LTRANS
Model Description

E. North, 18 April 2008

Overview

The **L**arval **TRANS**port Lagrangian model (LTRANS) is an off-line particle-tracking model that runs with the stored predictions of a 3D hydrodynamic model, specifically the Regional Ocean Modeling System (ROMS). Although LTRANS was built to simulate oyster larvae, it can easily be adapted to simulate passive particles and other planktonic organisms. LTRANS is written in Fortran 90 and is designed to track the trajectories of particles in three dimensions. It includes a 4th order Runge-Kutta scheme for particle advection and a random displacement model for vertical turbulent particle motion. Reflective boundary conditions, larval behavior, and settlement routines are also included. LTRANS was built by Elizabeth North and Zachary Schlag of University of Maryland Center for Environmental Science Horn Point Laboratory. Funding was provided by the National Science Foundation Biological Oceanography Program, Maryland Department of Natural Resources, NOAA Chesapeake Bay Studies, and NOAA-funded UMCP Advanced Study Institute for the Environment. Relevant publications include North et al. 2006a, North et al. 2006b, and North et al. *in press*.

Model structure

The larval transport model is designed to predict the movement of particles based on advection, turbulence and larval behavior. It has an external and internal time step (Fig. 1) and boundary condition algorithms that keep particles from leaving the model domain. The external time step is the time step of hydrodynamic model output (e.g., 10 min). The internal time step is the time interval during which particle movement is calculated (e.g., 120 s). The internal time step is smaller than the external time step so that particles do not move in large jumps that could cause inconsistency between predictions of the hydrodynamic model and the particle tracking model. At each internal time step of the larval transport model, particle motion is calculated as the sum of movement due to advection, turbulence and larval behavior. The larval transport model

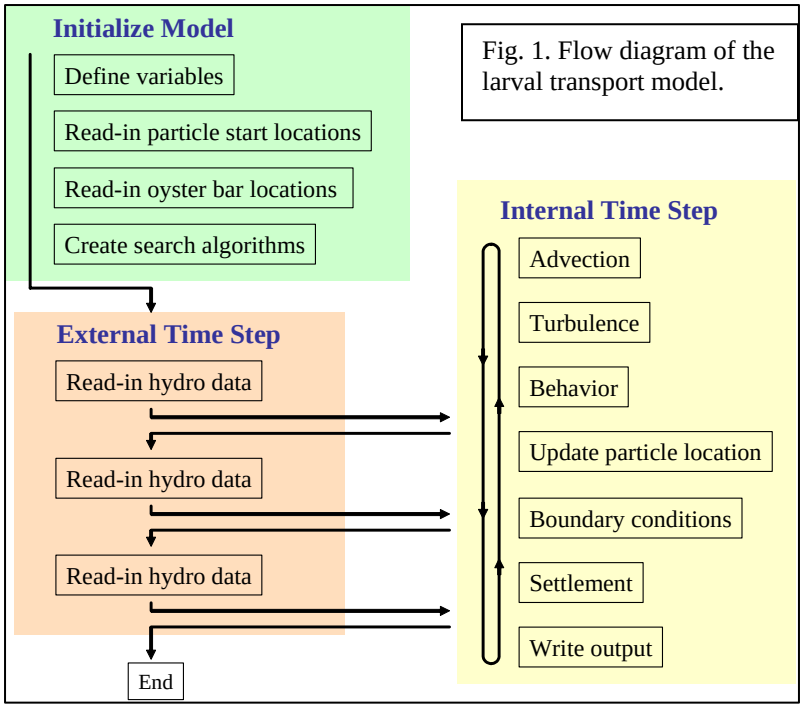

Fig. 1. Flow diagram of the larval transport model.

contains sub-models for each of these components. The turbulence and behavior routines can be turned off so that particle movement is based solely on advection. LTRANS also includes sub-models for boundary conditions and pediveliger settlement as well as specially designed search algorithms that significantly increase the speed of model computations.

