From: Laura Blake [mailto:Laura.Blake@cadmusgroup.com]
Sent: Monday, February 13, 2012 8:29 AM
To: Roberts, Mindy (ECY); Carlin.Jayne@epamail.epa.gov; Mann.Laurie@epamail.epa.gov; Ragsdale, Dave (ECY); Pelletier, Greg (ECY); Erickson, Karol (ECY); Kendra, Will (ECY)
Cc: Fitzpatrick, James
Subject: Budd Inlet/Capitol Lake WQ Model Review

Attached and ready for your review is the memorandum that summarizes Jim's review of the model.

Please let me know if you would like to schedule a call to discuss Jim's comments.

Laura

****

Laura J. Blake
Senior Associate
The Cadmus Group, Inc.
57 Water Street
Watertown, MA 02472
Phone: (617) 673-7148
Fax: (617) 673-7348
Email: laura.blake@cadmusgroup.com

2-13-12

GEMSS/WQ3DCB Code Review

Dinoflagellate Equations and Literature Review

James Fitzpatrick (HDR|HydroQual), subcontractor to The Cadmus Group, Inc.

Introduction

At the request of the U.S. Environmental Protection Agency and the State of Washington's Department of Ecology, a review of the dinoflagellate kinetics used in the Budd Inlet/Capitol Lake water quality model was performed. The review included the following tasks:

1. Review of Model Theory
    a. Review the Kamykowski et al. (1988) paper upon which the dinoflagellate phytoplankton state-variable in the Budd Inlet/Capitol Lake model is based.
2. Review of Source Code
    a. Review the WQ3DCB module within the GEMSS model code to establish consistency between the theory presented in Kamykowski et al. paper and its implementation within the GEMSS model.
    b. Review Appendix J.1 (GEMSS Code Review as performed by Robert Ambrose) and Appendix J.2 (GEMSS code corrections by Ecology).
3. Review of Verification Tests for GEMSS
    a. Review the Verification Tests performed by the State of Washington's Department of Ecology on the GEMSS model as an additional confirmation of the correctness of the GEMSS phytoplankton code.
4. Review of Model Calibration Results
    a. A limited review of the model calibration results was performed. The purpose of this review was to evaluate whether the model responded as expected to variations in various model parameters related to phytoplankton growth dynamics.

Task 1. Review of Model Theory

The Kamykowski et al. (1988) paper was reviewed. The paper presents a summary of experimental findings concerning the swimming ability of *Gyrodinium dorsum*, a photosynthetic marine dinoflagellate, in response to changes in temperature, light intensity and buoyancy. In addition, the paper presents the results of the application of a computer model to predict the instantaneous translational velocity of *G. dorsum* against observed data. The paper presents the development of a model framework that characterizes swimming speed as a non-linear function of temperature (without time lag), a hyperbolic function of light, and Stokes' law dependent equation for settling. The resulting model framework essentially establishes a temperature and phototaxic dependency for swimming. Although the reviewer is not familiar with the implementation of such a model framework in other commonly accepted computer codes (such as WASP, EFDC, CE-QUAL-ICM, RCA, Delft3D), the theoretical basis presented in the Kamykowski paper appears reasonable and is supported by the experimental data. Further, the

Kamykowski et al. paper has been cited in at least 18 other peer-reviewed journal articles, as found by a Google Scholar search. In addition, a number of papers have reported similar observations of diel vertical migration for dinoflagellates that support the model framework developed by Kamykowski et al. (ex., Kamykowski and Yamazaki, 1997, MacIntyre et al., 1997, Ralston et al., 2007, Hall and Paerl, 2011).

A difference between the phototaxic-based swimming model for dinoflagellates developed by Kamykowski et al., (1988) and more recent models of dinoflagellate swimming is the addition of metabolism influences, i.e., nutrient-based affects (Kamykowski and Yamazaki, 1997, Liu et al., 2001). However, as reported by Aura Nova Consultants and J.E. Edinger Associates (1999), field data in the Budd Inlet seldom indicated nutrient depletion, therefore, including metabolism influences on swimming behavior of dinoflagellates is likely not necessary.

