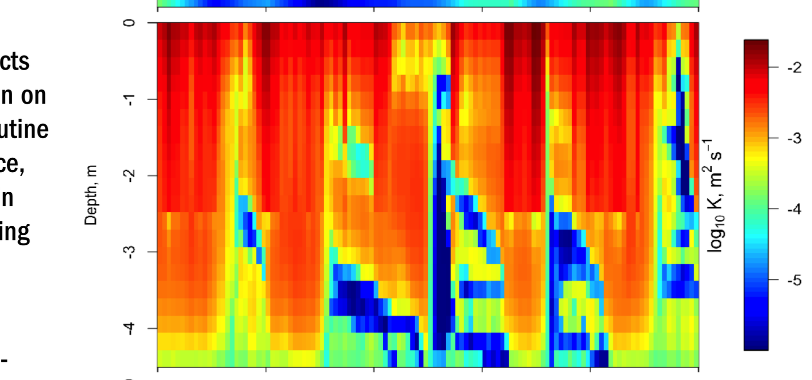
Wind speed interpolated from meteorological stations surrounding Lake Erie provided surface forcing to the FVCOM hydrodynamic model. Wind speed in this simulation varied from 1-7 m s^{-1} (2-14 kt).



Water temperature simulated by the FVCOM hydrodynamic model varied over a limited range of only 1.5 °C. However, this limited temperature variation had an important influence on static stability of the water column and vertical mixing, as shown in the plots below. The date stamp tick marks are at midnight GMT (8 PM local time). Net heating of the surface during the day due to warmer air temperature, as well as net short wave and long wave irradiance, resulted in warming of the surface, which increased the static stability of the water column. Conditions reversed at night, resulting in cooling of the surface and unstable (convective) water column.

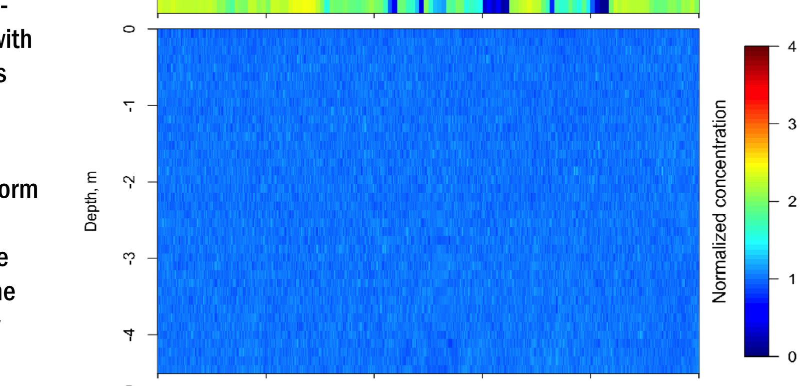


Turbulent diffusivity (K $m^2 s^{-1}$) simulated by the FVCOM hydrodynamic model reflects the net effect of wind stress at the surface and static stability of the water column on turbulent mixing, and provides the forcing for the vertical random-walk mixing routine in the Lagrangian particle model. Turbulent diffusivity is strongest near the surface, in periods of high wind, and at night when the water surface is cooled, resulting in convection. Episodes of low turbulent diffusivity occurred most often in the morning in this simulation.

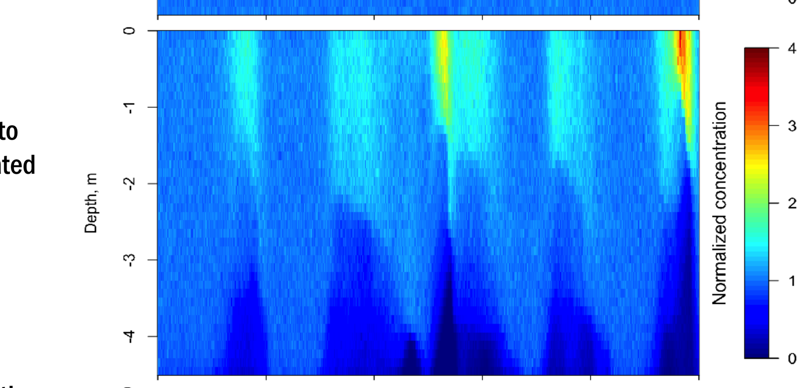


The next three figures show results of 1-D column simulations of vertical random-walk mixing from the Lagrangian particle model. The simulations were initiated with 10,000 particles uniformly distributed through the water column, and mixing was simulated with the turbulent diffusivity shown above.