Interpolation scheme

Hydrodynamic model predictions (stored in NetCDF format) are read-in and interpolated in space and time to the particle location. The first step in the process of interpolating the water properties (e.g., salinity, current velocities, sea surface height, and vertical and horizontal diffusivities) to the particle location is to determine the grid cell in which the particle is located. For this, we use the 'crossings' point-in-polygon approach (described in more detail in the settlement model section) coupled with a search algorithm for computational efficiency. Once the particle is located in a grid cell, water properties are interpolated in space to the particle location using bilinear interpolation for two-dimensional water properties (sea surface height, water depth). For three-dimensional water properties (current velocities, diffusivities, salinity), a water-column profile scheme is applied (North et al. 2006a). In this scheme, values are interpolated along each s-level to create a vertical profile of values at the x-y particle location (Fig. 2). Then a tension spline curve is fit to the vertical profile and used to estimate the water property (e.g., current velocity) at the particle location. The interpolation scheme was adapted from North et al. (2006a), streamlined to increase computational speed, and enhanced to handle model domains with irregular bottoms and non-rectangular grid geometries.

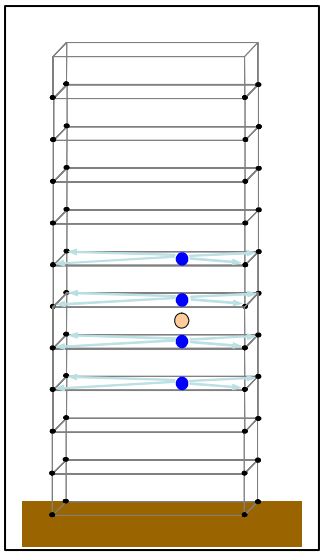

Fig. 2. Schematic of ROMS model grid and 'water column' interpolation scheme. Hydrodynamic models predictions are interpolated along s -levels to the x-y locations (blue circles) above and below a particle (orange circle). Then a tension spline is fit to the values at the x-y locations to determine the water property at the particle location.

It is necessary to interpolate in time as well as in space because the duration between successive outputs of the hydrodynamic models (i.e., the external time step) is longer than the time step of particle motion (i.e., the internal time step). To do so, water properties are estimated at the particle location (as above) at three time points that correspond to the hydrodynamic model output (i.e., at the 10-min intervals of the external time step). Then a polynomial curve is fit to the water properties at three time points and used to calculate the water properties at the time of particle motion (i.e. for the internal time step). The advection, turbulence and behavior sub-models incorporate these spatial and temporal interpolation techniques; specifics associated with each sub-model are discussed below.

Advection sub-model. A 4th order Runge-Kutta scheme in space and time is used to calculate particle movement due to advection. This scheme solves for the *u*-, *v*-, and *w*- current velocities (representing the x-, y-, and z-directions) at the particle location using an iterative process that incorporates velocities at previous and future times to provide the most robust estimate of the trajectory of particle motion in water bodies with complex fronts and eddy fields like Chesapeake Bay (Dippner 2004). Current velocities

(m s^{-1}) provided by the Runge-Kutta scheme are multiplied by the duration of the internal time step (δt) to calculate the displacement of the particle in each component direction. Displacements (m) are then added to the original location of the particle (x_n, y_n, z_n) in order to calculate the new location of the particle ($x_{n+1}, y_{n+1}, z_{n+1}$):

(1) $x_{n+1} = x_n + u\delta t$

(2) $y_{n+1} = y_n + v\delta t$

(3) $z_{n+1} = z_n + w\delta t$

The *u* and *v* current velocities are separated into north and east component directions before particle motion is estimated. Law-of-the-wall (a log layer calculation) is applied to the current velocities within one s-level of bottom to simulate reduction in current velocities near bottom.

Turbulence sub-model

Hydrodynamic models do not simulate turbulent motion at scales smaller than the grid resolution of the model. In particle-tracking models, particles can be moved in millimeter to centimeter steps, much less than the hydrodynamic model grid scale. It is necessary to add a random component to particle motion in order to reproduce turbulent diffusion that occurs at the scale of particle motion (Hunter et al. 1993, Visser 1997, Brickman and Smith 2001). A random displacement model (Visser 1997) is implemented within the larval transport model to simulate sub-grid scale turbulent particle motion in the vertical (z) direction:

(4) $$z_{n+1} = z_n + K_v'\delta t + R\left[2r^{-1}K_v\delta t\right]^{1/2}$$

where z_n = initial particle location, K_v = vertical diffusivity evaluated at ($z_n + 0.5K_v'\delta t$), δt = time step of the random displacement model, $K_v' = \partial K_v/\partial z$ evaluated at z_n, and *R* is a random number generator with mean = 0 and standard deviation *r* = 1. Unlike random walk models, random displacement models do not result in numerical artifacts if the vertical resolution is adequate to resolve sharp variations in vertical diffusivity (Visser 1997; Brickman and Smith 2002). In LRTRANS, the turbulent particle motion sub-model uses the same approach for determining K_v and K_v' at the particle location that is used in the advection model, except that 1) a smoothing algorithm is applied to the water column profile of K_v to prevent artificial aggregation of particles in regions of sharp gradients in diffusivity (North et al. 2006), and 2) a 4th order Runge-Kutta was applied in time but not in space due to computational constraints. Diffusivities at the surface and bottom are set to zero.

A random walk model is used to simulate turbulent particle motion in the horizontal direction (x- or y- directions). When K_h is constant, the random displacement model defaults to a random walk model (Visser 1997):

(5) $$x_{n+1} = x_n + R\left[2r^{-1}K_h\delta t\right]^{1/2}$$

where K_h = horizontal diffusivity evaluated at (x_n). This was acceptable for the ROMS model for which LTRANS was developed (Li et al. 2005, 2006, Zhong and Li 2006) because it was implemented with a constant value for K_h (1 m^2 s^{-1}). The model output was interpolated to the particle location using the same approach as advection (described above), except that a 4th order Runge-Kutta was applied in time only (not space) due to the computational constraints.

Behavior sub-model

The behavior sub-model includes a swimming speed component and a behavioral cue component that can depend upon species and developmental stage. The swimming speed component controls the speed of particle motion due to behavior. Swimming speeds can be set as constant or as a function of particle age. The behavioral cue component regulates the direction of particle movement. To simulate random variation in the movements of individual larvae, the direction of particle motion is assigned a random component that can be weighted so that particles have a tendency to move up or down depending on species and/or age of particle.

Settlement sub-model

The purpose of settlement sub-model is to determine if a particle is inside or outside suitable habitat. Once a particle reaches a specified age, the settlement module tests the location of pediveliger-stage particles every internal time step (e.g., every 2 min) to determine if they are within the boundaries of a cultch polygon. If so, then they settle and stop moving (Fig. 3). To determine if the particle is inside or outside an irregularly shaped polygon, the 'crossings method', a 'point-in-polygon' technique is applied. A ray, parallel to the x-coordinate axis, is shot from the particle (a point) to the east. The number of times the ray intersects with the line segments of each polygon is calculated. If the number of intersections is odd, then the particle is within the polygon. If the number is even, then the particle is outside the bar boundaries. A search restriction algorithm ensures that the locations of particles are tested only for nearby polygons to reduce computation time.

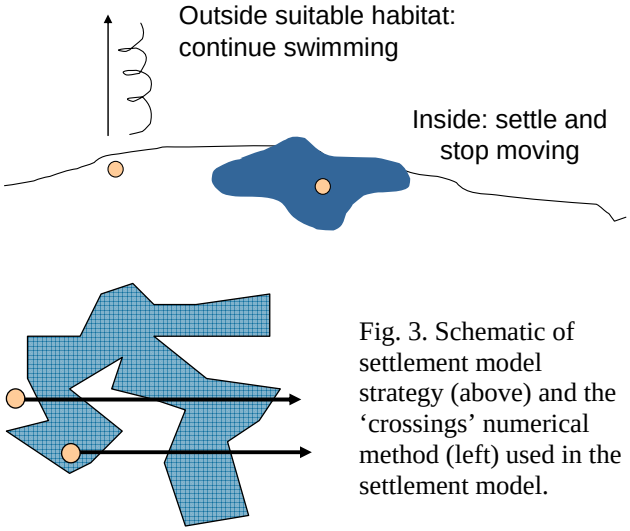

Fig. 3. Schematic of settlement model strategy (above) and the 'crossings' numerical method (left) used in the settlement model.

Boundary conditions

Before particles settle or die (i.e, between the time they are released and the time they stop moving), the location of each particle is tested every internal time step to ensure that it remains within the model boundaries. If the motion of the particle causes it to exceed the boundaries, the particle is placed within the model domain as specified below.