Review of Source Code

The GEMSS WQ3DCB module was reviewed to establish consistency between the theory presented in the Kamykowski et al. (1988) paper and its implementation within the GEMSS model. This reviewer found that the theory presented in the Kamykowski et al. paper was properly implemented in the GEMSS code, but did identify the following issues:

1. In converting radiation from Watts/m^2 to µEinstein/m^2-sec, a conversion factor of 4.15 (lines 369 and 425) was used. Assuming that PAR represents the 400-700 nm spectral range of solar radiation used for photosynthesis and assuming that 550 nm as the average of that range and which is typically used for the conversion, a value of 4.6 should be used for the conversion factor. However, as will be shown below, the value of 4.15, which was used in the model, is unlikely to have a significant affect on the model computations.

   The value of 4.6 results from the following computations:

$$1\frac{Einstein}{m^2-day}\times\frac{6.02\times10^{23}quanta}{Einstein}\times\frac{Watts-sec}{2.77\times10^{18}quanta}\times\frac{day}{86400sec}=2.515\frac{Watts}{m^2}$$

   or 1 Watt/m^2 = 0.3976 Einstein/m^2-day $\times$ 10^6 µEinstein/Einstein $\times$ day/86400 sec = 4.6 µEinstein/m^2-sec

   (ref: http://www.seabird.com/pdf_documents/ApplicationNotes/appnote11GeneralFeb11.pdf)

2. The Kamykowski et al. (1988) paper provided a functional description of the light dependency of the swimming speed for *G. dorsum* as

   $S_L = S_M[\tanh(\alpha I/S_M)]$,

   where S_L is the swimming speed at light intensity I, S_M is the asymptotic maximum swimming speed and α is the initial slope.

   For G. dorsum, Kamykowski et al. reported a value of S_M = 109.89 µm/sec and α = 0.55 µm m^2/µEinstein. The values reported and used in the Washington Department of Ecology model were S_M = 35 µm/sec and α = 10 µm m^2/µEinstein. Figure 1 presents a comparison between the

Kamykowski et al. coefficient set and the Washington Ecology coefficient set. As can be seen, the Kamykowski coefficient set (Figure 1a) provides more of a hyperbolic shape than does the Washington Department of Ecology coefficient set (Figure 1b) for the range of PAR presented in the Kamykowski et al paper. It is not until you get to low values of PAR that the hyperbolic shape becomes evident (Figure 1c). This is not a problem with the implantation of the Kamykowski et al theory, but rather, apparently reflects a choice in model coefficients necessary to achieve satisfactory calibration to observed field data. The end result is that the coefficient set reflects more of an "on/off" or binary switch for swimming speed as a function of ambient light, i.e., if there is any light then the dinoflagellates will begin swimming and will swim at an almost constant speed of 35 µm/sec.

As mentioned in (1) above, the conversion factor of 4.15 as opposed to a value of 4.6 has almost no affect on the resulting model computations for swimming speed (see Figure 2). The difference between swimming speeds using the 4.15 vs. 4.6 conversion factor is less than a few percent and only at very low light intensities.

Review of Verification Tests for GEMSS

A review of the verification tests for the GEMSS code was performed and all tests results verify that the model code is performing in a mass conserving and functionally expected manner.

Review of Model Calibration Results

A limited review of the model calibration results, including the by Aura Nova Consultants and J.E. Edinger Associates (1999) report, indicates that the model modifications to include vertical swimming for the dinoflagellates appears to be functioning correctly and has resulted in an improved model calibration.