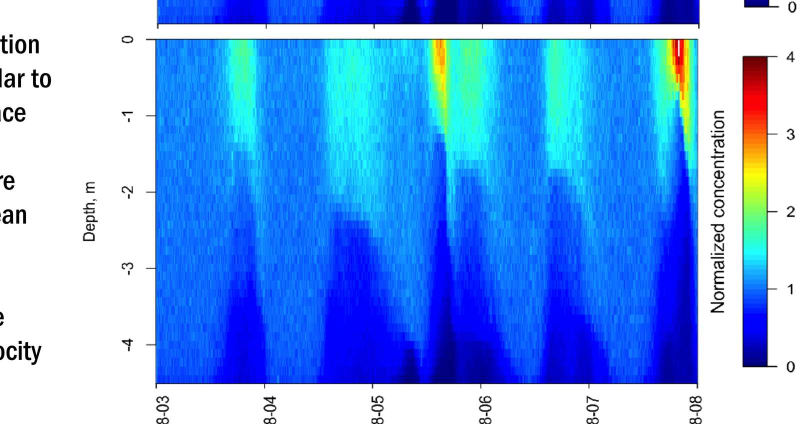
This figure shows results of a simulation with the buoyant velocity set to zero (neutrally buoyant particles). With no buoyancy, the concentration remained uniform (±25%) throughout the simulation even though diffusivity varied over orders of magnitude. This is actually an important performance test for Lagrangian particle dispersion models, called the "well-mixed condition test". If an inappropriate time step or numerical scheme is selected, particles can concentrate in low-diffusivity areas, creating artifacts that are easy to misinterpret as features of interest.



In this simulation, the buoyant velocity was set to 100 μm s^{-1}, uniformly applied to all the particles. During periods of low diffusivity the buoyant particles concentrated at the surface, resulting in surface concentrations of up to 3.6 times the mean concentration. Concentrations at the bottom reached zero.



In the final simulation, particles were assigned buoyant velocity from the distribution shown in Figure 6, representing *Microcystis* colonies with a size distribution similar to the field sample collected near the Toledo water intake on August 4, 2014. Surface concentrations were more variable than in the simulation with uniform buoyant velocity because some particles had greater buoyant velocity and responded more quickly to changes in diffusivity. Surface concentration reached 4.9 times the mean concentration (30% higher than the simulation with uniform buoyant velocity). Because some particles in the distribution had relatively small buoyant velocity, concentration at the bottom did not quite reach zero (0.4% of the mean), but the difference in bottom concentration from the simulation with uniform buoyant velocity is likely negligible.



Conclusion

1. The Visser scheme with 1 s time step performed well in the "well-mixed condition test, providing evidence that artifacts were not produced in the simulated concentrations.
2. Simulations with uniform buoyant velocity performed similarly to simulations with a realistic distribution of buoyant velocity, but maximum surface concentrations reached 30% higher in the simulation with realistic velocity distribution, showing the influence of the relatively rare large-diameter colonies.

Future Work

Additional measurements of colony size distribution are planned, along with direct measurements of colony buoyant velocity to better constrain the distribution of colony buoyant velocity in Lake Erie. The simulations shown in this poster considered only floating colonies, but *Microcystis* colonies also sink under some conditions, which would result in very different vertical distributions than what is shown here. Direct measurements of buoyant velocity will allow us to better understand the conditions under which colonies sink, and result in more accurate simulations of surface concentrations and vertical distribution.

References

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