Vertical boundaries (surface and bottom) are specified for each particle by interpolating sea surface height and bottom depth to the x-y location of the particle. If a particle passes through the surface or bottom boundary due to turbulence or vertical advection, the particle is placed back in the model domain at a distance that is equal to the distance that the particle exceeds the boundary (i.e., it is reflected vertically). If a particles passes through the surface or bottom due to particle behavior, the particle is placed just below the surface or above the bottom (i.e., it stops near the boundary).

Reflective horizontal boundary condition routines keep particles within the model domain. For ROMS, boundaries are taken to be half-way between water and land grid points. Boundary points of the main land/sea boundary and each individual island are ordered to create closed polygons. The ‘crossings’ point-in-polygon approach is used to determine if a particle is inside or outside the model boundaries. If the particle is on land or on an island, the particle is reflected off the boundary with an angle of reflection that equals the angle of approach to the boundary. The distance that the particle is reflected is equal to the distance that the particle exceeded the boundary. The horizontal boundary condition routine allows multiple reflections within one time step.

Concluding thoughts

The LTRANS model is designed to maintain fidelity with hydrodynamic model predictions. All interpolation occurs from the original staggered grid of the u, v, and rho grid points directly to the particle location. In addition, horizontal interpolation occurs along s-levels in an attempt to follow the structure of the hydrodynamic model in regions of changing bathymetry. The cost of these interpolation schemes is likely in computation time; the benefits have not been quantified. The LTRANS model was developed to simulate oyster larvae in Chesapeake Bay, a region with complex bathymetry and horizontal and vertical current shears. It is not know whether the LTRANS interpolation schemes would be appropriate in other systems, and, if so, in what conditions they should be used.

Literature Cited

Brickman, D., and P. C. Smith. 2002. Lagrangian stochastic modeling in coastal oceanography. Journal of Atmospheric and Ocean Technology 19: 83-99.

Dippner, J. W. 2004. Mathematical modelling of the transport of pollution in water, in *Mathematical Models*, edited by J. A. Filar and J. B. Krawczyk in *Encyclopedia of Life Support Systems* (EOLSS), Developed under the Auspices of the UNESCO, Eolss Publishers, Oxford,UK, [http://www.eolss.net].

Hunter, J., P. Craig, and H. Phillips. 1993. On the use of random-walk models with spatially-variable diffusivity. Journal of Computational Physics 106: 366-376.

Li, M., L. Zhong and W.C. Boicourt. 2005. ROMS simulations of Chesapeake Bay estuary: sensitivity to turbulence mixing parameterizations and comparison with observations. Journal of Geophysical Research v.110: C12004, doi:10.1029/2004JC002585.

Li, M., L. Zhong, W. C. Boicourt, S. Zhang and D.-L. Zhang. 2006. Hurricane-induced stormsurges, currents and destratification in a semi-enclosed bay. Geophysical Research Letters 33: L02604, doi:10.1029/2005GL024992.

North, E. W., R. R. Hood, S.-Y. Chao, and L. P. Sanford. 2006a. Using a random displacement model to simulate turbulent particle motion in a baroclinic frontal zone: a new implementation scheme and model performance tests. Journal of Marine Systems 60: 365-380.

North, E. W., Z. Schlag, R. R. Hood, L. Zhong, M. Li, and T. Gross. 2006b. Modeling dispersal of *Crassostrea ariakensis* oyster larvae in Chesapeake Bay. Final Report to Maryland Department of Natural Resources, July 31, 2006. 55 p.

North, E. W., Z. Schlag, R. R. Hood, M. Li, L. Zhong, T. Gross, and V. S. Kennedy. *in press*. Vertical swimming behavior influences the dispersal of simulated oyster larvae in a coupled particle-tracking and hydrodynamic model of Chesapeake Bay. Marine Ecology Progress Series 359: 99-115.

Visser, A. W. 1997. Using random walk models to simulate the vertical distribution of particles in a turbulent water column. Marine Ecology Progress Series 158: 275-281.

Zhong, L. and M. Li. 2006. Tidal energy fluxes and dissipation in the Chesapeake Bay. Continental Shelf Research 26: 752-770.