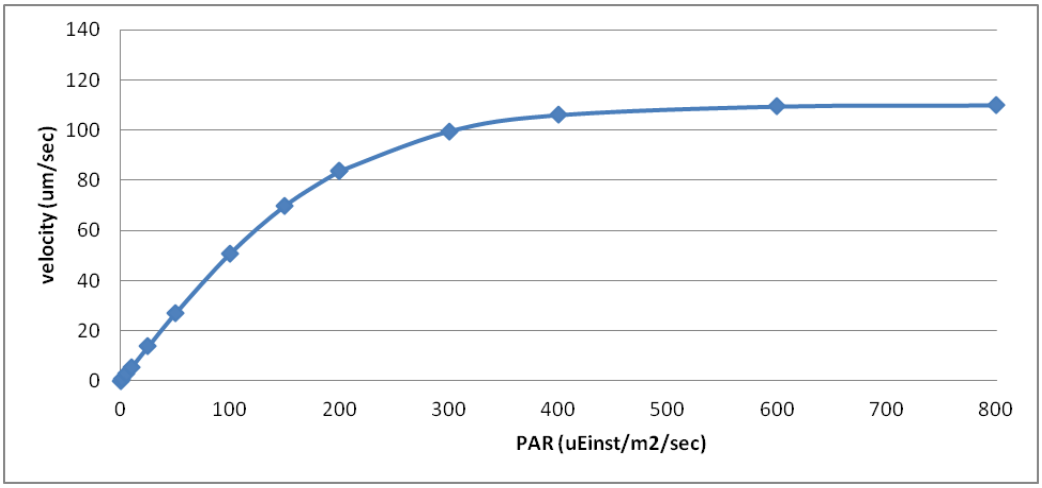

Figure 1a. Kamykowski et al. (1988) Coefficient Set

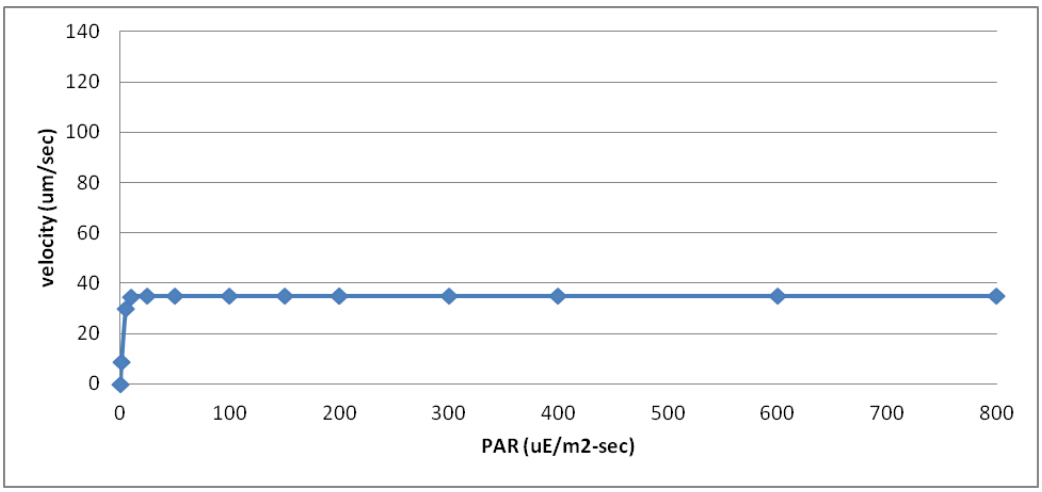

Figure 1b. Washington Dept. of Ecology Coefficient Set

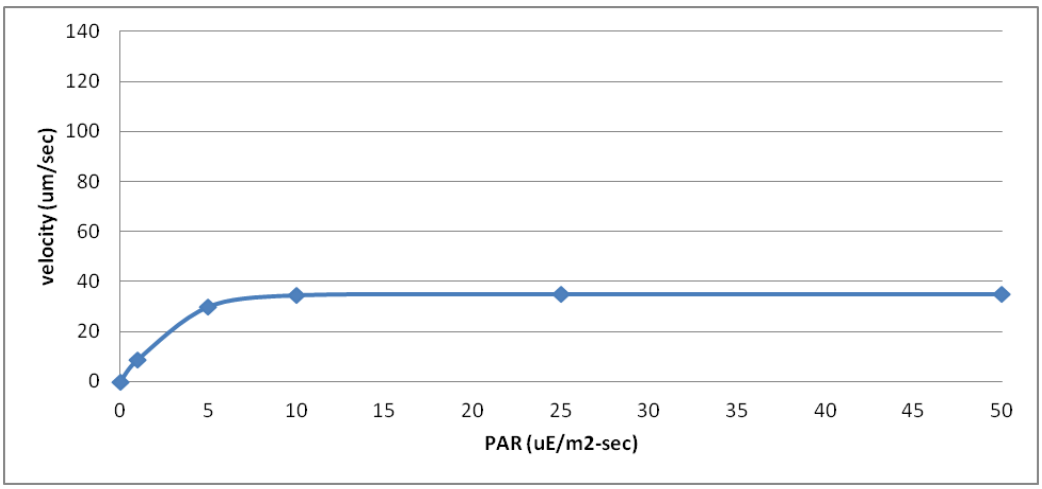

Figure 1c. Washington Dept. of Ecology Coefficient Set – Compressed PAR scale

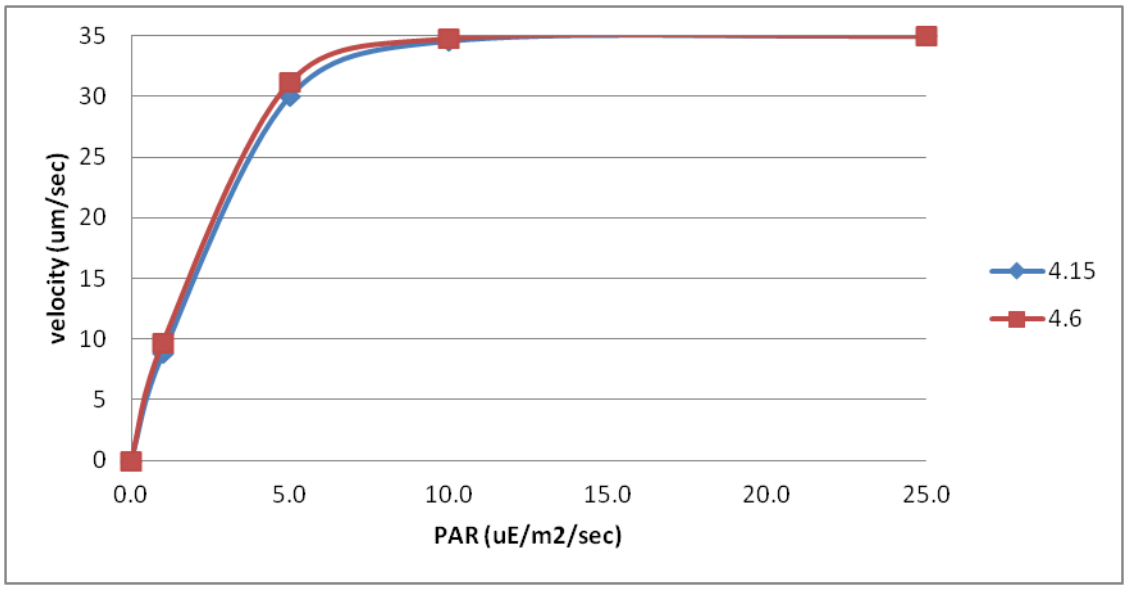

Figure 2. Comparison of Swimming Speed as a Function of Light Conversion Factor

References

Aura Nova Consultants, Inc. and J.E. Edinger Associates, Inc.,1999. LOTT NPDES Permit Modifications Modeling: Revised Interim Report. Prepared for: The Lacy, Olympia, Tumwater County Partnership (LOTT).

Hall, N.S. and H.W. Paerl, 2011. Vertical migration patterns of phytoflagellattes in relation to light and nutrient availability in a shallow microtidal estuary. Mar. Ecol. Prog. Ser. 425:1-19.

Kamykowski, D, S.A. McCollum and G.J. Kirkpatrick, 1988. Observations and a model concerning translational velocity of a photosynthetic marine dinoflagellate under variable environmental conditions. Limnol. Oceanogr. 33(1): 66-78.

Kamykowski, D. and H. Yamazaki, 1997. A study of metabolism-influenced orientation in the diel vertical migration of marine dinoflagellates. Limnol.Oceanogr. 42(5): 1189-1202.

Liu, G., G.S. Janowitz, and D. Kamykowski, 2001. A biophysical model of population dynamics of the autotrophic dinoflagellate *Gymnodinium breve*. Mar.Ecol.Prog.Ser. 210: 101-124.

MacIntyre, H.L., J.J. Cullen, A.D. Cembella, 1997. Vertical migration, nutrition and toxicity in the dinoflagellate *Alexandrium tamarense*. Mar.Ecol.Prog.Ser. 148:201-216.

Ralston, D.K., D.J. McGillicuddy, D.W.Townsend, 2007. Asynchronous vertical migration and bimodal distribution of motile phytoplankton. J. Plankton Res. 29:803-821.